Digital in-line holography for near field observation of liquid-liquid flow

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Abstract

Liquid-liquid extraction is used in many industrial processes. Such processes involve liquid-liquid flows, called emulsions, which can be successfully characterized by especially suited holographic techniques. Because the droplets are millimeter size, a near-field diffraction regime is observed. This regime departs from conventional holography and requires adapted numerical solutions. Due to droplets transparency positioning could not be achieved by usual focusing methods based on research of singularities. The only suitable method is based on calculating an indicator. To be effective a segmentation of the image into individual diffraction patterns is needed. As initial reconstruction can lead to errors, to further improve robustness, the hologram restitution is checked, and then the four parameters, radius and position, are optimized to fit the acquired hologram. If some missing droplets are found, they are identified and included. As a result about slightly less than twice as many drops are included, leading to a shadow density of 20%. Results presented in this communication are on a dedicated device. Outlooks are regarding the adaptation to cylindrical geometry of industrial columns. To address this point a prospect study, using fractional Fourier transform and transfer matrix models, has been conducted.

1 Introduction

Digital holography (DH) is a suitable technic, by which particles can be positioned in 3D space using a single camera. It is used for a broad range of applications including particle image velocimetry (PIV) and particle tracking velocimetry (PTV) [1], live cell imaging [2], and microscopy [3]. The first applications this technique to the characterization of dispersed phases in a two-phase flow were recently described [4], demonstrating that it is capable of simultaneously measuring the size and 3D position of droplets in rapid motion in the continuous phase [5]. Regardless of their applications, most of the examples reported in the literature refer to diffracting objects typically ranging in size from a few micrometers to a few hundred micrometers, observed at distances of the order of ten millimeters. This corresponds to a Fresnel number ($N_f = \pi d^2/4\lambda z$, where d is the particle diameter, λ the laser wavelength, and z the distance between the particle midplane and the observation plane) not exceeding 10^{-2}, i.e. to diffraction conditions intermediate between Fresnel diffraction and Fraunhofer diffraction.

Moreover, the small particle size allows the presence of a large number of elements in the field of view without any significant degradation of the signal to noise ratio, as defined by Royer's criterion [6]. According to this criterion, holograms remain usable as long as the shadow density ($SD = \pi \sum_i d_i^2 / 4S$ if S is the sensor area) remains below 10%. Conversely, when characterizing emulsions the droplets range in diameter from a few hundred micrometers to two or three millimeters and are observed from a distance of a few tens of centimeters [7]. The Fresnel number is then between 0.5 and 15, which corresponds to nearfield diffraction of transparent objects and requires special hologram processing.

In this communication we propose a hologram processing method to address these issues. The specifics of observing phase objects in the very near field are outlined and the hologram processing method is then presented. This is a two-step process: initial focusing followed by optimization, in which the holograms are processed in sections. The measurement of millimetric transparent droplets ascending in a liquid-liquid flow is then described as an example of processing experimental results. Finally an outlook addressing measurements in astigmatic conditions induced by the geometry of industrial columns is presented.

2 Characterization of nearfield transparent droplets in holographic images

The use of digital holography to characterize millimeter-size transparent droplets observed in the near-field requires taking into account the refraction effect. As illustrated in Figure. 1, synthetic holograms produced by using exact electromagnetic calculations, based on generalized Lorenz–Mie theory (GMLT) [8], exhibit a refraction effect for millimeter-size transparent droplets. It could prevent hologram processing. Taking refraction into account requires an addition to the opaque disk model usually used in digital holography. Fitting on the experimental results have demonstrated that refractive effect could be simulated by adding a phase term at the center of the opaque disk model [7].

Moreover By reconstructing GLMT synthetics holograms using free-space transfer function in the Fresnel approximation [9], differences in the size and structure of the diffraction patterns appear for both the phase and intensity (Figure. 1). For small to intermediate size droplets, which holograms are rather similar to ones of fully opaque disks, the intensity is virtually constant, dropping to a single local minimum at the position of the droplet. The phase varies with 1/z [10], with a characteristic jump on the droplet midplane. For millimeter-size droplets, the intensity varies according to the reconstruction distance with two local extrema, a minimum on the focusing plane (in the direction of reconstruction) and a maximum on the focal plane. Apart from these extrema, the evolution of the function is not monotonic as in the case of small droplets. The phase exhibits a much more complex structure that is no longer symmetrical with respect to the midplane and has multiple jumps.

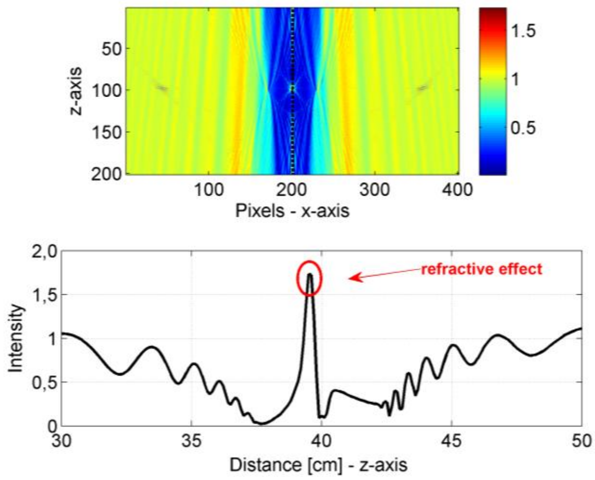

Figure 1 *Cross sections of modulus of the field reconstructed from simulations calculated with the generalized Lorenz-Mie theory (the section plane passes through the center of the droplet and contains the z axis) – Case of a 1 mm droplet observed at 40 cm, Nf ≈ 3.*

These characteristics make it difficult to achieve positioning on the optical axis by searching for singularities. Similarly, the existence of a local maximum intensity will require modification of most of the focusing methods described in the literature, which are generally based on an opaque disk model. The only suitable focusing method is based on calculating an indicator [7]. Two scalar indicators can be used, one based on calculating the sum of the Laplacian of the imaginary part of the reconstructed field (Eq. (1)), the other on calculating the sum of the variance (Eq. (2)) of the imaginary part of the reconstructed field.

$$LAP(z) = \sum_{x,y}\{\nabla^2\Im(A(x,y;z))\}^2 \quad (1)$$

$$VAR(z) = \frac{1}{N}\sum_{x,y}\{\Im(\mathrm{A}(x,y;\mathrm{z})) - \Im(\bar{\mathrm{A}}(\mathrm{z}))\}^2 \quad (2)$$

where $\Im(\mathrm{A}(\mathrm{x},\mathrm{y};\mathrm{z}))$ is the imaginary component of the field reconstructed at distance z, and $\Im(\bar{\mathrm{A}}(\mathrm{z}))$ is the mean value of the imaginary component of the reconstructed field. Focused plane corresponds to a minimum of the variation of these indicators versus z [7].

3 Hologram processing

Holograms are processed in sections based on the information around each diffraction pattern. First, each diffraction pattern is identified by image processing [11]. An initial position is then assigned after calculating the indicators on the reconstructions. The final optimization step deals with poorly positioned or missing droplets.

Obviously, the precision on the z axis depends on the selected reconstruction step. Thanks to initial focusing about 50 droplets can be correctly positioned on each hologram. When there are more than approximately 50 droplets in the field of view, initial reconstruction can lead to positioning errors or to missing droplets. This limitation is mainly caused by a low SNR of the focus function as soon as many droplets are overlapped. It is therefore necessary to verify their positions and optimize the reconstruction.

Using a transmission model mixing the opaque disk model with a phase term at the droplet center, an hologram synthesized from the expected positions and diameters is built [7]. It's then compared with the acquisition. As a result, missing and poorly reconstructed droplets are identified and can be optimized. For this purpose the simplex method, proposed by George Dantzig in 1947 [12], is particularly suitable. This algorithm is efficient in finding the minimum of a merit function of several variables. This function is minimal as the difference between acquisition and restitution is low. The Euclidean matrix norm is used for this study but sequentially on one droplet mask at a time. The whole hologram optimization is finally the result of the optimization of each droplet restitution. On numerical simulations, this optimization, even if it increases significantly processing time, raises the number of well-positioned droplets in a hologram from around 50 to 80.

4 Experimental results

Acquisitions were conducted on an experimental setup designed to produce droplets of known diameter and velocity as well as an unknown polydisperse droplet population. A detailed description of this setup can be found in [7]. In order to verify the relevance of droplet positions and sizes assessed by holography, all measurements were performed by a dual acquisition set-up. This set-up is as follow: a classical holography assembly on the first axis and a shadowgraphic setup on the second one, perpendicular to the first one. In comparison with the conventional methods [13–15] used to characterize emulsions (shadowgraphy, laser induced fluorescence, etc.), we obtained on this device the following results:

- The maximum number of droplets measurable (around 80 droplets assuming a mean diameter of 1mm) concurrently is practically the same as with other field measurement techniques (Figure. 2). In this respect, holography is equivalent to the other techniques.
- The measured diameter range is adapted to the requirements of liquid-liquid extraction devices: from 50 µm to 3 mm.
- When the number of droplets is limited (fewer than 30 droplets with a mean diameter of 1 mm), the shadow density is less than 10% and the Royer [6] criterion is met. The paths of droplets with polydisperse diameters can then be reconstructed by successive acquisitions.

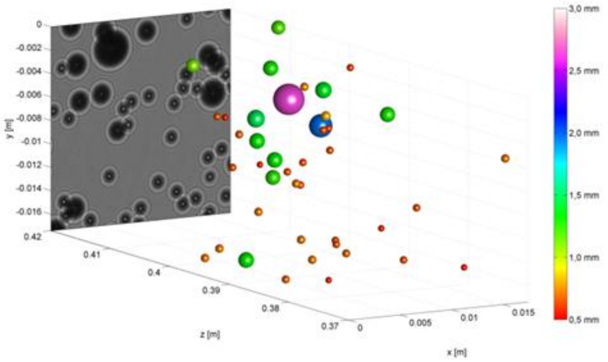

Figure 2 *3D visualization of 43 droplets cloud processed from a single shot hologram.*

5 Outlooks: measurement under astigmatic conditions

As mentioned in introduction, the cylindrical geometry of the columns induces a strong astigmatism and perturbs the acquisition of holograms. This issue could be addressed by using the Fractional Fourier Transform (FrFT) to process the holograms [16]. A first successful prospective test has been conducted, with the experimental setup in cylindrical configuration, on a monodisperse droplets train. It has confirmed the suitability of FrFT for astigmatic holograms processing. However, as the FrFT impose a quadratic phase term, indicators defined in paragraph 2 cannot be directly used. It's a key point currently under study.

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