Circular Dynamic Stereo and Its Image Processing

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Abstract - A new approach to the measurement of three-dimensional movement of particles is introduced. A single TV camera with an apparatus to rotate the image enables us to record the three-dimensional movement of particles as spiral streaks on a single image. Every shape of the spiral streak on the image plane is related to the position and the velocity of the individual particle. The information about three-dimensional movement of particles is extracted from the image using an image processing technique. We applied the technique to the measurement of three-dimensional water flow field and obtained satisfactory results.
Key Words: three-dimensional, refractor, CCD camera, measurement, rotation, multiple points, image processing, calibration.

1 Introduction

Image processing systems(Particle Tracking Velocimetry) for two-dimensional flow measurement have been exploited since the system can determine the instantaneous velocity distribution without any contacts to flow[1],[2],[3]. In these systems, TV camera records the movement of suitable tracer particles suspended in the fluid. Computer determines the velocity vector by measuring the translational displacement of tracer particle during a constant time interval. These 2-D particle tracking velocimetry yield only the two components of the velocity vectors, which are measured over a planar region. Recently, the desire to measure the three-dimensional fluid velocity within a finite volume is very strong among both engineers and researchers in the area of fluid dynamics. Therefore 3-D PTV systems yield all three components of the location and the velocity vector for each tracer particle are now studied. Stereoscopic imaging is a 3-D PTV, in which moving particles are recorded simultaneously from two different angles. Particles are triangulated individually, and are tracked from one image to the next image to recover velocity information. One difficulty of the stereoscopic imaging is to uniquely match many particles viewed from different angles[4].

In this paper, a new technique to measure the instantaneous three-dimensional velocity of moving particles is introduced. The main feature of our technique is to use a single TV camera with an image shifting apparatus. By introducing a refractor on the TV camera lens, the image of the particle is displaced with the corresponding displacements related to the distances between the TV camera and particles. When the refractor is rotated physically at high speed during the exposure of the TV camera, spiral streaks of moving particles appear on an image since the rotational shift is added to the movement of particles. Since the size of the streak is inversely proportional to the distance of the particle from the camera, each spiral streak has three-dimensional information of a moving particle. The three-dimensional velocity vector can be calculated using image processing technique. Reliable information can be obtained since our system is free from difficult matching task of small tracer particles between different frames. We applied this technique to the measurement of three-dimensional water flow field and obtained satisfactory results.

2. Circular dynamic stereo

A simplified setup of our imaging system is shown in Fig. 1 and the photograph of the system is shown in Photo.1. By introducing a refractor on the TV camera lens, the image of the measuring point is displaced with the corresponding displacement related to the distance between the TV camera and a measuring point. That is, the displacement *r* in the image is inversely proportional to the distance *D* between the measuring point and the camera as:

$$D = \frac{f \cdot d}{r} \tag{1}$$

where *f* is the focal length of the camera and *d* is the magnitude of the image shifting by the refractor. When the refractor is rotated physically at high speed during the exposure of the TV camera, annular streak of a measuring point appears on an image since the rotational shift is added to the image.

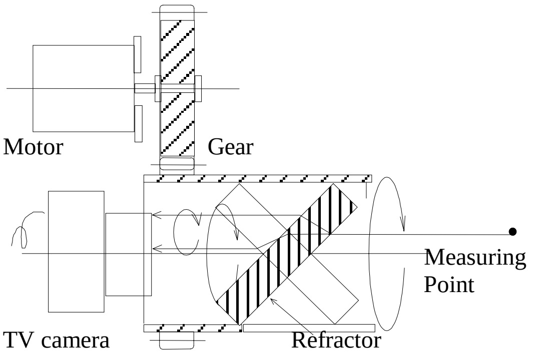


Fig.1 System setup

Photo.1 Circular dynamic stereo system

Stationary particle Moving particle
Fig.2 Spiral image

Fig.2 shows examples of the streak. In the case that the particle is stationary during the exposure, the streak draws a circle whose diameter is inversely proportional to the distance between the particle and the camera. If a particle is moving from left to right, it draws spiral streak from left to right and the radius of streak varies depend on the variation of the distance. The location and the size of the spiral streak in the image is related to the three-dimensional location of the particle, and the pitch and size variation of the streak is related to the three dimensional velocity of the particle.

3 Image processing

3.1 Analysis of the streaks on a single image

In the case that the measuring points are dense, streaks on the image plane would be overlapped each other. By considering the feature that the segment of an annular streak appearing on the image plane is concentric, each streak can be extracted automatically by the following procedures. Firstly, the intensity gradient is first estimated at all location in the image and then gated at certain threshold level to extract the positions of significant edge of circle. Next, lines in the direction of edge normal against the segment of the annular streak are generated in the 2-Dimensional parameter space. The slope of the line along the edge normal is calculated by use of the components of intensity gradient on the segment of annular streaks as,

$$\theta = \tan^{-1}(g_y / g_x) \tag{2}$$

where g_x and g_y are the local components of intensity gradient.

Then the points along a line in the directions of the edge normal are accumulated in parameter space. Fig.3 shows an example of annular streaks overlapped and lines in the directions of the edge normal.

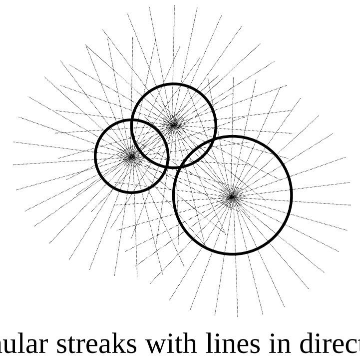


Fig.3 Annular streaks with lines in direction of edge Normal

Since the lines in the direction of edge normal are converged at the center of annular streaks, the peak caused by this accumulation in parameter space might be interpreted as a possible center. The parameter space is gated at the certain threshold level to extract blobs that include a peak. Then, each blob extracted in the parameter space is labeled and the peak in the blob is found to be a center of the annular streak. The position of the peak in the blob is calculated in sub-pixel accuracy by

$$x_c = \frac{\sum x \cdot f_p}{\sum f_p} \qquad y_c = \frac{\sum y \cdot f_p}{\sum f_p} \qquad f_p > \text{certain threshold value} \tag{3}$$

where p is a point located at (x,y) and f_p is the amount of the accumulation of possible center at p in the parameter plane. Once all centers of annular streaks were found, each annular streak can be extracted easily regardless of their overlapping.

Since the streak is circular, the diameter of this streak can be measured many times at various angles and the final result of the diameter is obtained by taking the average. This mathematical operation of an annular streak enables a high accurate measurement. In order to simplify the operation, the following method is adopted in our system.

For the first step, the accumulation of the pixel intensity where the distance is r from the center point Po is calculated by

$$F(r) = \sum_{\theta=0}^{2\pi} f(r,\theta) \tag{4}$$

where $f(r,\theta)$ is pixel intensity at (r,θ). This method is also illustrated in Fig.4. For the second step, the graph of $F(r)$ as Fig.5 is drawn by use of the results of (4). The size of annular streak r_p is determined by finding the peak in Fig.5.

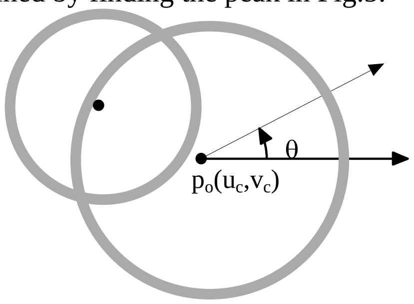


Fig.4 Measurement of the size of annular streak

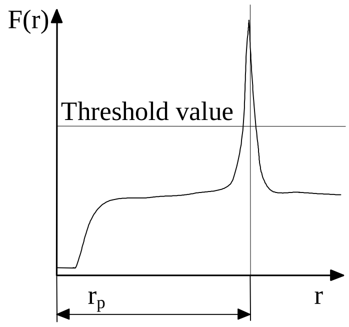


Fig.5 Accumulation of pixel intensities along the streak

The position of peak in F(r) is calculated in sub-pixel accuracy by

$$r_p = \frac{\sum F(r) \cdot r}{\sum F(r)}. \tag{5}$$

The center (x_c, y_c) and the size r_p of circular streak obtained by above procedure are converted to the world coordinate (x_w,y_w,z_w) by ,

$$\begin{bmatrix} x_w \\ y_w \\ z_w \end{bmatrix} = \frac{d}{r_p} \begin{bmatrix} x_c \\ y_c \\ f \end{bmatrix} \tag{6}$$

where d is a magnitude of shift by the refractor and f is a focal length of the TV camera.

3.2 Analysis of streaks on consecutive images.

The moving information can be obtained by analyzing the consecutive images. When the measuring points are moving, the spiral streaks are appeared on a field image. As the rotation of the refractor is enough faster than the movement of particles, the particle images draw nearly annular streaks on an each image field and approximate center and size of the streaks can be calculated in the same manner as 3.1. This image processing using the approximation is shown Fig. 6 Since the rotational frequency of the refractor is synchronized to the field frequency of the TV camera, the each corresponding streak and blob generated by the accumulation of the lines of edge normal have a same shape between field images. The pair of corresponding streaks can be found easily by the image correlation method. After finding the correspondence of streaks, the spiral equations are generated by considering the size of streaks, the displacement of blobs between field images, and the rotational frequency of the refractor. Extracted information from the spiral streaks is converted to the three-dimensional moving data.

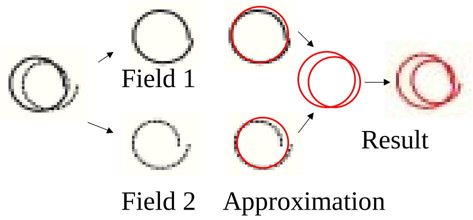


Fig.6 Analysis of spiral streak

4 Experiment

Two kinds of applications using our system will be introduced. One of the applications is a measurement of multi laser spots projected on the surface of an object. The other is a measurement of tracer particles in water flow.

4.1 Measurement of laser spots position.

The multi laser spots are projected onto the surface of object from the position of TV camera. The setup is shown in Fig.7. The laser spot on the surface of object draws an annular streak in the image plane using our system and the diameter of the streak concerns to the depth from the TV camera to the laser spot. It means that three-dimensional information of multiple points is recorded in a single image. Fig.8.a shows the multi laser spots projected on the surface of object and Fig.8.b shows the image with circular shift by our system. Smaller annular streaks concern to laser spots on the surface of far object and bigger annular streaks concern to laser spots on the surface of near object. The average error of this measurement was under 2mm when the depth was under 500mm.

Next example is a measurement of moving laser spots. The spiral streaks appear on the image by moving the laser spots. Fig.9.a is an example of the spiral streaks appeared on an image field and Fig.9.b is an analyzed spiral by our method.

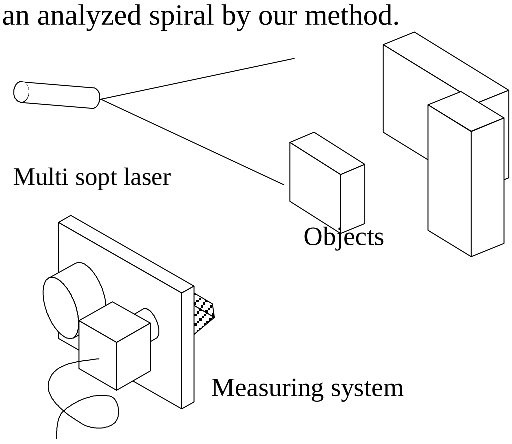
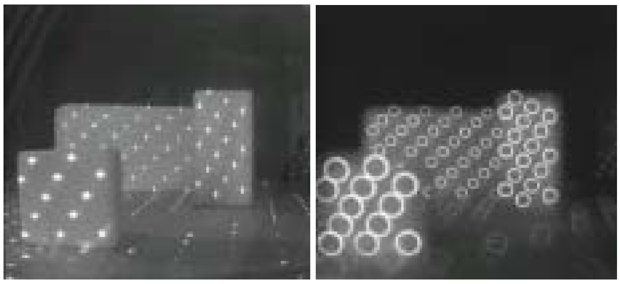
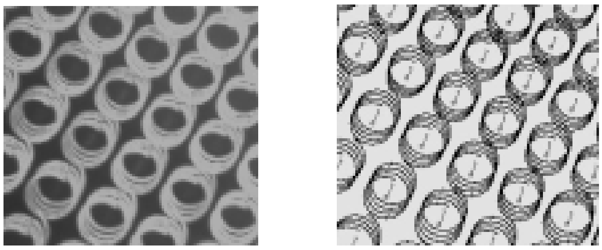


Fig. 7 Experimental setup using multi laser spots.


a. b.

a. Multi laser spots projected on the surface of objects.
b. Image with circular shift.

Fig.8 Example image of multi laser spots


a. b.

a. Example image of moving laser spots
b. The redrawn spiral using the result of processing

Fig.9 Image of moving laser spots

4.2 Measurement of water flow

Second application is a measurement of flow. Experimental setup is shown in Fig.10. Tracer particles of 0.5mm, or less, in diameter are introduced in the water. The particles have a specific gravity of 1.03, so that they may be considered neutrally buoyant in water.

As the rotation of refractor is fast enough than the movement of tracer particles, the particles draw annular streaks on the image plane. Fig. 11 shows the one example of particle streaks obtained by our system. In this experiment the rotational frequency is synchronized to the field frequency of TV camera (3,600r/min). In order to measure the movement of tracer particles, 24 consecutive fields are recorded. The information of motion can be estimated by the difference of the streaks of correspond particles between these fields. After analyzing the streak of each field, the spiral equation is generated and position and moving information is obtained to estimate the three-dimensional velocity information. The velocity distribution of flow in a tank is estimated by interpolating the all particle information. Fig.12 shows the one example of velocity distribution in our experimental tank.

5 Conclusion

The new approach to obtain the depth information is introduced. A single camera and an image rotation apparatus record the three-dimensional information on a single image.

In the case that many measuring points are existed in a frame, there are possibilities that some annular streaks are overlapped each other. By generating lines in the direction of edge normal against the segment of an annular streak, each annular streak could be extracted efficiently. Sub-pixel analysis also could be executed by considering the pixel intensity of an annular streak.

The measurement of surface position of object and particle position in water flow is introduced for one of the multiple applications of our system. Our compact system can be applied also for a Robot vision system.

Our proposed system used a TV camera. The use of a still camera or a digital camera that has a higher resolution is also possible. Therefore, if a more accurate measurement is required, another image capturing device could be used.

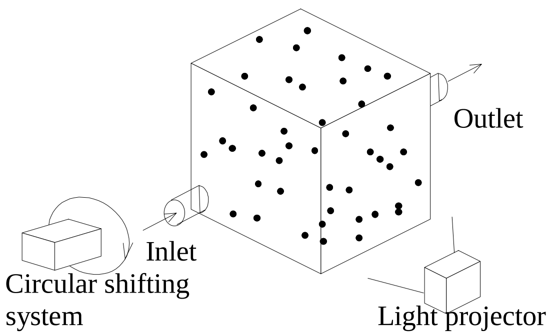


Fig.10 Experimental setup of flow measuring

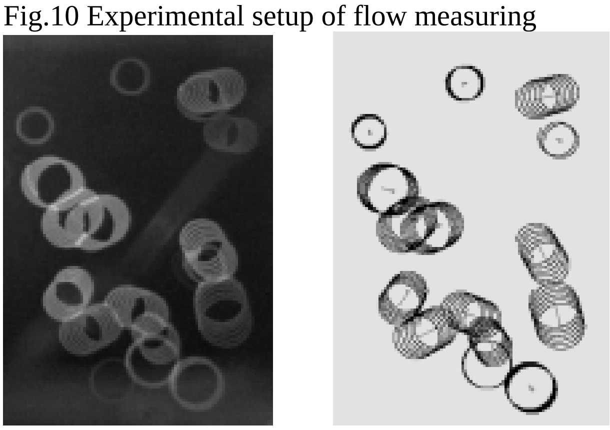


Fig. 11 Example of the streaks of tracer particle

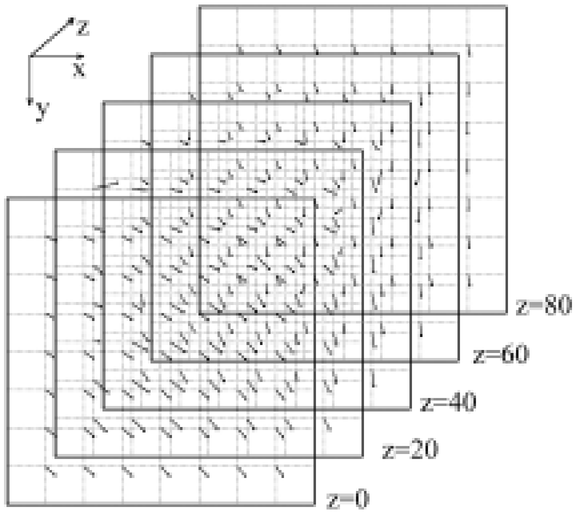


Fig.12 Velocity distribution in water tank

References:

[1]Luke J. Chen and Ching-Jen Chen, “Visualization of three dimensional flow in a Cubic chamber with digital correlation method”, FLUCOME ‘91, pp.407-410

[2]C.Shih, L.Lourenco, L.Van Dommelen, and A.Krothapalli,” Unsteady flow past an airfoil pitching at a constant rate”, AIAA Journal, Vol.30, No.5, May 1992, pp.1153-1161

[3]K.Kawasue, T.Ishimatsu and C.Shih, “Fast processing technique of particle image velocimetry”, FLUCOME ‘94, pp.209-214

[4]K.Nishino,N.Kasagi,M.Hirata, “Three-dimensional particle tracking velocimetry based on automated digital image processing”, Transactions of the ASME, Vol. 111, Dec. 1989, pp. 384-390