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Interferometric particle sizing with overlapping images despite Moiré

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ABSTRACT

Interferometric particle imaging is investigated in the case of overlapping images and sub-sampling conditions. It is shown that particle size estimation of a pair of particles remains possible despite Moiré. Particle sizing can be achieved although the determination of the separation between both particles is no longer possible.

1. Introduction

Interferometric out-of-focus imaging enables the determination of the size of regular or irregular particles with mean diameters in the micrometric range (from a few micrometers to hundreds of micrometers) [1–7]. With this technique, the working distance between the measurement volume and the instrument can be larger than 10 cm while the field of view can exceed tens of cm^2. The technique is thus well adapted to the characterization of particles in hostile environments, or the analysis of triphasic flows as mixing of liquid water droplets and ice crystals in clouds [8–13]. This latter application attracts much attention for meteorology and aircraft safety. Airborne instrumentation has been already developed and the principle of rough particle size estimation using the technique has been described.

In the case of irregular rough particles, the interferometric out-of-focus image of the particle is a speckle-like pattern. From this pattern, it is possible to estimate the size of the particle with relatively reduced error rate [5,14,15]. Unfortunately, it is not possible to determine the exact morphology of the particle. Previous studies show that the autocorrelation of the 2D-contour of the particle (that would be projected in the plane of the CCD sensor) can be determined from the 2D-Fourier transform of the speckle pattern [16].

As the technique is based on out-of-focus imaging, the images of two nearby particles can overlap [17]. A recent study has shown that under certain conditions (sufficient separation between both particles in respect with their respective sizes), the distance between both particles can be determined and their sizes can be estimated [18]. In this case of overlapping images, an important problem needs to be clarified: the influence of high distances between the particles that will generate Moire effects in the interferograms. When the distance between both particles becomes high, the estimate of the particles sizes will indeed be still possible in many cases, although the estimate of their relative positions by 2D-Fourier transform will be wrong. This is due to the emergence of high frequencies in the image. They will generate aliasing. It is the aim of this paper to investigate these phenomena. Section 2 will present the set-up and the theoretical backgrounds that will be used. Section 3 will show experimental results. Section 4 will establish experimental conditions that enable an evaluation of particles sizes in the case of overlapping images of two particles, although the estimation of their separation is no longer possible. Section 5 will finally discuss the case of three particles whose out-of-focus images overlap.

2. Set-up and backgrounds

2.1. Backgrounds

This study will be carried out on irregular translucent particles made from dehydrated hydrogel beads. They have a stick-like shape, whose size is in the range [0.5 mm, 2 mm]. Assuming that these particles can be assimilated to an ensemble of many emitters located on the envelope of the particles [19,20], it has been shown in [16] that the projected contour of the particle (which is obtained on the CCD sensor) is linked to the 2D-Fourier transform of the interferometric out-of-focus image. Actually, the 2D-autocorrelation of the projected in-focus shape is quantitatively given by the 2D-Fourier Transform of the out-of-focus speckle pattern. This can be described by the following scalar equation (1):

$$|TF_{2D}[I](\lambda Bu, \lambda Bv)| \propto |A_{2D}[G_0](dx, dy)| \quad (1)$$

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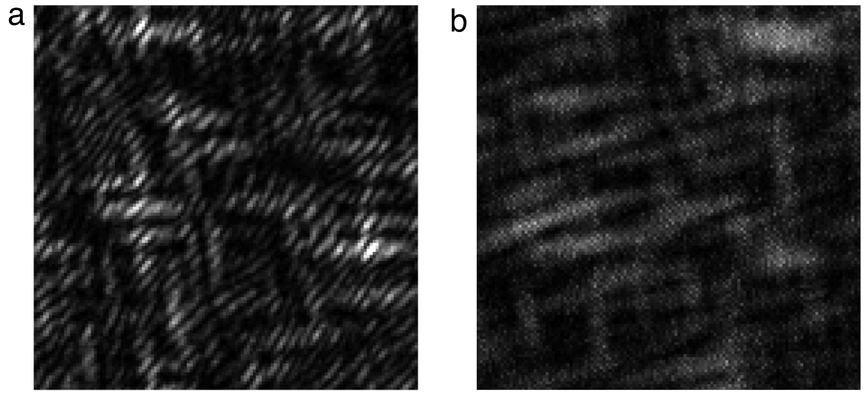

Fig. 1. (a) Image recorded for close particles. (b) for remoter particles.

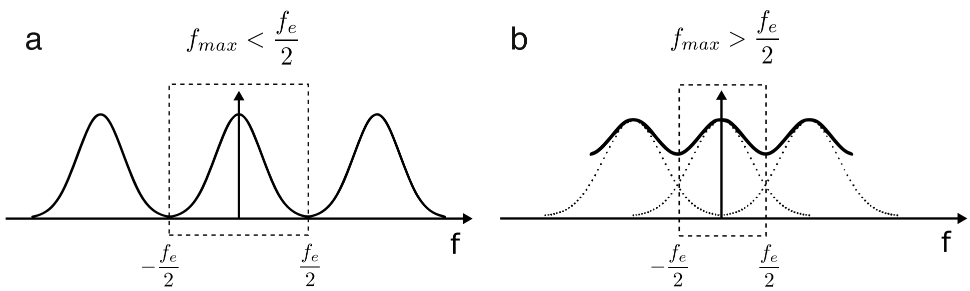

Fig. 2. (a) Figure of Fourier transform of a one-dimensional signal, when Nyquist theorem is respected. (b) when Nyquist theorem is not respected (aliasing).

where I is the intensity of the out-of-focus pattern of the particle and G_0 the electric field emitted by the illuminated particle. λ is the wavelength of the laser. λB_{tot} is a scaling factor between both functions. B_{tot} is obtained from optical ray matrix formalism (in the case of our set-up, B_{tot} will be in the range $-0.04615\text{ m} \leqslant B_{tot} \leqslant -0.03712\text{ m}$ according to the various experimental cases analyzed in Section 3). This result has been validated in the case of rough sand particles [12] and could be extended to irregular transparent particles as ice crystals when roughness of the particles induces the presence of glare points on the whole envelope of the particle [7]. One goal of the present paper is to use relation (1) to highlight aliasing that can happen in some specific cases (overlapping images with a high separation between particles). It can also lead to a wrong estimation of the particles positions.

Interferometric out-of-focus imaging requires indeed the analysis of overlapping images. This study relates to the case where the out-of-focus images of two particles overlap. The overlapping image is recorded by a CCD sensor composed of a pixel grid which samples the real image. The spectrum of the real image becomes a periodic function of f_e period (f_e is the sample rate) [21]. When particles are close to each other, overlapping is major and analysis may be done correctly (Fig. 1(a)). However, when the distance between both particles is higher, the offset between the two images becomes significant and leads to observation of moiré-effects. They correspond to the superposition of overlapping images with the CCD sensor pixels grid (Fig. 1(b)). This will cause the emergence of high frequencies in the image leading to non-compliance of Nyquist Shannon theorem (Fig. 2). So, aliasing will occur in 2D-Fourier Transform of the out-of-focus image. It will result in a wrong estimation of the particles positions as will be discussed in Section 3.

2.2. Set-up

The experimental set-up that has been realized is presented in Fig. 3. Two rough transparent particles of similar size (about 1.5 mm) are put on a glass plate and illuminated by a laser beam. The laser source is a Continuous Wave (CW) He–Ne laser, emitting 30 mW averaged power at 632.8 nm. The laser beam is focused by a lens (focus length 75 mm). It enables to illuminate an area of 1.5 cm in diameter. An optical system which consists of a diaphragm and a lens aligned with a CCD camera collects light scattered by the rough particles at 15° (scattering angle). The position of the optical system can be adjusted with a translation stage. We can thus observe in-focus images of particles deposited on the glass plate, or interferometric out-of-focus images of these particles. We will consider a multi-component object (couple of particles with overlapping out-of-focus images).

To simulate the out-of-focus imaging setup and interpret correctly the recorded images, it is important to know precisely the features of the experimental setup in all configurations: the in-focus imaging setup is presented in Fig. 3(a) and the out-of-focus imaging configuration on Fig. 3(b). First set-up consists in a CCD sensor (2048×2048 pixels, pixel size equal to 5.5 μm), a converging lens with a focus length $f = 24$ mm and an aperture of diameter 15 mm. The distance between the lens and CCD sensor is $z_2 = 34$ mm. In order to observe a focused image, the distance between the lens and the particles is equal to $z_1 = 81.6$ mm (see Fig. 3(a)). The out-of-focus imaging set-up is made of the same optical elements. Distance between the lens and the CCD sensor is equal to $z_2 = 44$ mm. Only distance z_1 changes. In order to observe overlapping images of particles, the distance between the lens and the particles will range among $108.181\text{ mm} \leqslant z_1 \leqslant 97.343\text{ mm}$ (see Fig. 3(b)), depending on the various cases analyzed in Section 3.

3. Experimental results

In this study, we analyze the interferometric out-of-focus images of two stick-shaped particles: one oriented horizontally and the other one oriented vertically. We will analyze three different configurations: In the first one, particles are deposited near from each other on a glass plate. Then, we increase gradually the spacing between both particles. For all configurations, we record systematically out-of-focus images and their corresponding in-focus images. The characteristics of the in-focus setup are the same for all configurations (Fig. 4(a), (e) and (i)) and are as follows: $z_1 = 81.6$ mm and $z_2 = 34$ mm. $\gamma = -0.417$ is the magnification factor of the in-focus setup.