Conditional Sampling Stereoscopic-PIV Measurement around Rotating and Revolving Cylinder in Internal Swirly Flow Generated by Tangential Suction Jet

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A conditional sampling stereoscopic-PIV has been developed for the flow field measurement around a rotating and revolving cylinder. Four Fiber sensors are used to detect the location and the orientation of the rotating and revolving cylinder and to activate the stereoscopic-PIV system. The flow characteristics around a rotating and revolving cylinder in an internal swirling flow generated by tangential suction jet in a vertical pipe with a length of 600mm are investigated by the use of the conditional sampling. The radial distribution of the azimuthal velocity component around a rotating and revolving cylinder has peak at inner position from the vertical pipe wall in the upper, middle and lower vertical positions. The difference of the radial peak position depending on the vertical position and the flow velocity are discussed.

Key words: Swirling Flow, Tangential Suction Jet, Rotating and Revolving Cylinder, Fiber Sensors, Conditional Sampling Stereoscopic-PIV

1. Introduction

A pneumatic conveyance system has been widely adopted for industrial material transportation11. However it has the problems that are the deterioration of material quality caused by a collision to the pipe inner wall and the low transportation efficiency. Therefore, studies of swirling flow pneumatic conveyance systems are performed to avoid the deterioration of the material quality. The swirling flow pneumatic conveyance systems have two types which are generated by a suction tangential jet and a blowing tangential jet. Li et al. (2000) investigated the particle behaviors in the internal swirling flow generated by suction tangential jet using materials of polyethylene and polyvinyl to report the pressure drops in a horizontal pipe6. However, spherical materials are assumed for pneumatic conveyance material in these researches, these are not cylinder materials used in actual industry. The cylinder materials in the internal swirling flow generated by the suction and blowing tangential jets have characteristics that the long axis of the cylinder material is orientated in the main direction. The orientation efficiency can be improved by using an internal swirling flow by a suction tangential jet12. These researches are for experiments about the orientation efficiency, not for the surrounding flow. Even though forces acting on a cylinder material with orientation are studied11, experimental reports on the flow around a rotating material in an internal swirling flow are very few. Therefore, the velocity measurement around a cylinder materials is necessary to discuss experimentally the forces acting on rotating and revolving cylinder.

Recently, stereoscopic-PIV technique is widely used for the measurements of flows in various engineering fields590. PIV measurements become popular to measure flow around static spherical ball3, around a rotating ball99 and an orbiting cylinder39. However, there is not an example which measured a flow around a rotating cylinder by PIV. In order to achieve the flow measurement around a rotating and revolving cylinder, a conditional sampling method is necessary. Namely PIV irradiates laser sheet when the orientating cylinder passes through a certain position. With regard to the conditional sampling method, Hu et al. (2006) developed a conditional sampling technique due to a combination of the phase-averaged PIV and hotwire measurements in order to characterize quantitatively the effect of corner radii on the near-wake flow structure99. However, a few studies of conditional sampling for rotating materials exist.

The authors clarified the flow characteristics around a rotating and revolving cylinder between internal swirling flows generated by blowing tangential jet and generated by suction tangential jet using fiber sensors in a very limited velocity condition11, and then carried out the frequency analysis12. The purpose of this study is to establish a conditional sampling method of stereoscopic-PIV system for the flow characteristics around a rotating and revolving cylinder in an internal swirling flows generated by suction tangential jet. With the developed system, the three dimensional flow components around a rotating cylinder and revolving cylinder in the internal swirling flows generated by suction tangential jet in order to discuss the flow characteristics difference in the different flow velocity conditions.

2. Conditional Sampling Stereoscopic-PIV

2.1 Conditional Sampling

The authors have developed a conditional sampling device of a sensor unit that measures surrounding flow of a rotating and revolving cylinder orientation. The conditional sampling stereoscopic-PIV measurement for the rotating and revolving cylinder is performed by a sensor unit to activates stereoscopic-PIV system. Fig.1 (a) shows the mechanism of the conditional sampling. The sensor unit activate the laser sheet when the orientating cylinder passes through the red LED emitting from the sensor unit. The sensitive sensor area is a vertically front plane of the orientating cylinder. The sensor unit is composed of four reflection type fiber sensors. The fiber sensor embedded in the pipe wall. The unit is set up at the same vertical plane of the laser sheet. All fiber sensor detect their red lights reflected from the cylinder, the generated pulse signal implies the cylinder orientation. The red LED wave length is
680 nm. Fig.1 (b) shows all sensors detect the orientating cylinder, which means the rotating and revolving cylinder stands upright and turns in the swirling flow with the orientation, because the length of the sensor unit \( l_c = 57 \text{ mm} \) almost corresponds to the length of the rotating cylinder and revolving, \( l_r = 60 \text{ mm} \). On the other hand, Fig.1 (c) shows the less than four sensors detect the cylinder, which means the rotating and revolving cylinder turns in the swirling flow without the orientation. In this non-orientating case, the sensor unit does not activate the laser sheet. The fiber sensor is made by OMRON Corporation (E3X-NA11F). The fiber sensor is capable of a response speed 20 \( \mu \text{s} \). The sensor adjust the detecting distance \( w_s = 10 \text{ mm} \) from the pipe wall. Therefore, the rotating and revolving cylinder which has the inclination of less than 10 degrees is detected as an orientating cylinder. The polystyrene revolving cylinder which has the inclination of less than 10 degrees is detected as an orientating cylinder. The polystyrene foam cylinder has the diameter \( d_c = 12 \text{ mm} \), the length \( l_c = 60 \text{ mm} \) and density 220 \( \text{kg/m}^3 \). The cylinder was put into the swirling flow field in order to investigate the flow characteristics at a certain height from the main pipe bottom where its posture was revolving with orientation.

2.2 Stereoscopic-PIV system

In this study, a hybrid stereoscopic-PIV is used. The hybrid stereoscopic-PIV introduces, a geometric transformation to consider the refraction and the aberration of the lens and the camera calibration method used for the 3D-PTV measurement developed by Doh et al. (2004). In order to attain three-dimensional measurement with two cameras, it is necessary to know their camera parameters. The ten-parameter method is used. Since the arrangement of the cameras has a large view angle, the obtained images are strongly distorted, which makes the camera calibration difficult. To overcome this matter, a two-dimensional image transformation on each camera image: warping, is carried out before using the original images for the camera calibration.

The calibrator image before and after transformation are shown in Figs.2 and 3. In this study, the image at the center physical plane \((Z = 0 \text{ mm})\) was used to calculate the elements of the camera calibration matrix.

In the ten-parameter method, 10 parameters \((6 \text{ exterior parameters: } l, \alpha, \beta, \gamma; m_s, m_c, 4 \text{ interior parameters: } c_x, c_y, k_x, k_y)\) are obtained. \((\alpha, \beta, \gamma)\) represent the tilt angles of the photographic coordinates axes to the absolute axes. Fig.4 shows a coordinate relation when the photographic axes are set parallel to the absolute coordinate by the tilting angles \((\alpha, \beta, \gamma)\). \((X, Y, Z)\) represents the absolute coordinate, and \((x, y, z)\) represents the photographic coordinate of the image centroid of the calibration targets. The \( l \) means the distance between the origin \((0, 0, 0)\) and the principal point \((X_0, Y_0, Z_0)\) of the camera.

The coordinate \((X_m, Y_m, Z_m)\) represents the point P position of the calibrator when the camera coordinate is rotated with the tilting angles to make the collinear set in one line as shown in Fig.4. The \( m_s \) and \( m_c \) means the point at which the normal vector from the origin O \((X_0, Y_0, Z_0)\) of the camera coordinate meets with the X-Y plane. The collinear equation for every point between the two coordinates is expressed as Eq. (1). The \( c_x \) and \( c_y \) are the focal distances for \( x \) and \( y \) components of the coordinate. \( \Delta x \) and \( \Delta y \) are the lens distortions as expressed as Eq. (2). The Eq. (1) can be converted to the following Eq. (3).

\[
\begin{align*}
\Delta x &= c_x \frac{X_m - m_x}{\sqrt{X_m^2 - m_x^2 - m_y^2 - Z_m^2}} + \Delta x' \\
\Delta y &= c_y \frac{Y_m - m_y}{\sqrt{Y_m^2 - m_x^2 - m_y^2 - Z_m^2}} + \Delta y'
\end{align*}
\]
\[ \Delta x = \frac{x}{r} \times (k_r r^2 + k_t r^2), \quad \Delta y = \frac{x}{r} \times (k_r r^2 + k_t r^2), \quad r = \sqrt{x^2 + y^2} \]  
\[ F = \frac{X_m - m_x}{\sqrt{l^2 - m_x^2 - m_y^2}} - (x - \Delta x) = 0 \]
\[ G = \frac{Y_m - m_y}{\sqrt{l^2 - m_x^2 - m_y^2}} - (y - \Delta y) = 0 \]  

Since this equation is a strong non-linear, an improved Gauss-Newton calculation method (3) is adopted to obtain all necessary parameters using the above two equations in Eq. (3). Once all camera parameters are obtained, the relations between the photographic coordinate and the absolute coordinate of the target image or the particle image can be expressed as the following Eq. (4).
\[
\begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix} = 
\begin{bmatrix}
X_n \\
Y_n \\
Z_n
\end{bmatrix} = M_{\theta}^{-1} \begin{bmatrix}
X_m \\
Y_m \\
Z_m
\end{bmatrix} - d - t
\]  

Where, \( M_{\theta} \) is the matrix for the rotational transformation is expressed in the form of Eq. (5).
\[
X_m = \frac{x - \Delta x}{c_x} + m_x, \quad Y_m = \frac{y - \Delta y}{c_y} + m_y, \quad Z_m = d - t
\]  

\[ (d = \sqrt{l^2 - m_x^2 - m_y^2}, \quad t = d - Z_m) \]  

If the camera center is set to a vector (\( X_0, Y_0, Z_0 \)), the collinear equation for one target (or particle) can be expressed as \( P(X, Y, Z) = (a_1 t + X_0, a_2 t + Y_0, a_3 t + Z_0) \). The cross-sectional points constructed from the following two collinear equations for the two cameras are defined as the three-dimensional positions in the absolute coordinate.

\[ A(X, Y, Z) = A(a_1 t_x + X_0, a_2 t_x + Y_0, a_3 t_x + Z_0) \]
\[ B(X, Y, Z) = B(b_1 t_y + X_0, b_2 t_y + Y_0, b_3 t_y + Z_0) \]  

Where, \( t_x \) and \( t_y \) are obtained by the least square method (LSM). Since the cross-sectional points do not always intersect on one point, the below Eq. (7) is used for the definition of the last three-dimensional position of the targets (or the particles), which implies the center of the shortest distance between the two collinear equations.
\[
\begin{bmatrix}
X_p' \\
Y_p' \\
Z_p'
\end{bmatrix} = \begin{bmatrix}
\frac{1}{2} \\
\frac{1}{2} \\
\frac{1}{2}
\end{bmatrix} \begin{bmatrix}
X_A & X_B \\
Y_A & Y_B \\
Z_A & Z_B
\end{bmatrix}
\]  

Where, \( X_A, Y_A \) and \( Z_A \) represent the absolute coordinates for camera A defined by Eq. (6). \( X_B, Y_B \) and \( Z_B \) represent the absolute coordinates for camera B. After obtaining the positions of the vector grid points (vector start points), the three-dimensional vector terminal points are calculated by combining the two-dimensional vector terminals of each camera’s image. The two-dimensional vectors are obtained by the conventional gray level cross-correlation method (9).

3. Experimental Equipment and Measurement Procedures

The experimental setup is composed of a vertical pipe, 200 mm long spacer pipe a unit for the swirling flow, a flow meter, a suction blower, a controller, a laser, two CMOS cameras, a pulse generator, an optics sensor unit, and a computer as shown in Fig.5. The acrylic vertical pipe is \( L = 600 \text{ mm high} \), the internal diameter is \( D = 100 \text{ mm} \). The unit for the swirling flow has through four small horizontal and tangential pipes with diameter \( d = 10 \text{ mm} \) as shown in the Fig.5. The both ends of the vertical pipe are closed. The swirling flow is generated by suctioning the main pipe air from the four small inlet pipes installed at the top of the main pipe tangentially. The suction blower provides the air and the smoke including the tracer particles, and the volume of the flow is adjusted by the controller. The air is naturally sucked from the four small outlet pipes installed at the bottom of the main pipe tangentially. The smoke (Glycol, particle diameter \( e = 0.5 \text{ μm} \)) was used as seeding particles to be sucked into the main pipe. Nd-Yag laser (wave length 532nm, power 120 mJ, pulse 15 Hz) was used for flow field visualizations. Two digital cameras (Kodak ES1.0, 1008 × 1018) were vertically installed for the stereoscopic measurements and arranged as shown in the Fig.5. The revolving position of the cylinder was controlled by adjusting the blower suction power related to the rotation speed, 200 rpm and 255 rpm. The velocity components are measured around the rotating and revolving cylinder inside 10mm from the pipe wall of the main pipe. In the case of 200 rpm, the suction flow rate is \( 1.7 \times 10^{-3} \text{ m}^3/\text{sec} \) and the mean velocity \( V_{z1} \) is 1.86 m/sec and Reynolds number is \( Re_{Vs1} = 1500 \). In the case of 250 rpm, the suction flow rate is \( 2.3 \times 10^{-3} \text{ m}^3/\text{sec} \) and the mean velocity \( V_{z2} \) is 2.47 m/sec and Reynolds number is \( Re_{Vs2} = 2000 \). These velocities \( V_{z1} \) and \( V_{z2} \) are calculated by based on the flow meter.

Measurements were carried out at two suction flow rates, while the cylinder rotates at 240 mm from the bottom of the main pipe in the case of \( V_{z1} \) and and 440 mm in the case of \( V_{z2} \). That is, the measurements were carried out when the cylinder was at the sensor unit vertical position. The measurement
vertical position is adjusted to 240 mm and 440 mm by means of spacer pipe attachment change between the upper and the lower. The images of the two cameras were captured simultaneously through an image grabber installed on the host computer. Fig.6 shows the procedure of capturing images. When all four sensors detect, the laser sheet is shot for capturing two images. The time interval of two images is 1/60 sec. The camera calibration was carried out before commencing the main experiments. A flat camera calibrator (56 mm × 48 mm) was attached onto a traverse and was moved to several planes Z= (-12 mm, -8 mm, -4 mm, 0 mm, 4 mm, 8 mm, 12 mm) with 4 mm distance in the vertical pipe at which the images of the plate were captured for camera calibration. Fig.7 shows the detection area and direction of coordinate. The detection area is 40mm × 40mm at 10mm distance from the wall. The captured raw images of the detection area are 1008 × 1018 pixel and processed to the 40 × 40 pixel PIV velocity vector field data. X is the radial direction of the vertical pipe. Y is the axial direction of the vertical pipe. And Z is the azimuthal direction of the vertical pipe. U is the radial velocity component of the vertical pipe. V is the azimuthal velocity component of the vertical pipe. And W is the axial velocity component of the vertical pipe.

4. Measurement Results and Discussion

4.1 Velocity Vector Fields

Fig.8 shows instantaneous raw images taken by the conditional sampling at a time with the vertically installed camera 1 and camera 2. In this figure, the white part is the cylinder. The tracer around the cylinder is confirmed at the high contrast image. Every instantaneous velocity vector field was obtained at the time when the cylinder came into the same orientating posture. One frame of three dimensional velocities is shown in Fig.9 in the case of $V_{s1}$ as a sample. The color legend means the W component of the three-dimensional velocity vector field. The red means the high value, and the blue means the low value. The results of three dimensional velocities were obtained from the average of N=1024 frame of the PIV velocity image at the same condition. Fig.10 shows the three dimensional velocity vector field in the case of $V_{s1}$. The color legend means the W component of the three-dimensional velocity vector field. The red means the plus direction (front direction of the paper), and the blue means the minus direction (rear direction of the paper). The azimuthal velocity at the upper position of the cylinder is higher than that at the other position. Fig.11 shows the velocity profiles of three components in X direction at three different $Y$ positions. Fig.11 (a) is the upper position in the case of $(Y/R=-0.32, Z/R=0)$, Fig.11 (b) is the middle position in the case of $(Y/R=0, Z/R=0)$ and Fig.11 (c) is the lower position in the case of $(Y/R=-0.32, Z/R=0)$. All component velocities are non-dimensionalized with the mean velocities $V_{s1}$ and $V_{s2}$. In Figs. 10 (a), (b) and (c), $X/R=0.8$ means 10mm point from the pipe wall. If the cylinder is attaching to the pipe wall as shown in Fig.7 (b), the covered area of 2mm ($X/R=0.05$, equivalent to 2 measurement points) from $X/R=0.8$ to the pipe center point in the $X/R$ axis is behind the cylinder because the cylinder diameter is $d_c=12$ mm. On the other hand, $X/R=0.0$ means the pipe center position of the main vertical pipe. The velocities of $U$ and $W$ at the pipe center point
are not zero because the rotating and revolving cylinder makes the flow asymmetric in the main vertical pipe.

From Fig. 11 (a)-(c), the radial components of the three-dimensional velocity vector field $U/V_{s1}$ and $U/V_{s2}$ (the red line) are small values as compared with the tangential component $W/V_{s1}$ and $W/V_{s2}$ (the blue line) except for the pipe center area. $U/V_{s1}$ is slightly higher than $U/V_{s2}$ in the three vertical ($Y$ directional) position.

With regard to the tangential component $W$, the following four new findings are pointed out. 1) $W/V_{s1}$ and $W/V_{s2}$ (the blue line) are relatively high values. $W/V_{s1}$ and $W/V_{s2}$ are basically increased once and decreased as $X/R$ is increased in all vertical positions. Namely the $W$ component consists of freely swirling region located near the pipe wall and forced swirling region located near the pipe center area. This characteristic is influenced by an orientating cylinder, because the $W$ component must consist of only forced swirling region without an orientating cylinder. 2) The peak radial ($X$ directional) position of $W/V_{s1}$ (marked with ▲) is located near the pipe wall rather than that of $W/V_{s2}$ (marked with ▼) in all $Y$ directional position. It means that the fast swirling flow $W/V_{s2}$ makes the peak position located toward the pipe center position. Aldoss et. al (1990) points out the peak point exists just behind the rotating cylinder at fixed position in cross flow as the azimuthal velocity is increased\(^{15}\). However, the peak position of rotating and revolving cylinder in this paper shifts to the pipe center area. Therefore, the free vortex region gets larger because the rotation velocity of cylinder is increased.

3) The peak radial position of $W/V_{s1}$ and $W/V_{s2}$ at only lower position ($Y/R = -0.32$) is located toward the pipe center position rather than that at the other vertical position. 4) The peak value of $W/V_{s1}$ and $W/V_{s2}$ is decreased as the vertical position is lower. This characteristic is influenced by the flow interference between the vertical velocity $V$ and the azimuthal velocity $W$ at the cylinder bottom. This interference results in $W$ energy dissipation.

On the other hand, the vertical component $V/V_{s1}$ and $V/V_{s2}$ (the green line) are small values as compared with the tangential component $W/V_{s1}$ and $W/V_{s2}$. However, they have unique velocity distribution which is not shown in normal single phase swirling flow. Basically, $V$ velocity is decreased as the $X/R$ is
2. The vertical component has positive value near pipe wall; however, it has negative value near the pipe center. The position where the vertical component transits from positive value to negative value is \( X/R \approx 0.6 \) in the case of \( V_{xz} \) and \( \approx -0.3 \) in the case of \( V_{xy} \), irrespective of the vertical \( Y \) position. It means that the position shifts to the pipe center in the case of high mean velocity \( V_{xz} \). This \( V \) velocity distribution means that large vortex is generated in the radial \((X-Y)\) plane because of existence of rotating and revolving cylinder.

4.2 Turbulent Kinetic Energy

Fig. 12 shows the turbulent kinetic energy \( TKE \) calculated from

\[
TKE = \frac{1}{V} \sum_{t=1}^{N} \left( \sqrt{U'_t^2 + V'_t^2 + W'_t^2} \right)^2 \times \frac{1}{N} \times 100 \% 
\]

(8)

where \( U'_t, V'_t \) and \( W'_t \) are turbulence velocities in time \( t \) in \( X, \) \( Y \) and \( Z \) components respectively.

\[
\begin{align*}
U'_t &= U_t - \bar{U} \\
V'_t &= V_t - \bar{V} \\
W'_t &= W_t - \bar{W}
\end{align*}
\]

(9)

Where \( \bar{U}, \bar{V} \) and \( \bar{W} \) are the time averaged velocity in \( X, \) \( Y \) and \( Z \) components respectively. \( N=1024 \) is the frame number of the PIV velocity images.

The turbulent kinetic energy has two high values in the case of rotating and revolving cylinder in a vertical pipe, which are high values near the cylinder bottom area and the pipe center area. The above mentioned interference between \( V \) and \( W \) in energy dissipation is confirmed by the \( TKE \) high value location under the cylinder. The high value position is just under the bottom in the case of \( V_{xz} \). However, the value position shifts to \( X/R = 0.6 \) area in the case of \( V_{xy} \). It means vortex shedding is developed in the case of \( V_{xz} \), because of high \( V \) velocity. With regards to \( TKE \) value at the pipe center area, in the low \( V_{xz} \), \( TKE \) is quite low because \( V \) and \( W \) near the pipe center is nearly zero, and \( U \) velocity is quite small. However, this tendency is reversed when the swirling velocity is high \( V_{xy} \). The position shifts to the pipe center because of high \( V \) and \( W \) velocity near the center, which implies that the turbulent kinetic energy results from the large scale vortex in \( X-Y \) plane as mentioned before.

5. Conclusions

A conditional sampling stereoscopic-PIV has been developed for the flow field measurement around a rotating and revolving cylinder in an internal swirling flow generated by tangential jet. Four fiber sensors are embedded into a pipe wall for detecting the cylinder orientation. All sensors detecting the rotating and revolving cylinder means the rotating and revolving cylinder stands upright with the orientation. The less than four sensors detecting means the cylinder is non-orientation. Three velocity components profile are measured when the cylinder is orientating. The flow characteristic nearby a rotating, revolving and orientating cylinder has been observed as following.

1) The tangential component is relatively high value, which consists of freely swirling region and forced swirling region. The radial peak position of the tangential component in the low velocity is located near the pipe wall rather than that of the tangential component in the high velocity at all vertical position because of influence of the cylinder rotation. The radial peak position of the tangential component at only lower position is located at the inner region rather than that at the other vertical position. The peak value of the tangential component is getting lower as the vertical position is lower because of influence of \( V \) and \( W \) interference resulting in \( W \) energy dissipation.

2) The vertical component has positive value near pipe wall; however, it has negative value near the pipe center. The position where the vertical component transits from positive value to negative value shifts to the pipe center in the case high velocity. It implies that the large scale vortex is generated in \( X-Y \) plane.

3) Turbulent Kinetic Energy (\( TKE \)) value at the center area in the low mean velocity \( V_{xz} \) is quite low because the velocity is quite small. However, the \( TKE \) value at the center area in the high mean velocity \( V_{xz} \) is high, because \( W \) and \( V \) are very high near the pipe center.

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