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Application of particle streak velocimetry based on binocular vision in cascade flow channel

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ABSTRACT

Particle streak velocimetry (PSV) has become one of the important branches of measurement methods for fluid flow. A new kind of particle streak velocimetry method based on binocular vision and single-frame multi-exposure technology is proposed. The direction of the flow is judged by the combination of short and long exposures, the gray-level fitting method is used to identify the trajectory features. This method uses nearest neighbor matching and angle of inclination constraints to match and sort multiple trajectories of the same particle, uses epipolar constraints to accomplish binocular matching based on trajectory feature points, and adopts B-spline fitting on the three-dimensional reconstructed feature points to calculate the three-dimensional velocity of particles. The actual measurement of the fluid flow in a gas pipeline shows that this method can be reliably used for unsteady flow measurement.

Keywords: binocular vision; particle streak velocimetry; single-frame with multi-exposure; cascade flow channel; three-dimensional velocimetry.

INTRODUCTION

Fluid flow is closely related to research fields such as hydrodynamics and aerodynamics. A reliable three-dimensional flow field measurement method is the prerequisite for analyzing and studying fluid motion(Yang Y and Kang B S, 2015). Particle image velocimetry has the advantages of non-contact flow field, high precision, etc. It realizes multi-point transient measurement of fluid flow while avoiding the interference of measurement equipment and is an important experimental method in the field of fluid mechanics research. Particle Image Velocimetry (PIV), Particle Tracking Velocimetry (PTV) (Adrian R J, 1991) and Particle Streak Velocimetry (PSV) (Adamczyk A A and Rimai L, 1998) are the three main methods of particle image method for fluid flow measurement. Particle streak velocimetry can be considered as a kind of PTV, but it is different from PTV in their principles and image processes. The PSV method records the particle trajectory under long exposure time, and calculates the particle velocity in the flow field by the particle trajectory length and the exposure time. In the flow field measurement, the PIV method and the PTV method need a high frame rate image acquisition system and a high-energy light source in order to avoid particle motion blur, so its required equipment costs are relatively high. What the PSV method collects is the movement trajectories of the particles, without considering the blur caused by the high-speed movement of the particles, so it can be realized by using a common industrial camera and a low-power light source, and the equipment cost is relatively low.

The problem of the PSV method is that there is ambiguity in the direction of particle motion, it is difficult to distinguish the direction of particle motion through a single particle motion trajectory.Some researchers have proposed to start with the light source to solve this problem(Wang H et al, 2018; Wang H et al, 2019) : use colored light sources to illuminate the particles, and use different colored light sources to record the positions of the particles at different times, so as to determine the direction of particle movement, this method is called color sequence particle streak velocimetry(CSPSV).

Another major problem with the PSV method is the accuracy of location identification of the feature points. In general, it is achieved by binarization of gray image first, and then identifying the feature points after binarization, but the threshold value has a great impact on the accuracy of endpoint identification.

This study combines the single-frame with multi-exposure (combination of long and short exposures) PSV method to solve the problem of ambiguity in the direction of particle movement. It provides more matching constraints for binocular matching and improve the accuracy of binocular matching at the same time. The gray-level fitting method is proposed to identify the trajectory features which can accurately identify trajectory feature points.

METHODOLOGY

1. Single-frame particle trajectory velocity measurement method

The principle of particle trajectory velocity measurement is to appropriately extend the exposure time of the camera or the duration of the light source to obtain the particle motion trajectory image and calculate the particle motion speed through the trajectory image length l and the exposure time T. Figure 1 is an image of a trajectory when a particle is in motion.

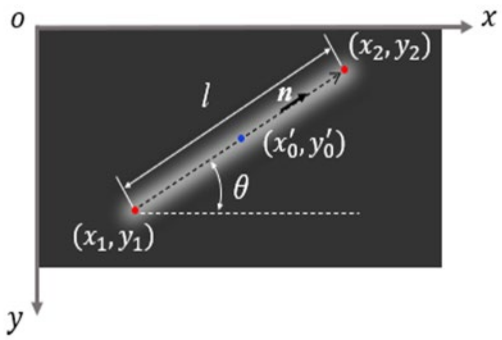

Figure 1 Trajectory of single particle

The velocity of a single particle can be expressed as:

$$v = \frac{l}{T} \tag{1}$$

Where T is the camera exposure time, and l is the length of the particle trajectory. The camera exposure time T is known, so the problem of calculating the particle trajectory velocity is transformed into calculating the particle trajectory length. The particle trajectory length l can be obtained by extracting the coordinates of the trajectory feature points, and the identification method of the trajectory feature points will be proposed in this article.

2. Recognition of feature points of particle trajectory

The feature points of the particle trajectory are its two endpoints, and the accurate extraction of the feature points of the trajectory is the prerequisite for the accurate result of the particle trajectory velocity measurement. This paper adopts the method of trajectory image gray distribution fitting proposed by Hering et al (Hering F et al, 1997). The trajectory gray distribution within the exposure time can be expressed as:

$$g_s(x') = A\frac{G(\frac{1}{\sigma}|x' \times n|)}{l\sigma}\int_{1/\sigma(x' \cdot n+l/2)}^{1/\sigma(x' \cdot n+l/2)} G(\tau)d\tau \tag{2}$$

Where x' is the two-dimensional coordinate vector with the origin of the particle trajectory centroid; n is the particle motion direction vector, which represents the particle motion angle θ; l is the particle motion distance within the exposure time; σ is the width of the trajectory or the degree of gray distribution in the width direction; A is a normalized parameter, which represents the sum of the gray values of the image; $G(x)$ is a one-dimensional Gauss function with a variance of 1.

$$G(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} (-\infty < x < +\infty) \tag{3}$$

According to formula (3), the particle trajectory is fitted to obtain the parameters l 、 θ 、 (x'_0, y'_0), and the trajectory endpoint coordinates can be accurately obtained by formulas (4) and (5).

$$(x_1, y_1) = (x'_0 - \frac{l}{2}\cos\theta, y'_0 + \frac{l}{2}\sin\theta) \tag{4}$$

$$(x_2, y_2) = (x'_0 + \frac{l}{2}\cos\theta, y'_0 - \frac{l}{2}\sin\theta) \tag{5}$$

3. Matching and sorting of multiple trajectories

Due to the ambiguity of direction, it is difficult to determine the direction of particle movement based on the trajectory of a single particle. This paper adopts the particle streak velocimetry measurement based on single-frame with multi-exposure. It analyzes the particle motion direction and calculates the particle motion speed by combining multiple long and short trajectories. The principle is to add multiple pulse signals to the light source during the single exposure of the camera, or use a camera with multiple exposure modes in conjunction with a continuous laser to make a single particle form multiple motion trajectories in the same image. The long trajectory is used to calculate the particle motion speed, and the short exposure point is used to determine the particle motion direction.

In this way, there will be multiple trajectories of many different particles on the same image, and the matching of multiple trajectories of the same particle is a problem that needs to be solved first. This paper proposes nearest neighbor matching(Baek S J and Lee S J, 1996) and tilt angle constraint to match multiple exposure trajectories of the same particle in a single frame of image. First, determine the short exposure point or long trajectory by the size of the connected domain; secondly, obtain the endpoint coordinates of the long trajectory according to the gray-scale fitting method described in section 2.2, and then sort the long trajectory according to the position of the short exposure point. This paper proposes a trajectory matching method based on nearest neighbor matching and tilt angle constraint. The principle of matching and sorting is shown in the Figure 2 :

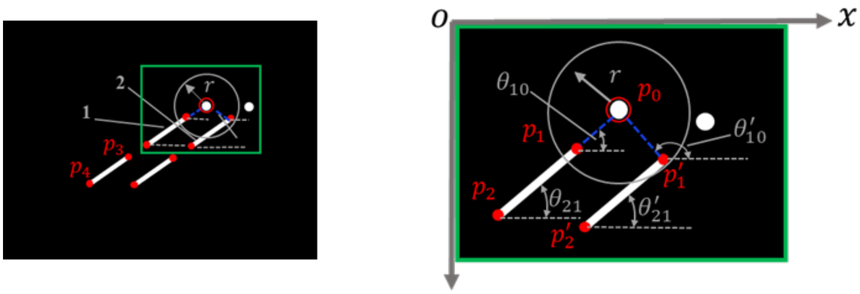

Figure 2 Particle trajectories matching

The red circle in Figure 2 marks the short exposure point $p_0(x_a, y_a)$ of a certain track. At this point, the circle of radius r is used as the search area to find the endpoint of the long trajectories in this area. The value of the search radius r is related to the particle movement speed and the exposure time interval. As shown in Figure 2, $r = 7$ pixel is selected as the search radius, $p_1(x_b, y_b)$ and $p'_1(x'_b, y'_b)$ are searched, and the inclination angles θ_{10} and θ'_{10} of the connecting line with the short exposure point are calculated respectively. The calculation formula is as follows:

$$\begin{cases} \theta_{10} = \arctan(\frac{y_a - y_b}{x_a - x_b}) & x_a \neq x_b \\ \theta_{10} = 90° & x_a = x_b \end{cases} \tag{6}$$

$$\begin{cases} \theta'_{10} = \arctan(\frac{y'_a - y'_b}{x'_a - x'_b}) & x'_a \neq x'_b \\ \theta'_{10} = 90° & x'_a = x'_b \end{cases} \tag{7}$$

When one endpoint of the long trajectory is determined, the other end will also be determined. The inclination angles θ_{21} and θ'_{21} of the long trajectory can be determined by formulas (6) and (7). If the inclination angle of one endpoint of the long track and the short exposure point is the same or close to the inclination angle of the long trajectory, it means that the endpoint matches the short exposure point. Increase the maximum difference in tilt angle matching constraint condition, and select 5° as the absolute value of the maximum difference in tilt angle that can be matched as the matching basis for adjacent endpoint matching.

Since the angles of θ'_{10} and θ'_{21} are quite different, point p'_1 does not match p_0. After determining the first matching trajectory, continue the above search process until the endpoint p_4 is found, thus completing the matching and sorting of the trajectory. Then, according to the previously set multi-exposure time sequence, it can be known that the direction of the particle movement is p_0 to p_4.

Compared with the nearest neighbor trajectory matching method, this trajectory matching method increases the constraint condition of the maximum difference of the trajectory inclination angle, avoids removing the trajectory that fails to match, improves the trajectory utilization rate and improves the accuracy of trajectory matching. It laid a good foundation for the subsequent calculation of the three-dimensional velocity field.

4. *Binocular matching and 3D reconstruction*

Binocular vision is that two cameras shoot objects in different directions, and calculate the depth information of the object through the parallax of the image, which can be used in the reconstruction of the position of three-dimensional particles in this article. In order to reconstruct the position of the particle in the three-dimensional space and find the same particle trajectory under different viewing angles, it is necessary to match the particle trajectories under different viewing angles. Figure 4 is a schematic diagram of binocular trajectory endpoint matching. In the left image, there is a particle trajectory (there are two long exposures, and the endpoints of the two trajectories have been sorted). In the right image, there is a trajectory image corresponding to another perspective of the particle. This paper uses epipolar matching constraint conditions to match the trajectory feature points, the principle is as follows: First, perform epipolar constraint matching on the first trajectory feature point (the red line indicates the corresponding epipolar line), and find the trajectory of the first feature point whose distance to the epipolar line meets the constraint condition in the middle image are candidate trajectories, as shown the trajectory 1,2 in the right figure. Finally, calculate the sum of the distance between the endpoints of the two candidate trajectories and the epipolar lines of the corresponding sequence endpoints in the left figure as:

$$D_i = \sum_{j=1}^{3} d_{i,j}, i = 1,2,\cdots n; j = 1,2,3 \tag{8}$$

In the above formula, i represents the number of trajectories to be matched, j represents the sequence number of feature points on the trajectory, and only three feature points are selected in this paper. After calculating the D_i of each trajectory to be matched, select the trajectory with the smallest D_i. If D_i is less than 6 pixels, the trajectory is the final matched trajectory.

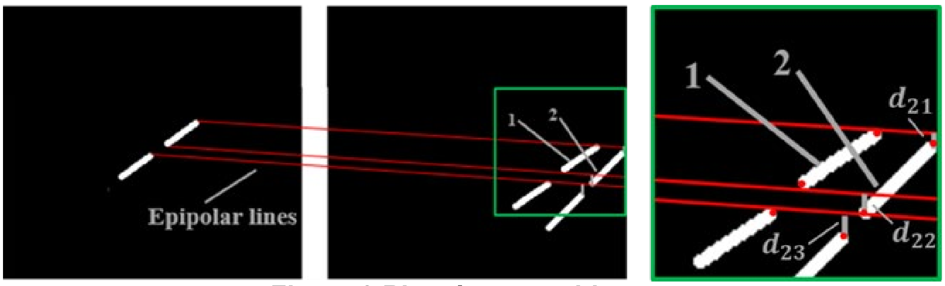

Figure 3 Binocluar matching

According to the principle of binocular vision, the trajectory feature points are reconstructed in three dimensions. When the trajectory feature point is known in the image coordinates of the left and right cameras, according to the system calibration parameters, the three-dimensional position coordinates of this feature point can be obtained.

5. *Spline fitting and 3D velocity calculation*

After obtaining the world coordinates of the feature points, a three-dimensional cubic B-spline curve is used to fit the three-dimensional trajectory, then the velocity is calculated. The particle trajectory speed can be calculated from the length of each fitting curve and the exposure time, the calculation formula is:

$$v_i = \frac{s_i}{t_i} \quad i = 1, 2, 3, \cdots \tag{9}$$

$$s_i \approx \sum_{j=1}^{k} \sqrt{(X_{i,j+1} - X_{i,j})^2 + (Y_{i,j+1} - Y_{i,j})^2 + (Z_{i,j+1} - Z_{i,j})^2} \tag{10}$$

In the above formula, i is the trajectory number. In this paper, three trajectory endpoints are selected for fitting, and j is the interpolation point on each trajectory. In order to approximate the length of the real curve as much as possible, the total number of interpolation points for each trajectory is 11. Then k is taken as 10 in this paper; t_i is the set camera exposure time or interval time. X 、 Y 、 Z is the world coordinate of the interpolation point.

RESULTS AND DISCUSSION

1. *Experimental device*

In this paper, a gas pipeline experiment system is built to measure the gas velocity field. The experimental system is composed of laser (light source), gas rectifier, cameras, computer, lens, gas pipeline, air compressor (air source), particle generator, flowmeter, computer, signal generator. In order to ensure the stability of the gas flow in the measurement area, a gas rectifier is added at 300 mm in front of the measurement area to effectively avoid the influence of gas turbulence on the measurement results. The air compressor is used to press the tracer particles into the area to be measured, while giving a certain velocity to the gas flow; The gas flow meter is used to measure the flow in the pipeline, and it is installed at the outlet of the air compressor to prevent the tracer particles from entering the gas flow meter and causing damage; the signal generator is used to synchronously control the cameras and laser; the computer is used to collect particle trajectory images taken by the cameras and perform subsequent processing.

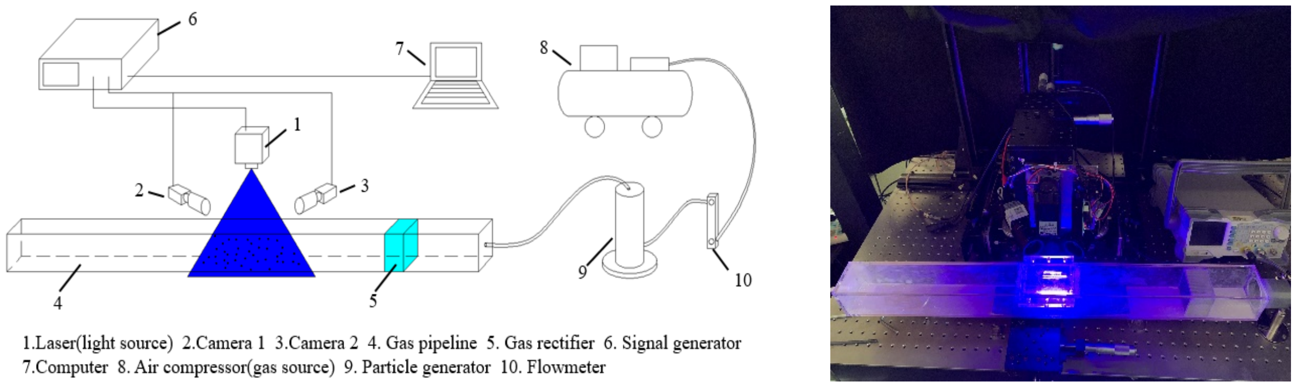

Figure 4 Experimental system

2. *Measurement result*

Figure 5 is a pair of experimental images taken by the left and right camera after image enhancement processing. Figure 6 marks the identified and matched trajectories on the basis of Figure 5. The blue dots represent the trajectories that a single camera has identified successfully. The colourful dots represent the trajectories which match successfully. Figure 7 shows the three-dimensional position and trajectories of the particles calculated after image processing. The measurement area is the middle section of the pipeline. From the results, it can be seen that the flow direction is from left to right. The dot represents the endpoints of the 4 trajectories, the connecting line is a B-spline fitting curve, and the arrow represents the direction of the gas flow.

The calculation results show that the particle velocity in the *X*, *Y*, and *Z* axis directions are within the range of 46~106 mm/s, 2~15mm/s, and 5~64 mm/s, respectively. The measurement results show that the gas flow is three-dimensional, which is more consistent with the theoretical analysis results, indicating the effectiveness of this measurement method.

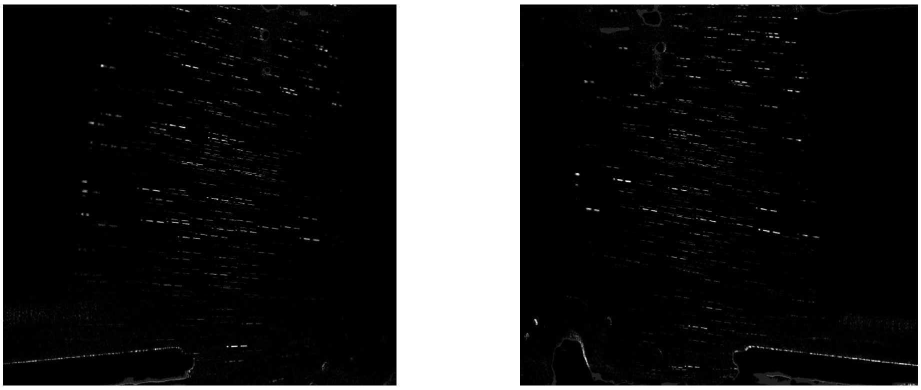

Figure 5 Experimental images after enhancement processing

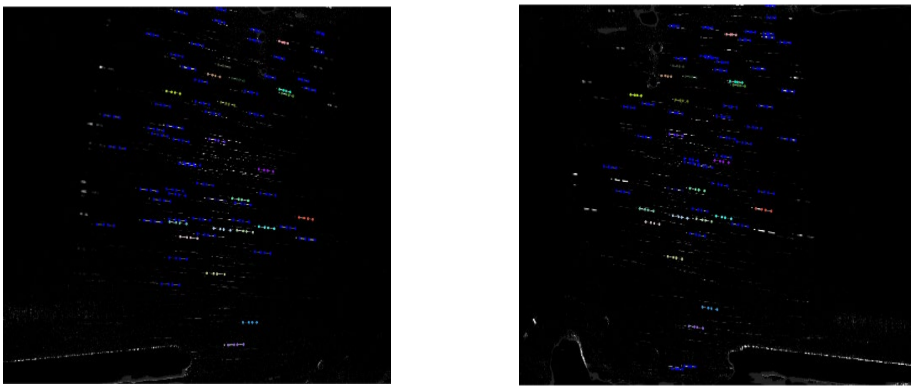

Figure 6 The identified trajectories

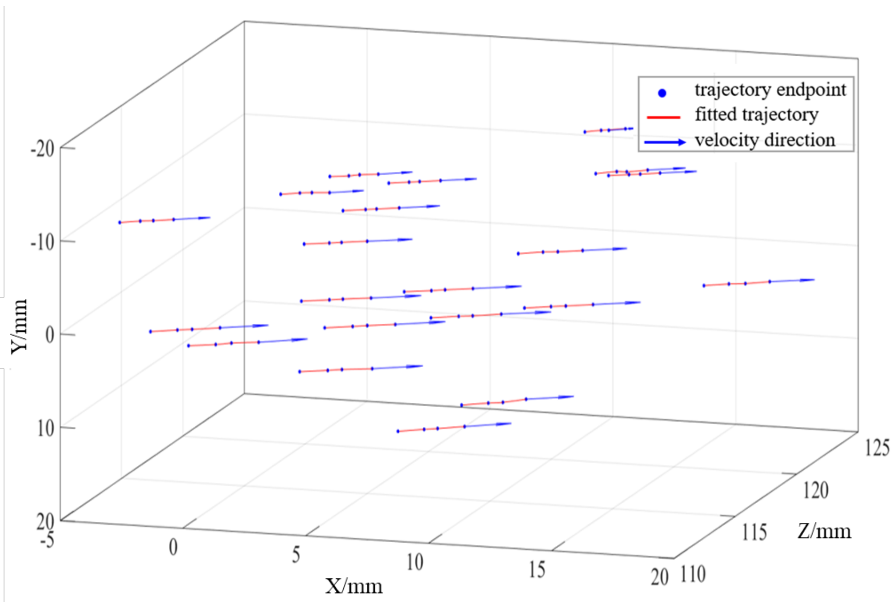

Figure 7 Measurement results

CONCLUSIONS

In summary, the PSV method uses motion blur generated by particle motion for fluid flow measurements. Under the same hardware conditions, the PSV method has the advantage of higher upper limit of velocity measurement compared to the PIV method and the PTV method. Similarly, the former requires less hardware cost when measuring the same velocity in the flow field.

The main work of this paper is as follows:

(1) It is proposed that the combination of binocular vision and single-frame with multi-exposure particle streak velocimetry is used to determine the speed direction through the long trajectories and short exposure points.

(2) A method of gray-scale fitting to identify the feature points of the particle trajectory is proposed.

(3) It is proposed to use B-spline fitting to obtain the trajectory in three-dimensional world coordinates for velocity calculation.

(4) A flow field measurement system was built, and the particle streak velocimetry (PSV) based on binocular vision was used for actual measurement, and the measurement results were analyzed and evaluated.

(5) Provide a new fluid flow measurement method for the three-dimensional gas flow field, and then apply this method to measure the cascade flow channel.

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