Optics Communications 312 (2014) 312–318

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

High-accuracy particle sizing by interferometric particle imaging

Lü Qieni*, Jin Wenhua, Lü Tong, Wang Xiang, Zhang Yimo

College of Optoelectronics & Precision Instrument Engineering, Tianjin University, Key Laboratory of Opto-electronics Information Technology, Tianjin University, Ministry of Education, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 10 June 2013
Received in revised form
4 September 2013
Accepted 22 September 2013
Available online 6 October 2013

Keywords:
Interferometric particle imaging (IPI)
Erosion match
Fourier transform
Modified Rife algorithm

ABSTRACT

A method of high-accuracy estimation of fringes number/fringes frequency of interferogram based on erosion match and the Fourier transform technique is proposed. The edge images of the interference pattern of particles and the particle mask image are detected respectively by erosion operating firstly and then subtracted with the respective original image, and the center coordinate of particles can be extracted through the 2D correlation operation for the two edge images obtained. The interference pattern of each particle can then be achieved using the center coordinate, the shape and size of the particle image. The number of fringes/fringe spacing of the interferogram of the particle is extracted by Fourier transform and the modified Rife algorithm, and sub-pixel accuracy of the extracted frequency is acquired. Its performance is demonstrated by numerical simulation and experimental measurement. The measurement uncertainty is ± 0.91 μm and the relative error 1.13% for the standard particle of diameter 45 μm. The research results show that the algorithm presented boasts high accuracy for particle sizing as well as location measurement.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Particle sizing plays an important role in many fields of engineering and research [1–12]. Interferometric particle imaging (IPI), based on Mie scattering theory, is a popular method for measuring instantaneous size and spatial distribution of the spherical particle, utilizing the interference fringes generated by reflection and first-order refraction ray scattered by a particle on a defocused image plane. And the particle diameter is proportional to the angular frequency/fringe counts of this interference pattern, and its measurement accuracy depends on the image processing technique for estimating the number of fringes/fringe spacing. Owing to out-of-focus image overlapping, especially, the high-degree overlapping of the fringe pattern in a higher particle number density region, it is very difficult to evaluate the individual particle image of IPI. No doubt, automatically extracting the location and fringe spacing/fringe counts of a particle from interferometric fringe pattern of IPI is both hard but crucial. Several methods have been proposed for IPI image processing so far [7–12,14–16]. For example, Glover et al. [9] first used the Gaussian blur, Canny edge detection and Hough transform to locate the individual droplet in the image field and then detected fringe spacing by least-squares fitting to a Chip function, which was applied to spatially sparse sprays. Niwa et al. [10] detected the position of bubble by using the template matching method with circular pattern in low number density of bubbles, and the fringe frequency of sub-pixel accuracy was achieved by Fourier transform and Gaussian fitting. The method includes 2D convolution and FFT was proposed to extract the special coordinate and fringe angle frequency of fringe pattern from interferometric particle image in Ref [14]. Quérel group [11] developed a global algorithm based on 1D Fourier transform to calculate the real-time droplet size distribution from IPI interferogram, and such method demands high speed to perform real time processing during a flight through clouds. Lacagnina et al. [12] carried out firstly the cross correlation between a Fourier spectrogram of interference fringe of a particle in the wavenumber domain and a reference image, and the area around the cross-correlation local maxima as the center was selected by a square window, and then the FFT and auto correlation for this area was performed to evaluate the fringe wave number and then the bubble diameter. Recently, we [16] developed a method of extracting the number of fringes/fringe spacing of circular interferogram based on wavelet matched filter and the Fourier transform technique, and sub-pixel accuracy of the extracted frequency was attained with the modified Rife algorithm and we are currently studying a new algorithm of extracting fringe counts/fringe spacing of interference fringe pattern. The present algorithm is based on erosion match and the Fourier transform technique, and frequency is subdivided by the modified Rife method. The paper recommends this algorithm for estimating the fringe spacing, whose performance is demonstrated through simulation and experimental measurements. Comparing this new

* Corresponding author. Tel.: +86 22 27401903.
E-mail address: qienil@tju.edu.cn (L. Qieni).

0030-4018/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2013.09.049

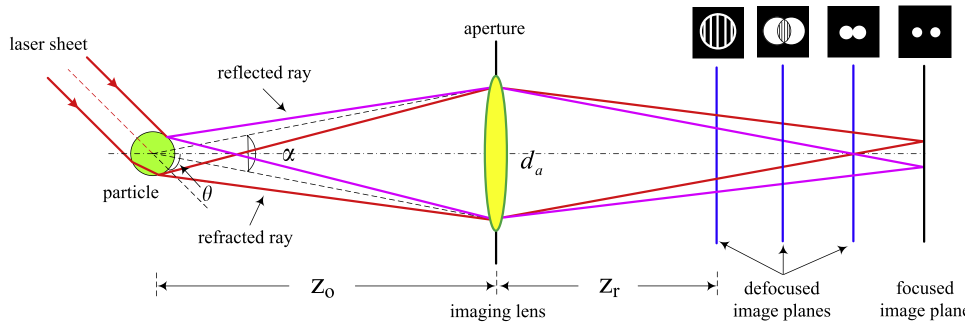

Fig. 1. Schematic of interferometric imaging of particle scattering light.

method with that of the wavelet matched filter, for the same algorithm recognition rate and measurement accuracy, the measurable particle number density doubles, then higher accurate position measurement can be realized, promising to apply to the high-density spray field.

2. Interferomemtic particle imaging

A diagram of interferometric particle imaging is shown in Fig. 1. When a transparent spherical particle is illuminated by a laser sheet, the reflected and first-order refracted ray scattered from the particle form two glare points on the focus image plane, one glare point representing the reflected ray and the other the refracted ray. And the interference fringe pattern is produced in an out-of-focus image plane. The shape of the defocused particle image relies on that of the receiving aperture, and size $d_i$of the defocused particle image is given by [7]

$$d_i = d_a\left|1 - z_r\left(\frac{1}{f} - \frac{1}{z_0}\right)\right| \quad (1)$$

where d_a is the diameter of the aperture, f is the focal length of the imaging lens, z_o is the object distance, z_r is the distance between the defocused image plane and the lens, as shown in Fig. 1. The size of the particle fringe pattern on the out-of-focus plane is independent of particle size. The diameter of particle is related to the fringe spacing of interferogram. Using geometrical optics, particle diameter d can be expressed as the following [13,17]:

$$d = \frac{2\lambda N}{\alpha}\left(\cos\frac{\theta}{2} + \frac{m\sin(\theta/2)}{\sqrt{m^2 - 2m\cos(\theta/2) + 1}}\right)^{-1} \quad (2)$$

Where λ is the wavelength of the laser light source, m is the refractive index of the particle, θ and α are the scattering angle and collecting angle, respectively, $N = \alpha/\Delta\varphi$ is the number of fringes and $\Delta\varphi$ the angular spacing of the interference fringe. From Eq. (2), for a given experimental system, that is, θ, m, λ and α given, particle diameter d is proportional to the number of fringes N, and can be calculated by measuring N or $\Delta\varphi$. Consequently, the accuracy of particle sizing using IPI depends upon the interferogram image analysis, and the automatic extraction of fringe spacing or fringe counts is one of the key aspects of the technique.

3. Algorithm

Fig. 2 shows the algorithm flowchart of automatically processing fringe image of IPI we present. The interference pattern of particles and the particle mask image (to construct a particle mask image according to Eq. (1)) are processed by eroding and subtracting, respectively; then, the edge images are obtained, and the position coordinate (x,y) of particle images can be extracted through

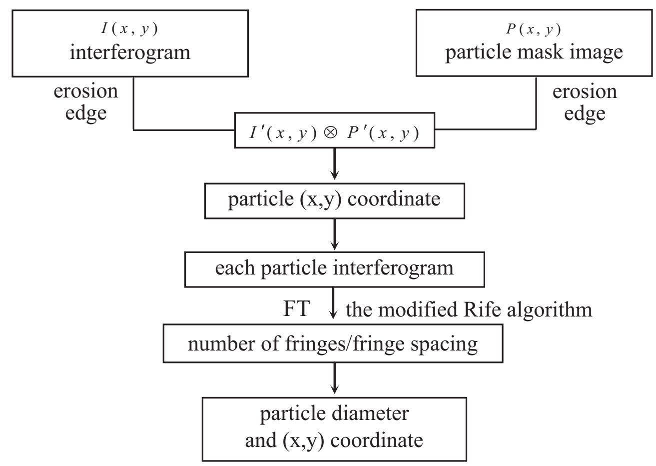

Fig. 2. Flowchart of particle measurement.

the 2D correlation operation for the two edge images obtained. The interference fringe image of each particle is extracted from raw images according to the center coordinate (x,y), the shape and size of the particle fringe image; then Fourier transform is performed to evaluate fringe angle spacing or the number of fringes, and sub-pixel accuracy of the extracted frequency is acquired by the modified Rife algorithm and then particle diameter.

3.1. Detection of particle center

The accurate identification of the location of particle center is crucial in interference fringe image processing of IPI. At first, the interference pattern of particles and the particle mask image are eroded using a disc with one pixel radius, the edge images are then extracted by subtracting the erosion image from the respective original image, respectively; the cross-correlation function between the two edge images obtained is calculated. Suppose that the interference pattern of particles $I(x,y)$ is the input image, and the particle mask image $P(x,y)$ the target image to be identified, after eroded and edge detected, are denoted by $I'(x,y)$ and $P'(x,y)$, respectively; the 2D correlation operation for the two edge images commanded is computed

$$I'(x,y) \otimes P'(x,y) = \iint I'^{*}(x',y')P'(x'+x, y'+y)dx'dy' \quad (3)$$

where $\otimes$ denotes correlation operation, and the peak values of the cross-correlation function of Eq. (3) is the center position of particle image. We designate this algorithm as erosion match algorithm or erosion correlated algorithm.

Download English Version:

https://daneshyari.com/en/article/7931727

Download Persian Version:

https://daneshyari.com/article/7931727

Daneshyari.com