Three-Dimensional Velocity Measurement of Moving Particles Based on Single-Lens Dual-Camera: Postprint

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Abstract

Based on the principle of depth from defocus, this paper proposes a method for measuring the three-dimensional velocity of moving particles using a single-lens dual-camera configuration. Incident light is directed through a beam splitter cube into two industrial cameras; by adjusting the thickness of the spacer between the beam splitter cube and the cameras, two images of the same object with different degrees of blur are acquired. The difference in blur is utilized to achieve positioning of moving particles within a three-dimensional field, and combined with a single-frame multi-exposure approach, their three-dimensional velocity is obtained. By capturing particle motion in slowly stirred water flow and analyzing images of particles under various motion conditions, the three-dimensional velocity of moving particles was successfully determined. The feasibility of the method was verified through calculations and experimental validation. This approach resolves both the depth-from-defocus ambiguity issue and the velocity direction ambiguity issue, offering a new direction for three-dimensional velocity measurement.

Full Text

3-D Velocity Measurement of Moving Particles Based on Single-Lens Dual-Camera

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Abstract

Based on the principle of depth from defocus, this paper proposes a novel method for measuring the three-dimensional (3-D) velocity of moving particles using a single-lens dual-camera system. Incident light is dispersed into two industrial cameras through a beam splitter prism, and two images with different blur degrees for the same object are acquired by adjusting the thickness of washers between the prism and the cameras. The orientation of moving particles in the three-dimensional field is obtained from the difference in blur degree between the images, and the 3-D velocity of the particles is then calculated by combining this with the single-frame multi-exposure method. Images recording particle movement in a water flow with slow agitation were processed and analyzed, yielding the 3-D velocity field of the moving particles. The feasibility of the proposed method was verified through comparison between the calculated results and experimental measurements. This approach solves problems related to the ambiguity of both defocus and velocity direction, and indicates a new way for measuring 3-D velocity.

Keywords: defocus blur; 3-D velocity; single-lens dual-camera; single-frame multi-exposure

1 Introduction

Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) are widely used techniques for flow field measurement. However, conventional PIV systems typically measure only two-dimensional velocity fields, while 3-D measurement remains challenging. Digital holography and tomographic PIV have been developed for 3-D velocity measurement, but these methods often involve complex optical setups and computational requirements. The depth-from-defocus technique offers an alternative approach for determining particle position along the optical axis by analyzing blur differences. Previous studies have demonstrated the potential of defocus-based methods for 3-D positioning, but challenges remain in determining velocity direction and achieving accurate 3-D velocity measurements.

2 Principle and Methodology

2.1 Depth from Defocus Principle

The depth-from-defocus method utilizes the relationship between object distance and image blur to determine spatial position. When a particle is located at different distances from the focal plane, it produces images with varying degrees of blur. By capturing two images with different blur characteristics simultaneously, the depth information can be extracted. The defocus blur imaging process for an object-space telecentric lens is illustrated in [Figure 1: see original paper].

The blur diameter can be expressed as a function of the object distance and system parameters. For a telecentric lens system, the blur circle diameter is directly related to the displacement of the object from the focal plane. The relationship between blur diameter and object distance is given by:

(*cid* : 25)*l*(*cid* : 25)*m*(*cid* : 25)*l*(*cid* : 25)*n*(*cid* : 25)*o*(11)(1)(12)(1)(13)(1)(14)(1)(15)(1)(16)(1)(17)(1)(18)(1)(19

where the parameters are defined in the system configuration.

2.2 Single-Lens Dual-Camera System

The proposed single-lens dual-camera system captures two images of the same particle field through a beam splitter prism. By placing washers of different thicknesses between the prism and the two cameras, we create a controlled difference in the optical path length, resulting in different blur characteristics for the two images. A schematic of this system is shown in [Figure 4: see original paper].

The system parameters are summarized in . The lens has a focal length of 16 mm, with L1 = 126.46 mm and L2 = 122.26 mm representing the distances from the lens to the two CCD sensors. The CCD sensors have a resolution of 1628×1236 pixels with a pixel size of 4.4 m × 4.4 m.

The blur difference between the two images allows determination of the particle's depth position. The relationship between the blur diameters in the two images can be expressed as:

(1)(129)(1)*m*(1)(129)(217)(240)(217)(215)(217)(216)(217)(246)(1)(130)(1)(131)(1)(132)(1)(133)(1).(1)*p*(1)*q*(1)

where s1 and s2 represent the distances from the lens to the two image planes, and f is the focal length.

2.3 Single-Frame Multi-Exposure Method

To measure particle velocity, we employ a single-frame multi-exposure technique. A light-emitting diode (LED) is used as the illumination source, and a multi-pulse driving signal is generated to create multiple exposures within a single frame. The exposure timing is controlled such that each particle produces a streak pattern consisting of discrete segments, with the spacing between segments representing the particle's displacement during the time interval.

The velocity components can be calculated from the streak patterns. For a particle moving with velocity components (vx, vy, vz), the projection in the image plane gives:

(1)*F*(1)*f*(1)*g*(1)(136)(1)(137)(7) ∼ (224)æ*v*(1)(16)(1)((1)_(1)−(1).(1)*v*(1)(16)(1)((1)(18)(1)(19)(21)(20)(1)(22 where Δx and Δy are the measured displacements in the image plane, Δt is the time interval between exposures, and M is the magnification factor.

3 Experimental Setup and Results

3.1 Experimental Configuration

The experimental setup for velocity measurement is shown in [Figure 5: see original paper]. The system consists of a water tank with slow agitation, PMMA particles with diameters of 1-2 mm and density of 1.18 g/cm^3, and the single-lens dual-camera imaging system. The LED illumination provides multi-pulse exposure with pulse intervals of 1-4 ms and total exposure time of 20 ms.

3.2 Data Processing

Image processing involves several steps: background subtraction, particle detection, blur diameter measurement, and streak analysis. The blur diameter for each particle is measured in both images, and the depth position is calculated using the depth-from-defocus principle. The streak pattern from the multi-exposure is analyzed to determine the in-plane velocity components.

The 3-D velocity field is reconstructed by combining the depth information with the in-plane velocity measurements. [Figure 6: see original paper] shows the experimental results for velocity measurement of moving particles, displaying the calculated velocity vectors in three-dimensional space.

3.3 Accuracy Analysis

The measurement accuracy depends on several factors, including the precision of blur diameter measurement, the stability of the optical system, and the particle tracking algorithm. The depth resolution is determined by the difference in blur sensitivity between the two cameras, while the velocity resolution depends on the exposure timing and image magnification.

The measured 3-D velocities for several representative particles are listed in . The results demonstrate that the system can effectively measure the three-dimensional velocity field with reasonable accuracy.

4 Conclusion

This study presents a novel method for measuring the 3-D velocity of moving particles using a single-lens dual-camera system based on the depth-from-defocus principle. The method successfully addresses the ambiguity problems associated with defocus and velocity direction determination. By combining depth-from-defocus with single-frame multi-exposure, we achieve simultaneous measurement of particle position and velocity in three dimensions.

The experimental results verify the feasibility of the proposed method for measuring 3-D velocity fields in fluid flows. This approach offers a simpler optical configuration compared to holographic or tomographic methods, making it potentially useful for various applications in multiphase flow research.

Future work will focus on improving measurement accuracy, increasing the measurement volume, and applying the technique to more complex flow conditions.

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Note: Figure translations are in progress. See original paper for figures.