Evolution of the Counter-Rotating Vortex Structure in a Crossflow Jet*

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The structure of a counter-rotating vortex pair of round jet issuing normally into a crossflow was studied using a flow visualization technique and PIV measurements. Experiments were performed at a jet-to-crossflow velocity ratio of 3.3, and the Reynolds number of 1,050, based on the crossflow velocity and jet diameter. Instantaneous velocity field was acquired using two frame cross correlation PIV technique. The angle of laser sheet beam was set to be perpendicular to the ensemble averaged trajectory of the crossflow jet. The mean velocity field was obtained by ensemble averaging over 300 realizations of instantaneous velocity fields for each plane. It was found that the counter-rotating vortex pair was initiated from the hanging vortices appearing at both sides of the jet column. The detailed characteristics of the velocity fields were discussed with the evolution of the counter-rotating vortex pair.

Key Words: Crossflow Jet, Counter-Rotating Vortex Pair, Laser Tomography, PIV Measurements, Hanging Vortex

1. Introduction

The jet in crossflow(JICF) is frequently encountered in engineering and environmental situations, and has long been studied in detail. Recently, many researches have paid attention to the structures of vortices associated with the near field of the crossflow jet. Fric & Roshko⁽¹⁾ suggested that the key features of vortex structures appearing in the JICF are the horseshoe vortices in front of the jet, the shear layer vortices at the edge of the jet, the vertically oriented vortices which connect the jet body with wall boundary layer in the wake region, and the counter-rotating vortex pair(CVP) which is often observed in the far-field aligned with the trajectory of the jet. Kelso et al.⁽²⁾ investigated the detailed structure of the jet employing dye tracer in a water tunnel and flying hot wires in a wind tunnel. They hypothesized that the initial vortical roll-up of the jet initiates the downstream development of the CVP

through a vortex breakdown. Kim & Shin⁽³⁾ reported through their laser tomographic flow visualization study that the Kelvin-Helmholtz(K-H) type roll-up structures are developed at both upstream and downstream shear layers of the JICF.

Among the various kind of vortical structures in the JICF, the most arguable one seems to be the counter-rotating vortex pair(CVP). Andreopoulos⁽⁴⁾ postulated that the downstream edge of each vortex ring is compressed by the mean strain, which eliminates the spanwise vorticity and contributes to the CVP. Coehlo & Hunt⁽⁵⁾ proposed a mechanism that the reorganization of jet shear layer vorticity caused by entrained cross flow fluid initiates the development of the CVP. Yuan et al.⁽⁶⁾ suggested that the far-field CVP is shown to originate from a pair of quasi-steady 'hanging' vortices. These vortices form in the skewed mixing layer that develops between jet and crossflow fluid on the lateral edges of the jet. All of the previous studies agree that the original source of the CVP is the jet shear layer, but the detailed mechanism of the vorticity realignment to produce the CVP is still unclear. Hence, the main focus of this study is to examine the development of CVP by using

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flow visualization method and PIV measurement at the cross-section planes along the centerline trajectory.

2. Experiment

The experiments were carried out in a low speed wind tunnel. The test section made of glass plates has 800 mm width, 300 mm height and 2,000 mm length. The air driven by a variable speed 3 HP centrifugal fan passes a settling chamber, a 2.67:1 area ratio contraction, then enters the test section through a fine mesh screen. The freestream turbulence intensity at the entrance of the test section was found to be 1%. The jet is issued normally to the bottom wall through a nozzle whose diameter(D) is 16 mm. The circular nozzle was mounted at the bottom plate of the wind tunnel and located at 25 cm downstream from the exit of contraction nozzle.

Measurements were made at a fixed velocity ratio of 3.3, and the Reynolds number of 1,050 based on the crossflow velocity and the jet diameter. The corresponding freestream velocity U_∞ was 1.0 m/s and the approaching boundary layer was considered to be laminar with 12 mm thickness at the position of the hole since we did not use any boundary layer tripping devices. The jet was generated by an air compressor then passed through a mixing chamber, a pressure regulator and a flowmeter. The incoming pipe flow Reynolds number was 3,470 based on the averaged velocity V_j and the pipe inner diameter. The initial condition of the jet was controlled to make a top-hat velocity profile using fine mesh screens and an axisymmetric contraction nozzle.

Images of instantaneous vortex structure were acquired by the laser tomographic method. The laser sheet whose thickness was less than 1 mm was illuminated by using a 200 mJ/pulse Nd:Yag laser during 5 ns. The scattering particles having 2 μ m diameter olive oil aerosols were supplied by a Laskin nozzle. The particles were injected through the nozzle

only, so the interface between the clean crossflow and the jet can be seen clearly.

The on-line PIV system consisting of a dual pulse Nd:Yag laser, a 1K $\times$ 1K CCD camera, a synchronizer and an analysis software was used to measure velocity fields. The interrogation of the velocity vector was carried out using INSIGHT-NT software adopting two frame cross-correlation method. We put a standard Nikon 50 mm lens in front of the CCD camera to avoid the image distortion error. The 2 μ m olive oil particles were supplied into both wind tunnel and pipe. The uniformity of the particle distribution and the intensity of the scattered light have been checked before experiment. The interrogation window size was selected as 24 $\times$ 24 pixels, and 50 % of overlap was permitted. Using the post processing software developed in the laboratory, we eliminated bad vectors, and accomplished various statistical calculations including velocity gradient estimates.

Before cutting the jet transversely to visualize the structure of CVP, the ensemble averaged trajectory of the JICF was obtained by using PIV method. Seven different observation planes with 10° increment of angle between the trajectory coordinate and the tunnel bottom plate are chosen from 0° to 60° to study the dynamics of CVP. The flow configuration and the coordinate system we use are depicted in Fig. 1. The origin locates at bottom plate level and in the center of the flush-mounted pipe. The Cartesian coordinate system (x, y, z) and the trajectory coordinate system (x', y', z') are used. Here, x represents distance in the streamwise direction, y in the spanwise direction, and z in the vertical. The distance along the trajectory is denoted as x' , and y' and z' represent the local spanwise and vertical coordinate, respectively. The angle between x and z' direction defines the angle α as shown in Fig. 1. Using a special jig and fixture, the CCD camera was located perpendicularly to each y' - z' plane where the laser sheet beam was illuminated.

3. Results and Discussions

Figure 2 shows the instantaneous flow pattern of JICF taken at the jet centerplane(x - z plane) when the Reynolds number is 1,050. Very well organized K-H type vortex roll-up phenomena occur at both upstream and downstream side of the jet shear layer. The shear layer vortices disappear suddenly when the jet bends over to the downstream. This nature might be strongly connected with the formation of CVP.

Ensemble averaged velocity field of the centerplane(x - z plane) is obtained by 300 instantaneous velocity fields. The jet trajectory can be defined by a streamline which begins at the origin.

Fig.1 Schematic of flow configuration and coordinate systems.

Fig.2 Instantaneous tomography image at the center of x - z plane.

Table 1. The position of origin point of each plane.

α	x/d	z/d
0°	0	0.3
10°	0.1	0.6
20°	0.2	1.3
30°	0.5	2.0
40°	0.9	2.6
50°	1.4	3.1
60°	2.4	3.8

Using this trajectory, the origins of transverse planes y' - z' are chosen as indicated in Table 1. To avoid the difficulty of illumination, the $\alpha = 0^\circ$ plane was chosen as the parallel plane at $z/d = 0.3$.

Figure 3 shows the typical instantaneous tomography of the jet in crossflow taken at the corresponding angles. At the angle 0° , which is the parallel plane and 5 mm above from the tunnel bottom wall, the jet has circular shape but there are two robes at both lateral sides. These robes due to the Kelvin-Helmholtz instability between the crossflow and the jet create hanging vortices which may initiate the CVP. Kelso et al.⁽²⁾ also observed that a large fraction of the dye through a circumferential slot is collected in tube-like structures which began directly above the exit on the lateral edges of the jet. With the increase in angle, the jet column changes its shape from circle to kidney-like. Along the transverse slice downstream of the jet, we observed a pair of unsteady counter-rotating vortices that ride on top of a steady pair of vortices. It is interesting to note that the vortex diameter expands dramatically after $\alpha=20^\circ$ and a weak counter-rotating vortex pair is formed that is aligned with the jet trajectory. It can be explained as that the hanging vortex encounters an adverse pressure gradient and breaks down. Since there exist well organized shear layer roll-ups at both upstream and downstream boundaries of jet column, one can

see cross-cut image of spanwise vortex structures in both $\alpha=20^\circ$ and 40° cases. However, many irregular streamwise vortical structures can be seen appearing in the backside of the jet column, and the overall shape indicates the existence of CVP. After bent-over process ($\alpha=60^\circ$), there is no sign of spanwise vortices, but irregular distribution of streamwise vortices is observed. Yuan et al.⁽⁶⁾ found the streaks of vertical vorticity in the main jet body. These streaks form when irregularities, or kinks, within each spanwise roller are stretched vertically by the local strain field. These structures are vividly seen in the near field of the jet, and are tilted into the streamwise direction by the mean strain field created by the curved flow field.

The instantaneous velocity fields were measured at the planes where the flow visualization images were obtained. The color contour of equi-vorticity patterns are also depicted in Fig. 4. At the angle 0° , one can see hanging vortices on each lateral sides of the jet. The direction of the fluid rotation is of a single sign, clockwise rotation at right hand side and counter-clockwise direction at left hand side looking upstream. As the crossflow deflects around the jet body, it accelerates on the lateral edges. Thus, a mixing layer forms between the crossflow and the jet whose velocities are not parallel. It was found that the hanging vortices do not shed regularly into the main flow. Instead, the hanging vortex seems to be a quasi-steady structure which oscillates around a fixed location. It is conjectured that the magnitude and location of the peak vorticity have nearly the same value at both instantaneous and ensemble averaged field at the $\alpha=0^\circ$ plane.

We observe another vortical structure downstream of the hanging vortices in the wake of the jet, vertically oriented vortex extending down from the jet body to the wall in Fig. 4(a). These wake vortices (upright vortices) shed rather regularly from the jet body. Vertically oriented vortices have been observed by Fric & Roshko⁽¹⁾ and Kelso et al.⁽²⁾. Yuan et al.⁽⁶⁾ explained that these structures are closely connected to the horseshoe vortex which forms upstream of the jet.

At $\alpha=20^\circ$, we can observe the vortex breakdown phenomenon at the right hand side. On the left hand side, the hanging vortex expands continuously. On the lateral edge of the jet, velocities are high and pressures low, so the adverse pressure gradient causes the vortex breakdown. In addition, a strong upstream flow in the wake of the jet generates compressive stresses on the lee side of the jet.

With the merging of upstream and downstream shear layer roll-up vortices, the bent-over process

Fig.3 Instantaneous traverse tomography of the jet in crossflow, $Re = 1,050$.

begins rapidly. Around the $\alpha=40^\circ$ plane, the local radius of curvature of the jet trajectory seems to be minimum as can be seen in Fig. 2. The spanwise roll-up structures lose their coherent nature abruptly with the bent-over process. With collapsing the spanwise vortical structure, there appear many vertical streaks around the jet main body. It is interesting to note that these vertical streaks have double roller structure in a manner similar to the formation of ribs observed in plane mixing layers.

The vertical streaks persist consistently as the jet bends into the crossflow direction as shown in Fig. 4(d). These vertical structures are tilted into the streamwise direction by the mean strain field and dispersed further by the local turbulence field. They contribute to the turbulent mix of vorticity in the far field. However, it is not easy to find any typical CVP motion in the instantaneous vorticity field, especially at $\alpha=60^\circ$ plane.

The ensemble averaged velocity fields and the vorticity fields demonstrate the existence of CVP clearly as shown in Fig. 5. Quite a strong vorticity occurs around the robes at $\alpha=0$, and the size of CVP becomes larger with increase in α . A symmetric pair of wake vortices appears at the lee-side of the jet column just behind the hanging vortex.

Although the breakdown of hanging vortex occurs from $\alpha=20^\circ$ plane, the CVP is evident in the ensemble averaged vorticity field. The maximum vorticity magnitude in the ensemble averaged field decreases rapidly with the vortex breakdown process while the maximum value of the local vorticity in the instantaneous field keeps their value nearly constant. Over the same length, maximum vorticity observed in the unfiltered velocity field decays by approximately 22%, while the filtered background vorticity in the CVP decreases by 89%.

After the bent-over, highly turbulent vertical streaks appearing at $\alpha=40^\circ$ and 60° planes are filtered out with ensemble averaging. Hence those structures eventually seem to be merged into the CVP motion. With increasing α , the center of CVP showing in the velocity field and the maximum value of the vorticity come close to coincide.

The CVP observed in the ensemble averaged vorticity field changes position and strength with streamwise location. The variations of the center position of CVP are demonstrated in Fig. 6. The solid circle denotes the transverse distance between centers of CVP. With developing of the hanging vortex, the y' distance comes close at first then increases with vortex breakdown process. It should be noted that the distance seems to be constant after the bent-over

(a) $\alpha = 0^\circ$ (a) $\alpha = 0^\circ$ (b) $\alpha = 20^\circ$ (b) $\alpha = 20^\circ$ (c) $\alpha = 40^\circ$ (c) $\alpha = 40^\circ$ (d) $\alpha = 60^\circ$ (d) $\alpha = 60^\circ$

Fig.4 Instantaneous velocity and vorticity fields.

Fig.5 Ensemble averaged velocity and vorticity fields.

Fig. 6. Kinematic properties of CVP along jet trajectory. ●; y' distance between centers of CVP, ▲; CVP center locations in z' direction from trajectory at each planes, □; circulation around a center of CVP

region within the range of experiment. The solid triangle symbols represent the vertical distances of CVP center from the trajectory at each plane. Continuous increasing of the z'/D reveals the increase of the size of CVP motion.

The vorticity carried by the hanging vortex provides the circulation necessary to create the CVP. However, the hanging vortex only accounts for a fraction of the total circulation flux carried by the jet. The remaining jet vorticity can be found in the spanwise rollers and vortical streaks which follow the trajectory of the jet. We present circulation along one side of CVP on each transverse plane as depicted in Fig. 6. The circulation is estimated using Stoke's theorem(Eqn.(1)) and the ensemble averaged vorticity field.

$$\Gamma = \oint \Omega \cdot n \, dA \quad (1)$$

The circulation increases with increasing angle α as the hanging vortex expands dramatically along the jet trajectory as shown in Fig. 6. Due to the vortex breakdown, the value of circulation cannot be increased any more beyond the angle $\alpha=20^\circ$. It should be pointed out that the circulation value keeps its value nearly constant in the bending process of the jet, while the ensemble averaged vorticity decreases quite rapidly along the streamwise direction. Slight decrease of the estimated circulation is observed at $\alpha=60^\circ$ plane, which attributes to the dispersion of vorticity by viscous dissipation of the fluid. Farther downstream, we can imagine that the magnitude of circulation in the CVP decays at a slower rate since the CVP becomes the dominant motion at lower wave numbers in turbulent motions of the JICF.

4. Conclusion

Flow visualization and the PIV measurements in the transverse planes of the JICF along its trajectory have been conducted. We found evidence of the CVP by the ensemble averaged velocity and vorticity fields. The origin of the CVP turns out to be the quasi-steady hanging vortices formed in the lateral side of the jet near the nozzle. The hanging vortices break down quickly due to the adverse pressure gradient and the highly turbulent nature of the wake flow behind the jet column. With destruction of the streamwise roll-up vortices appearing in the jet shear layer, vertical streaks are generated in the jet body with irregular manner. Eventually, they contribute to the vorticity of the CVP that is aligned with the jet trajectory. After the bent-over process, the center of CVP moves downward from the jet trajectory with the increase in the size of CVP, while the transverse distance between the centers of the counter-rotating vortices remains constant within the range of observation. The estimated circulation increases rapidly with the development hanging vortex, then stays nearly constant after the vortex breakdown.

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