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Visualization of Tip Vortex Flow in an Open Axial Fan by EFD

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***Abstract*:** The behavior of tip vortex in an axial fan without casing wall (called open axial fan) was discussed and analyzed. The velocity measurement was performed by using two-components Laser Doppler Velocimetry (LDV) system. The detailed velocity and vorticity distribution inside blade passage and downstream of rotor were obtained. Thus the structure of tip vortex and its behavior were graphically visualized by experimental fluid dynamics (EFD). The tip vortex flow trace was indicated with the calculation of vorticity. As a result, it was found that tip vortex was generated at blade tip region near leading edge and it extended to downstream of blade exit with its core tending inward to hub direction. In addition, leading edge vortex was also found at the forepart of the experimental open fan.

***Keywords*:** visualization, turbomachinery, open fan, tip vortex, LDV.

1. Introduction

In axial and diagonal rotor, the tip leakage flow has great influences on the rotor aerodynamic performances especially on fan efficiency, noise level and steady-work range (Inoue et al., 1986). Effects of the tip leakage flow on compressors and fans have been investigated by great deal of experimental and numerical studies. The feature in tip region is characterized by tip leakage vortex, which is formed due to the rolling-up of a shear layer between the leakage jet and main flow. The detailed structures of the tip leakage vortex including breakdown of vortex were also shown in many research works (Kaneko et al., 2000; Furukawa et al., 1999). On the other hand, few works were focused on the vortex flow phenomena in open axial fan.

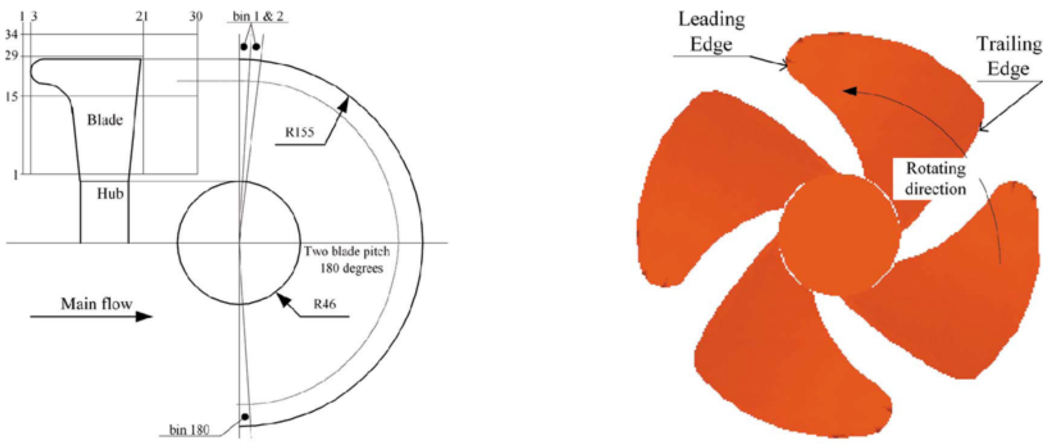
An open axial fan is widely used in ventilation system and some cooling equipment. Lower noise level is highly required in those application fields. The blade tip vortices are aerodynamically the most significant features in an open axial fan. The vortex strength, induced velocity field, spatial locations and orientations of the vortices relative to the rotor affect rotor blade loads and rotor noise levels. The blade also interacts closely with tip vortices generated by other blades, resulting in a phenomenon known as blade vortex interaction. The blade vortex interaction produces three-dimensional unsteady air loads that can manifest as high rotor vibrations and strong noise. Therefore, it is necessary to give a detailed measurement on tip vortex flow in an open axial fan.

In addition, Laser Doppler Velocimetry (LDV) system has been adopted for measurement in rotor flow field (Mahendra et al., 2000). LDV system offers an accurate and versatile measurement technique, and its non-intrusive nature makes it most suitable for rotating rotor experiments. They are able to detect and trace the tip leakage vortex flow disturbances through the rotor passage. Some other experiments were also conducted by using LDV in axial compressor. Thus, it is possible to detect and trace the tip vortex flow field in open axial fan by using LDV system.

One objective of the present work is to provide further physical insight into the structure of rotor tip vortices (TV) in open axial fan, with a goal of making the tip region flow feature visualization. Measurements were performed with the two-component LDV system; the three-dimensional velocity fields were obtained in blade passage and its downstream region. Based on those results, the tip vortex structure together with its developing process was also shown clearly.

2. Experimental Apparatus and Measurement

In the experiment, the velocity field was measured in blade passage of a room-ventilation open axial fan by using LDV system. There are four blade rotors and the fan blade has a diameter of 310 mm. The hub-to-tip ratio is about 0.31 and blade rotating speed is 900 rpm. Based on the mid-chord length of blade and its tip rotating speed, test Reynolds number is about 8.61×10^4. Figure 1 shows the outline of blade profile for this experiment.



(a) Measurement positions (b) Outline of blade profile

Fig. 1. Measurement positions and outline of fan blade profile.

As shown in Fig. 1, there are 34 measurement positions from 5 mm above hub to outside of tip. From measurement position 1 to 15, the distance between each position is 5 mm and above 15, the distance is 2.5 mm. Along with axial direction, there are 30 measurement cross sections from 10 mm upstream of leading edge (LE) to blade downstream with 5 mm distance between each measurement cross section. One rotation of rotor is divided into 360 bins; velocities measured in each bin were summed up and averaged to indicate velocity in that bin. At last, velocities in one rotation of 360 bins were phase-locked and rearranged to the two blade pitches of 180 bins due to the periodic regular flow in blade passage. Thus, velocity distributions were captured in blade passage and downstream region for two blade pitches.

In this system (Fig. 2), a fiber-optic LDV system was used for velocity surveys. It consists of an argon-ion laser, a multicolor beam separator, a two-component fiber-optic probe system, a signal processor, a three-dimensional traverse table driven by interface, and a personal computer with the flow information software. Laser probe was put on the three-dimensional traverse table that had the least step distance of 0.1 mm in each direction.

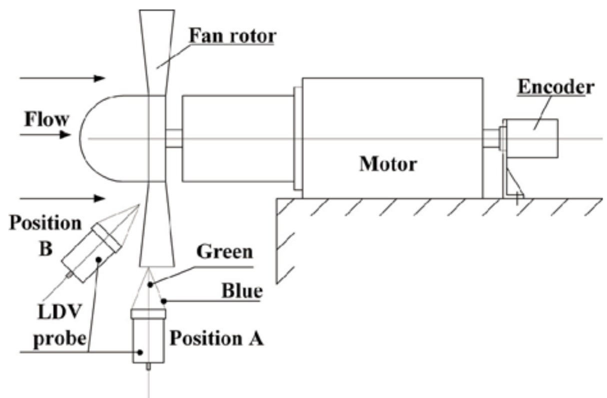


Fig. 2. LDV arrangement for the experiment.

At first, the axial velocity component V_z and circumferential velocity component V_θ were measured at position A. After then, the probe was shifted to position B and the radial velocity component V_r was measured. For every measurement point, 8000 data were sampled at least. All basic flow statistics, including mean velocity, standard deviation and turbulence intensity, could be drawn out with the processing of those data. As the acquisition mode used here was coincidence mode, the velocity components were obtained simultaneously and were statistically correlated. This ensures that the velocities were measured from the same particle. Therefore, this acquisition is essential and accurate to measure the high velocity gradients found inside the vortex cores.

The flow field was seeded with vapor by a steamer. The steamer generated seeding particles with a diameter of 1 to 10 μm. This particle size is small enough to minimize errors in velocity measurements resulting from acceleration effects on the seed particles (Mahendra et al., 2000). With the doppler-frequency of each channel real-time signal analyzer (RSA) was calculated which was subsequently transformed into two orthogonal velocity components. An encoder that was linked to the shaft of motor directly was adopted to continuously obtain the rotor phasing. This rotor phase was used to calculate the blade azimuth position that was digitally tagged in the velocity data to distinguish the velocity data among different bins.

In this experiment, phase (or bin) averages in LDV survey were computed from all velocity samples that were collected at the same bin. The vorticity fields $\vec{\zeta}$ were calculated from the obtained three velocity components in flow fields. The streamwise vorticity ζ_w and normalized helicity H_w (Furukawa et al., 1999) were defined as follows:

$$\zeta_w = \frac{\vec{\zeta}\cdot\vec{W}}{2\omega\left|\vec{W}\right|} = \frac{\zeta_r\cdot W_r + \zeta_\theta\cdot W_\theta + \zeta_z\cdot W_z}{2\omega\cdot\sqrt{W_r^2+W_\theta^2+W_z^2}} \tag{1}$$

$$H_w = \frac{\vec{\zeta}\cdot\vec{W}}{\left|\vec{\zeta}\right|\cdot\left|\vec{W}\right|} = \frac{\zeta_r\cdot W_r + \zeta_\theta\cdot W_\theta + \zeta_z\cdot W_z}{\sqrt{\zeta_r^2+\zeta_\theta^2+\zeta_z^2}\cdot\sqrt{W_r^2+W_\theta^2+W_z^2}} \tag{2}$$

Where, $\vec{\zeta}$ is the absolute vorticity, $\vec{W}$ is the relative velocity and ω is the angular velocity of the rotor. The absolute vorticity was calculated based on the following equation:

$$\begin{aligned}\vec{\zeta} &= \nabla\times\vec{V} = \zeta_r\vec{i}_r + \zeta_\theta\vec{i}_\theta + \zeta_z\vec{i}_z \\ &= \left[\frac{1}{r}\left(\frac{\partial V_z}{\partial\theta} - \frac{\partial(rV_\theta)}{\partial Z}\right)\right]\vec{i}_r + \left[\frac{\partial V_r}{\partial Z} - \frac{\partial V_z}{\partial R}\right]\vec{i}_\theta + \left[\frac{1}{r}\left(\frac{\partial(rV_\theta)}{\partial R} - \frac{\partial V_r}{\partial\theta}\right)\right]\vec{i}_z\end{aligned} \tag{3}$$

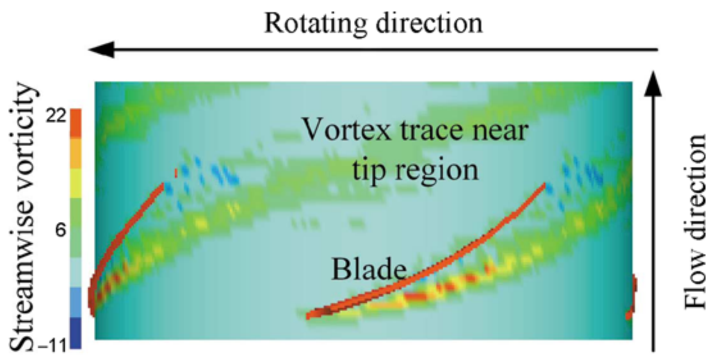
3. Experimental Results

Firstly, the streamwise vorticity was calculated by using three velocity components. Then, the helicity was also calculated around the area where the strongest streamwise vorticity was obtained. The streamwise vorticity can locate vortex area in flow passage and normalized helicity can indicate the core line of vortex (Furukawa et al., 1999).

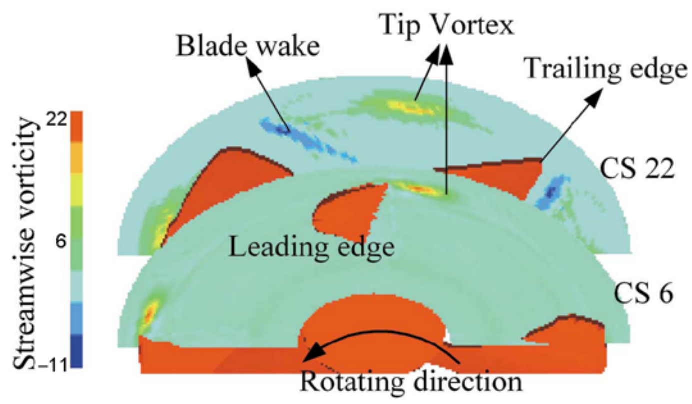
3.1 Streamwise Vorticity and Helicity

The distributions of streamwise vorticity are indicated in Fig. 3. The high streamwise vorticity, which is shown as a red region in the figure, reveals a clock-wise rotation that is considered as tip vortex (TV) in this experiment. On the other hand, the negative streamwise vorticity that is shown as blue area means a rotation that has the same direction with fan blade in our experiment. Figure 3(a) gives an upside viewing of streamwise vorticity distribution at tip region. Abscissa indicates pitch direction. Ordinate indicates axial position in blade passage. The red curve line is the tip of rotor with a rotation of counter-clockwise direction. The trace of TV that is characterized by high streamwise vorticity goes through the blade passage along a slant line contrary to the rotating direction.

Figure 3(b) shows the streamwise vorticity distribution at cross sections 6 and 22. It indicates in the figure that TV (red region in each cross section) existed not only at blade tip near leading edge (cross section 6), but also downstream of blade row (cross section 22). In addition, the blue region in cross section 22 represents the blade wake.



(a) Tip vortex trace near blade tip



(b) Streamwise vorticity distribution at cross sections 6 and 22

Fig. 3. Tip vortex flow feature.

Figure 4 shows the trace of tip vortex in blade passage and the downstream region by using iso-surface of streamwise vorticity that was calculated with Eq. (1). The positive iso-surface of streamwise vorticity indicates the trace of tip vortex with a clock-wise rotation in this open axial fan. It is shown obviously in Fig. 4 that the tip vortex was generated at suction side of blade tip region near leading edge. Also, the trace of tip vortex extends toward downstream of blade exit along a slant line that is inclined to the pressure side of following blade opposite to the blade rotating direction. Moreover, the vortex core tends to incline inward as it passes through blade passage to downstream region.

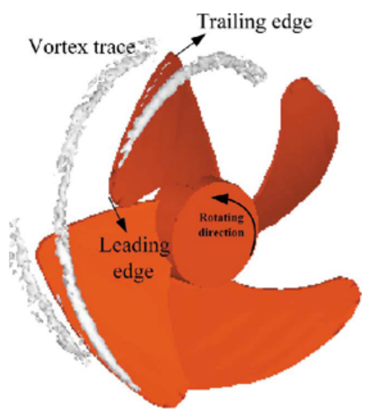


Fig. 4. Tip vortex trace in blade passage.

3.2 Velocity Distributions in Cross Section

In order to clarify the behavior of vortex, the velocity distribution at different cross sections is displayed in the following figures. Figure 5 reveals the velocity distribution in cross section 6 that is about 16% chord length downstream of leading edge and the blade is rotated in a counter-clock direction. Above blade tip line, the flow is mainly characterized with suck-in inward flow except a little outward flow near blade tip. Also in that cross section, the tip vortex can be found to roll up in a direction of clock-wise. The core of tip vortex located closely to the suction surface (SS) of blade tip. The reason for roll up of tip vortex is considered as follows. There is a shear layer between main axial flow and suck-in inward flow, and interference occurs between those two flows and the blade that rotates counter-clock wise direction. Therefore the tip vortex rolls up there in a clockwise direction.

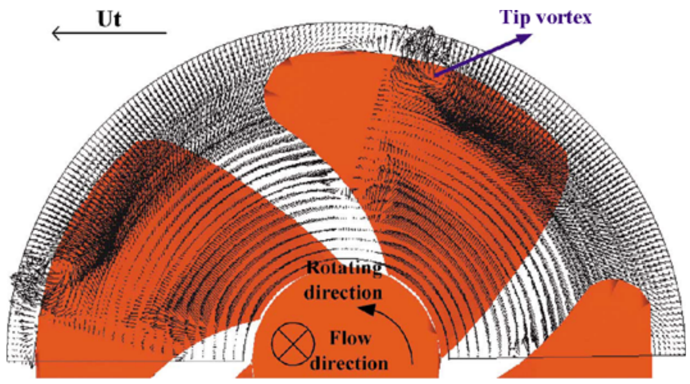


Fig. 5. Velocity distribution in cross section 6.

Figure 6 shows the velocity distribution of cross section 8 that is located about 30% chord length downstream of leading edge. The tip vortex is developed and can be found clearly on the blade surface. In addition, the flow separation at that inclined leading edge near hub can be found, and it leads to the formation of leading edge vortex.

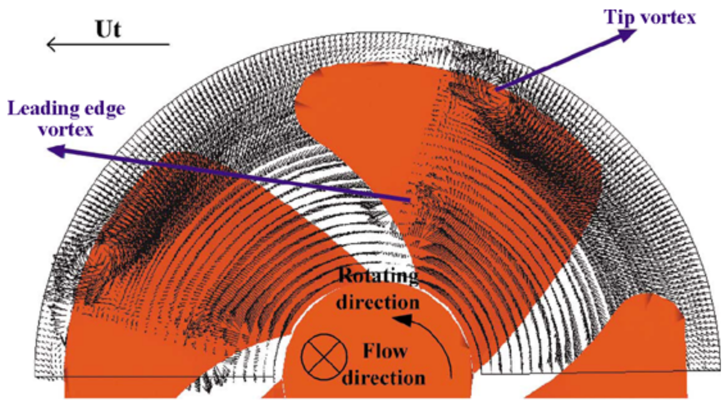


Fig. 6. Velocity distribution in cross section 8.

Velocity distribution in cross section 13 that is located at the middle position of blade chord is shown in Fig. 7. A vortex becomes strong and the area influenced by tip vortex flow becomes wider in pitchwise and thicker in radial direction. It implies that the tip vortex is rolled up through blade passage, and it is developed and becomes strong as it moves through the blade passage. However, the leading edge vortex appeared in cross section 8 is not found clearly. In addition, the core positions of tip vortex go a little inward to hub.

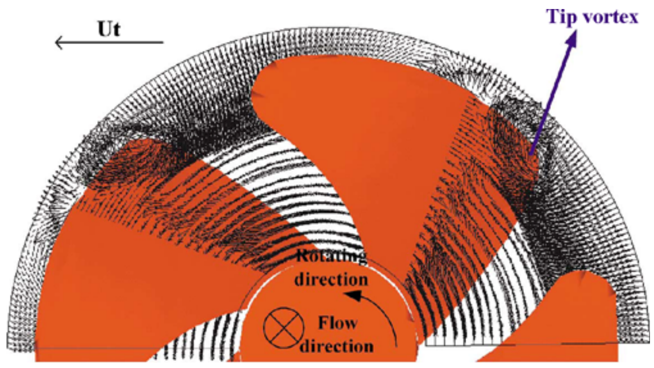


Fig. 7. Velocity distribution in cross section 13.

In Figs. 8 and 9, the velocity distribution at downstream of blade row are shown. Cross section 22 is about 5 mm downstream of trailing edge, the core of tip vortex and blade wake are also very strong there. Comparing with the tip vortex flow in blade passage of cross sections 6, 8 and 13, the distance from suction side of blade wake to core of tip vortex becomes longer in cross section 22 and also the core position of tip vortex goes more inward to hub direction. That means the tip vortex core goes away from the suction side of blade as it passes through the blade passage.

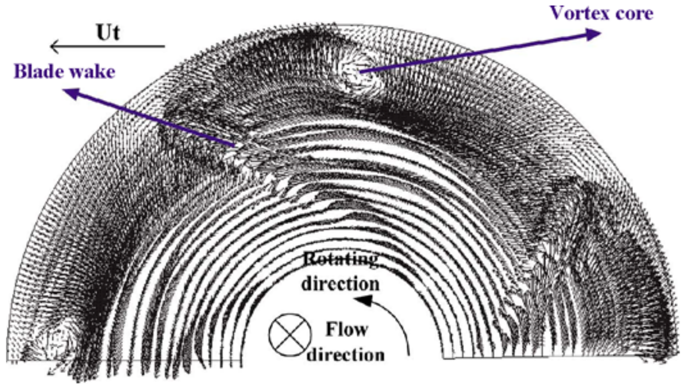


Fig. 8. Velocity distribution in cross section 22.

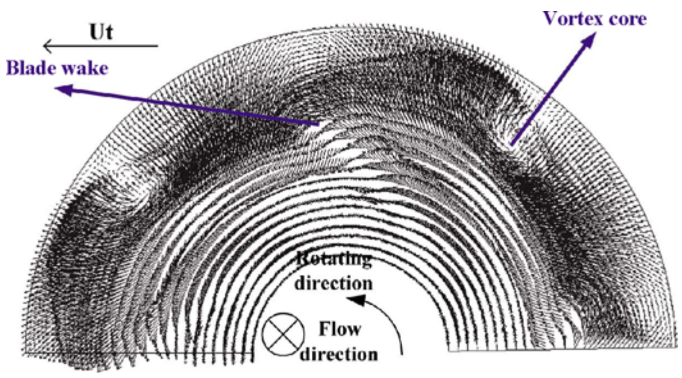


Fig. 9. Velocity distribution in cross section 28.

Cross section 28 is about half chord length downstream from trailing edge. Its velocity distribution was shown in Fig. 9. Although the wake of blade and vortex core can be found in this figure, it is true that the intensity of tip vortex core becomes weaker at downstream of trailing edge. Moreover, core position of tip vortex goes much more inwards and goes more away from blade wake in an anti-rotating direction.

All of the above figures indicate that the tip vortex and leading edge vortex obviously exist in this open fan with inclined leading edge. The flow feature of tip vortex is different from the tip leakage vortex observed in axial flow compressor that is formed due to the jet flow from pressure side to suction side. The trace of tip vortex passes through the blade passage along the slant line inclined to pressure side of following blade, and it extends downstream to exit accompanying with TV core going inward to hub direction.

4. Conclusions

Measurements on an open fan have been carried out by using LDV technique. The velocity distributions in several measurement cross sections were shown clearly. Based on those results, the following conclusions were obtained.

Firstly, the tip vortex (TV) exists obviously in the present open fan due to the strong suck-in flow. The rolling up process of tip vortex is different from that of tip leakage vortex observed in an axial compressor that is formed due to the jet flow from pressure side to suction side. In addition, the leading edge vortex is also found in some cross surfaces of that experimental fan.

Secondly, the tip vortex is formed at the suction side of blade tip region near leading edge in this open fan. Then, it is developed and becomes strong as it passes through blade passage. However, it diffuses and becomes weak at downstream of blade row.

The trace of tip vortex passes through the blade passage along the slant line contrary to rotation direction. The core of tip vortex goes inward to lower radius as it passes through blade passage to downstream.

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