Particle Image Velocimetry with Auto Calibration

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Abstract: PIV (Particle Image Velocimetry) for a flow measurement have been exploited since the system can detect the instantaneous velocity distribution without any contacts to flow. On the operation of PIV, laser-slit is projected against the flow and the movements of tracer particles on the laser-slit are recorded by CCD, and the computer calculates the velocity vector by analyzing the movements of tracer particles. In order to realize the quantitative measurement, the calibration is required between camera coordinates and world coordinates. The calibration is generally cumbersome and it should be executed on every change of the re-arrangement between CCD and laser projector. In order to reduce the cumbersome work, we developed the PIV system with automatic and real-time calibration using 3D magnetic sensor. The system enables a separated free arrangement of a CCD camera and a laser-slit without calibration. The velocity distribution of different views is reconstructed graphically on a computer display. Experimental results show the feasibility of our system.

Key-Words: PIV, Vision, Image processing, CCD, Calibration, Magnetic sensor.

1 Introduction

This paper addresses the new approach of easy use flow measurement system. Recently, PIV (Particle Image Velocimetry) is often used on the experiments of flow dynamics [1]-[4]. On the operation of PIV, many tracer particles are suspended in the flow and the laser-slit is projected against the flow. The movements of tracer particles on the laser-slit are recorded by CCD, and the computer calculates the flow velocity vector by analyzing the movements of tracer particles. The quantitative measurement is established by considering the geometric configuration between a CCD camera and a laser slit [4]. The calibration is generally cumbersome and it should be executed on every change of the arrangement between CCD and laser projector. Simple calibration method is required since many numbers of views should be recorded to analyze complex flow.

In this paper, measuring system that enables a free re-arrangement of each of a CCD camera and laser-slit without cumbersome calibration is introduced. The magnetic sensor (Polhemus Inc.) is attached in each of a CCD camera and laser projector. The sensor measures the each three-dimensional position and the orientation of the CCD camera and the laser at 60Hz. Many numbers of views of a flow from different orientations can be taken on measuring the configuration between a CCD camera and laser-slit simultaneously. The velocity distribution of different views is combined to reconstruct the 3D velocity distribution on a computer display.

Calibration is an important task in a quantitative measurement since it influences the measurement accuracy. Generally, calibration process is complicated and is not unified in measurement systems. The suitable initial calibration method for our system is introduced in this paper. Once initial calibration executed, re-calibration is not required on re-arrangement of CCD and laser projector.

The flow measurement of experimental tank with bubble generator is executed to demonstrate the feasibility of our system.

2 System Setting

Fig.1 shows the configuration of the measurement system. The system consists of a CCD camera, slit laser, and electric magnetic sensors. A slit ray is projected into the experimental tank filled with water and the CCD camera observes the movement of tracer particles on the slit-ray. The magnetic receiver

(Polhemus Inc.) is attached in each of CCD camera and the laser. The magnetic transmitter generates the magnetic field and the signal from the receiver is sent to the main controller to calculate the three-dimensional information of the receiver. This information consists of three-dimensional position parameter and rotational motion parameter (Azimuth, Elevation, Roll). The positions and the orientations of the CCD camera and the laser are observed at a rate of 60 Hz during the measurement; therefore, it enables the free scanning of the CCD camera and the laser.

Fig.2 shows the block diagram of the system. The image signal from the CCD camera is sent to an image processor. The image processor emphasis the image and reduce the noise from the image. Magnetic sensor controller controls the magnetic sensor and detects the position and the orientation of the CCD and the laser projector.

3 Measurement procedures

The measurement procedure is to estimate the intersection between the laser plane and the vector from the focal point of the CCD camera. The laser plane and vector from the focal point of the CCD camera is measured on real time during the measurement.

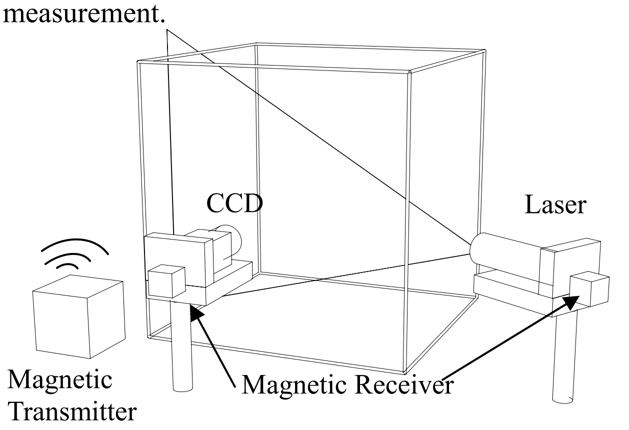

Fig.1 Configuration of the flow measuring system

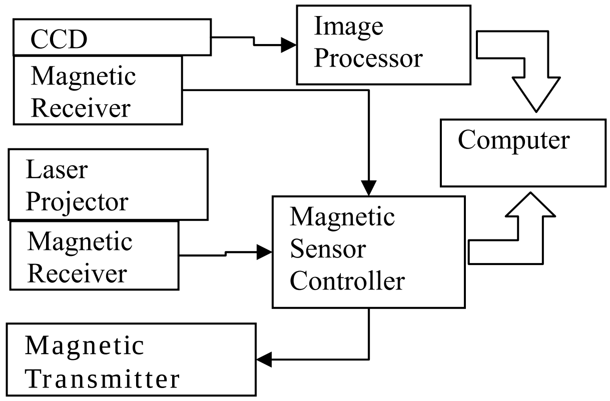

Fig.2 Block diagram of the system

3.1 Equation of laser plane

The electro magnetic sensor receiver attached on the laser slit projector enables the real-time detection of laser plane information. The information generated by the sensor is the three-dimensional position (x_{ow} ,y_{ow} ,z_{ow}) and the orientation (Ψ: Azimuth, Θ: Elevation, Φ: Roll) of the magnetic receiver. This information is used to determine the equation of the laser plane. The arbitrary points on a laser plane on receiver coordinate originated at the receiver position are converted into the world coordinates (x_{rw},y_{rw},z_{rw}) originated at the transmitter position by the following formula.

$$\begin{bmatrix} x_{rw} \\ y_{rw} \\ z_{rw} \end{bmatrix} = RPY(\Psi,\Theta,\Phi) \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} + \begin{bmatrix} x_{ow} \\ y_{ow} \\ z_{ow} \end{bmatrix} \quad (1)$$

where

$$RPY(\Psi,\Theta,\Phi) =$$

$$= \begin{bmatrix} C_\Psi & -S_\Psi & 0 \\ S_\Psi & C_\Psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_\Theta & 0 & S_\Theta \\ 0 & 1 & 0 \\ -S_\Theta & 0 & C_\Theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_\Phi & S_\Phi \\ 0 & S_\Phi & C_\Phi \end{bmatrix}$$

$$= \begin{bmatrix} C_\Psi C_\Theta & C_\Psi S_\Theta S_\Phi - S_\Psi C_\Phi & C_\Psi S_\Theta C_\Phi + S_\Psi S_\Phi \\ S_\Psi C_\Theta & S_\Psi S_\Theta S_\Phi + C_\Psi C_\Phi & S_\Psi S_\Theta S_\Phi - C_\Psi S_\Phi \\ -S_\Theta & C_\Theta S_\Phi & C_\Theta C_\Phi \end{bmatrix}$$

C: Cos., S: Sin.

Ψ: Azimuth, Θ: Elevation, Φ: Roll

Three arbitrary points on a laser plane are converted to world coordinate originated at the transmitter position by (1) and the laser plane equation is determined on the world coordinate as following equation.

$$[x, y, z]\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad (2)$$

where

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} x_{rw1} & y_{rw1} & z_{rw1} \\ x_{rw2} & y_{rw2} & z_{rw2} \\ x_{rw3} & y_{rw3} & z_{rw3} \end{bmatrix}^{-1} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

3.2 Camera parameter

The relation between the camera coordinate and the receiver coordinate is shown in Fig.3. The point appeared on the image plane is explained by using the camera coordinates with an origin at focal point as following.

$$u = f \cdot \frac{X}{Z}, v = f \cdot \frac{Y}{Z} \quad (3)$$

This relation can be expressed by matrix as following.

$$\lambda \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (4)$$

In order to convert this camera coordinate into the receiver coordinate with an origin at the receiver, parameters (k_{11}-k_{33}) are introduced on considering the rotation and displacement as following.

$$s \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} \\ k_{21} & k_{22} & k_{23} & k_{24} \\ k_{31} & k_{32} & k_{33} & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad (5)$$

Equation (5) indicates the relation between the camera coordinate and the receiver coordinate. This equation can be expressed also as following.

$$\begin{cases} (k_{31}u - k_{11})x + (k_{32}u - k_{12})y + (k_{33}u - k_{13})z = k_{14} - u \\ (k_{31}v - k_{21})x + (k_{32}v - k_{22})y + (k_{33}v - k_{23})z = k_{24} - v \end{cases} \quad (6)$$

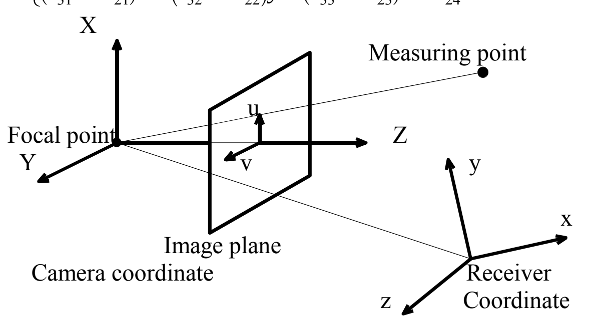

Fig.3 Relation between camera coordinate and receiver coordinate

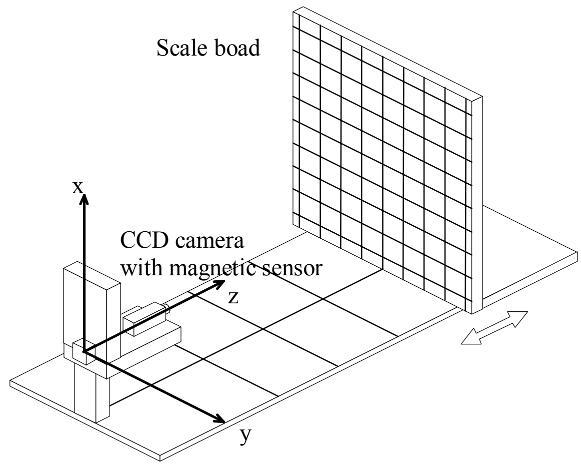

Fig.4 Calibration setup

The eleven parameters k_{11}-k_{33} can be determined by feeding some corresponding coordinates that the values are already known. The initial calibration setup is shown in Fig.4. The image of the scale board is recorded by the CCD camera and is displayed on the computer display. A mouse device and a keyboard feed the pair of position between the camera coordinates and the receiver coordinates, respectively. Once these parameters (k_{11}-k_{33}) are determined, the system does not require the calibration on re-arrangement of the CCD and Laser projector since the movements of these are observed anytime by magnetic sensor.

The equation (6) indicates the two planes and the intersectional line between these planes indicates the line from the focal point to the measuring point on the receiver coordinate. The line can be expressed as following.

$$\begin{cases} x = f \cdot t + m \\ y = g \cdot t + n \\ z = h \cdot t + l \end{cases} \quad (7)$$

where (f,g,t) is a vector that the direction is from focal point of the camera to the measuring point and (m,n,l) is a point on the line on the receiver coordinate. This receiver coordinate can be converted to the world coordinate with an origin at the transmitter as following formula.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = RPY(\Psi, \Theta, \Phi) \begin{bmatrix} f \cdot t + m \\ g \cdot t + n \\ h \cdot t + l \end{bmatrix} + \begin{bmatrix} w_x \\ w_y \\ w_z \end{bmatrix} \quad (8)$$

Where (w_x,w_y,w_z) indicates the position of the receiver.

3.3 Position of measuring point on world coordinates

The position of measuring point on the world coordinate can be determined as the intersection between the laser plane and the line from focal point of the CCD camera to measuring point. The position can be calculated from (2) and (8).

3.4 Estimation of velocity distribution

The velocity information is estimated using two consecutive images detected by CCD. In order to extract velocity at each location, a correlation function between the location (u,v) in the first image and the location (u+du,v+dv) in the second image is defined as follows;

$$\phi fg(u,v,du,dv) = \sum_{k+u}^{u+m} \sum_{l=v}^{v+N} (f(k,l) - g(k+du,l+dv))^2 \quad (9)$$

Where $f(k,l)$ and $g(k,l)$ are the intensity at the location (k,l) in the first image and the second image respectively. M and N denote the sizes of the interrogation region and they are determined considering the concentration of tracer particles and the maximum velocity of the flow. This correlation function is used to estimate the translational displacements of tracer particles between two consecutive images. The displacement at location (u,v) in the first image is estimated as follows. First, values of the above correlation function are calculated between the location (u,v) in the first field and the possible point (u+du,v+dv) in the second field. Second, the best estimate of the translational displacement of the tracer particles is determined as the pair (du,dv) which minimizes the correlation function The global velocity profile of the flow can be obtained by repeating the above computation at every location.

A feature of this method is that the velocity at one location is determined by the movement of a set of neighboring tracer particles.

Fig.5 shows the example of velocity distribution of water flow. The arrow origin (u,v) and arrow head (u+du,v+dv) is converted to (x,y,z) and (x+dx,y+dy,z+dz) by the procedure explained in 3.1 - 3.3.

4 Experiments

4.1 Performance of the system

Since the system is based on the principle of triangulation, the angle between the CCD camera and the laser slit influences the measurement accuracy. Therefore, in this experiment, the angle between the CCD and the laser slit was changed by 5 degree, and the accuracy of the measurement was evaluated. Fig. 6 shows the example of the measurement accuracy in this experiment when a plane board was set at distance 426 mm from the CCD. When the angle between the CCD camera and the laser slit was over 20 degree, the error was less than 1 mm.

4.2 Flow measurement

The experimental setup is shown in Fig.7. The water pump is set at the edge of the tank and it generates the water flow.

Laser-slit (20mW)is projected against the flow. The operator changes the area that to be measured by just changing the position of CCD and laser projector as is shown in Fig.8. Polystyrene tracer particles with10 micro meter or less are suspended in the water as seeding particles. The particles have a specific gravity of 1.03, so that they may be considered neutrally buoyant in the water. The tracer particles on the laser-slit are recorded by CCD, and the computer calculates the velocity vector by analyzing the movements of tracer particles. Fig.9 shows the velocity distribution at three different position and angles. In this system, the velocity distribution can be obtained just pointing the arbitrary area by a laser slit without calibration.

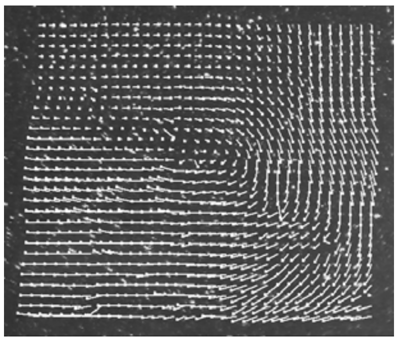

Fig. 5 Example of flow distribution

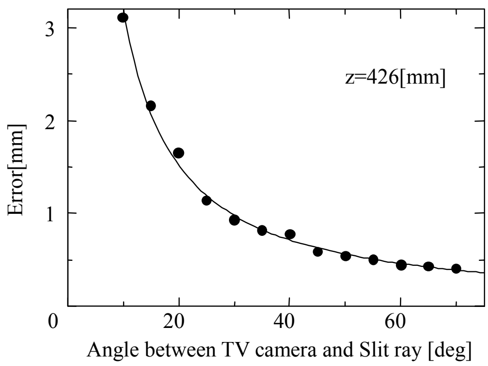

Fig.6 Measurement accuracy

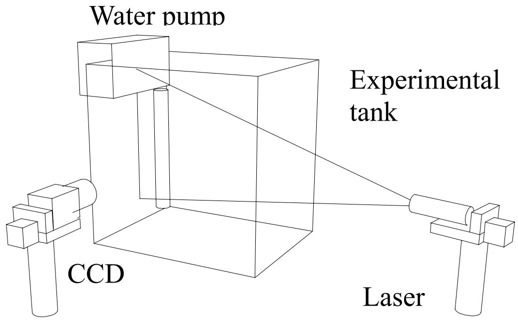

Fig.7 Experimental setup

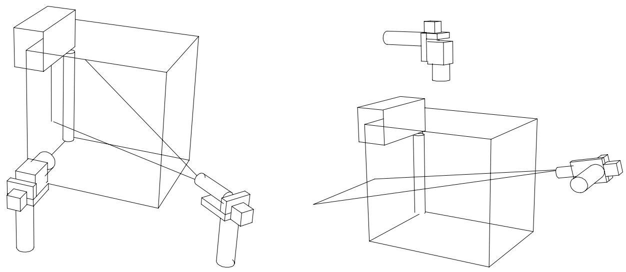

Fig. 8 Rearrangement of CCD and laser projector

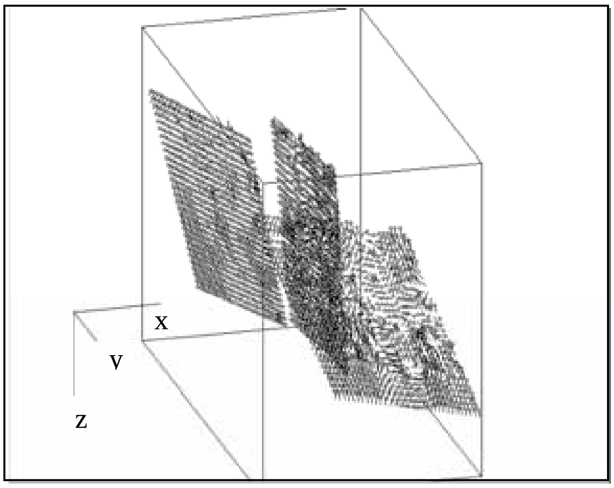

Fig.9 Flow distribution in the experimental tank

5 Conclusion

PIV (Particle Image Velocimetry) which enables a separated free arrangement of a CCD camera and a laser slit has been introduced. Operator can change the configuration flexibly between a CCD camera and a laser slit without calibration. It enable an easy measurement that operator can measure the desired area by just pointing the area by the laser slit projector.

The measurement of an experimental tank is introduced and the velocity distribution in the tank is displayed on the computer display graphically.

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