Measurement of Three-dimensional flow Structure around an Axial flow fan by using Stereoscopic PIV

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ABSTRACT
To analysis of a complex three dimensional flow structure of axial flow fan and determine the validity of its application, PIV system should be provided detailed space and time resolved experimental data for understanding and control of flow field. The high resolution stereoscopic PIV system, in this study was successfully employed at the investigation of flow structure near the axial flow fan. Using the once-per-resolution signal from the rotor, image fields were captured at a fixed poison of the blades and hence provides the ability to do phase-averaging. The three-dimensional instantaneous velocity fields and phase-averaged velocity fields, instantaneous and mean vorticity distributions and turbulent intensity of the stereoscopic PIV measurement result were represented at typical planes of the flow field. Phase-averaged velocity fields were calculated based on 200frames of the instantaneous stereoscopic PIV measurement results. From the velocity distribution, the vorticity and turbulent intensity distribution, which was known to be major factors of fan noise were calculated and its diffusion was discussed as they travel downstream. From the reconstructed three dimensional velocity iso-surface which is based on stereoscopic PIV results at 8 cross planes of the outlet flow fields, the three dimensional features can be seen clearly.

Keyword: stereoscopic PIV technique, Axial flow fan, once- per- resolution signal, velocity iso-surface

1. Introduction
In connection to the development of fluid machinery such as aircraft and vehicle dynamics the investigation of air flows have been motivated to improve the system performance in these years. Especially, axial flow fan is widely used for industrial equipment and household appliances like air-conditioner. Considerable efforts have been made to investigate transient events of axial flow fan in depth with developments in the vehicle and aircraft industry. In the design of Axial flow fan, however, has not yet been well established because of the complexity of the internal, in and out flow (turbulence near the suction side of blade, vortex shedding and inflow and outflow) which is major contributor to a source of noise. To improve the system performance and reduce the noise from that part, it is important to get further information of flow pattern around of axial flow fan. Although variety of experimental and theoretical approaches [1], [2] has been conducted in previous study, much work is still needed in order to examine the detailed flow property in and around axial flow fan. Especially in relation to the mechanisms of vortical and turbulent supply from the blades and its diffusion to the downstream. To analysis of increasingly complex three dimensional flow structure of axial flow fan and determine the validity of its application, conventional 2-D measurements [3] results would not allow insight into their nature of the flow. In order to reveal the three dimensional feature of axial flow fan, high-resolution stereoscopic PIV system [4], which can obtained the all three component of the velocity vector simultaneously, is used in this study to measure the flow field of axial flow fan. Stereoscopic PIV techniques, using two cameras viewing the flow from two perspectives, is a good potential for visualization and easy accomplished method for the velocity three components measurement in the illuminating laser sheet plane. By reconstructing the vector fields from the two cameras, the three-dimensional velocity field in the objective plane is measured. Based on the three measurement results of the stereoscopic PIV system, three component velocity fields, vorticity distribution and turbulent intensity distribution were represented.
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2. Experimental Apparatus and Setup

Fig. 1 represents a measuring region in geometric configuration of axial flow fan. The test fan named windward tilted blade fan has 5 blades with an angle of 18 degree. The blade tip to tip diameter and the hub diameter are 174mm and 80mm (tip clearance: 3mm, hub to tip ratio: 0.45) respectively and the width of the test fan is 90mm. The rotational speed of the impeller is maintained at 2500rpm. A test fan was mounted on a two-dimensional translation so that the distance between illuminating laser sheets and the different cross planes can be changed by sliding the two-dimensional translation mechanism. On those arrangements, the size of common measurement region of the two image recording camera is about 100mm by 100mm. It can be seen that region of measurement covered 25% of the flow field in the rotor exit region. At each of location (2 internal and 8 downstream) 200 images were obtained in the phase-locked mode. Fig. 2 represents the schematics of experimental setup used in this study. A pair of camera and laser light assembly were mounted on the same fixture to obtain the image field in the x-y plane at various z-axis location. For illuminating flow field, double pulsed Nd:YAG lasers (pulsed illumination duration 6ns) with the frequency of 15Hz and the power of 20±/pulse were used. The combined beam from the two laser tubes was delivered to the measuring region using the various optics. The optics installed in a laser head unit provides laser sheet (thickness is about 2.0mm), whose thickness and angle of divergence could be controlled. DEHS(Di-2-Ethlhexyl-Sebact) droplets were used as tracer particles and its diameter is 1μm. Those tiny particles were generated by a seeding generator that is composed by an air compressor and several Laskin nozzles.

To capture the flow field simultaneously with high resolution, a pair of cross-correlation CCD camera (TSI PIVCam 10-30) with 1000 by 1014 pixels resolution was used. In order to have the measurement field focused on the image planes perfectly, tilt-axis mounts were installed between the camera bodies and lenses. The distance between the illuminating laser and image recording plane of the camera is about 720mm and the angle of between the view axis of the two camera is about 50°. Camera and lasers were connected to a workstation (host computer) via a synchronizer (TSI Laser Pulse synchronizer), which controlled the timing of the laser sheet illumination and the CCD camera data acquisition. In the present study, the time interval between the two laser pulsed illumination was settled as 22±-30± at various z-axis locations. The high speed host computer allows stereoscopic PIV image pairs to be captured up to 250frames at the frame frequency of 15Hz. A once-per-revolution signal from the rotor encoder system was attached to the rotor was also used as the input to the synchronizer so that phase-locked image capture could be accomplished. This allows the flow fields to be acquired at a fixed position of the blades and hence provides the ability to do phase-averaging.

For the PIV processing cross correlation method was used in the present study to obtain the average displacement of the particles. The post processing procedures which including sub-pixel interpolation and velocity outlier deletion were used to improve the accuracy of the PIV result.

3. Experimental Results

Fig. 3 to Fig. 5 show the stereoscopic PIV measurement results at two typical planes of the flow field. In the present study, phase-averaged velocity fields were calculated based on 200 frames.
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Fig. 3 shows the phase-averaged velocity field at the \( z/R = 0.13 \) cross plane. The region of sudden decrease and direction change in velocity and behind the blade spacing between two adjacent blades indicates the fan blade wake, of which the right side correspond to the pressure side and the other the suction side. High magnitude of velocity shows existence at the leading edge where centrifugal force acts on fluid more strongly. Behind the blade tip, large depression of velocity and rolling up region toward the counterrotating direction appear where a large scale of vortex can be noticed from radial velocity distribution. When the downstream distance increase to \( z/R = 0.5 \) the overall flow structure is observed to rotated about 15° in the counter-clockwise direction plane with a small overall decay in magnitude.

Fig. 4 shows the streamwise vorticity distribution calculated from phase-averaged velocity data. Solid line represents positive (counter-clock) vortices and dashed lines represent negative clockwise vortices. At the cross plane \( z/R = 0.13 \), the negative vortices located along the blade tip. This is leakage vortex mainly due to rolling-up of tip leakage flow near the casing. Trailing vortex having high level of positive vorticity, which is ranged from near the hub to mid-span of the fan blade is observed with a single glance. This phenomenon mainly results from the interaction of the blade to blade and blade to hub wall boundary layer. In the \( z/R = 0.5 \) cross plane, the angular distance of vortices is changed comparing to that in the \( z/R = 0.13 \). The leakage vortex and trailing vortex keep the same structure with the magnitude reduction. All of the vorticity components show very high values behind the blade. However, trailing vortex has a higher decay ratio compared to the leakage vortex. The reason is for that the leakage vortex shedding into the flow with high energy due to the leakage jet flow by blade tip before rolling up.

Fig. 5 shows the turbulent intensity distribution. In the \( z/R = 0.13 \) cross plane, the distribution of the
turbulence level resembles that of velocity contour distribution. It is noted, however, that the magnitude becomes high on the rolling up region where the interaction between blade and casing occurred. When the downstream distance increase to $z/R=0.5$, strength of turbulent intensity decreased substantially and the relatively high level of intensity regions were concentrated mainly around the gap between the tip blade and housing.

Fig. 5 shows three-dimensional phase-averaged velocity iso-surface with the viewpoint from downstream. This features were based on the stereoscopic PIV measurement results at 8 cross plane in total at the near field of outlet side of the test fan $(1.5 < z/R < 5.0)$. The velocity magnitudes of this iso-surface are ranged from $-0.2.5\text{m/s}$ (negative velocity region on the rotor boss) to $13.4\text{m/s}$ (high speed velocity around tip blade) by changing the color from blue to red. From the reconstructed three-dimensional phase-averaged velocity iso-surface, the three dimensional mechanism can be seen clearly.

4. Conclusion

The stereoscopic PIV system was used to conduct three dimensional velocity measurement of internal and outlet side flow of axial flow fan. By use of these measurement technique, it is possible to elucidate quantitatively the three dimensional structure of various kinds of vortices generated behind the blade. The existence of large big scale vortices and turbulent intensity caused by fan blade orientation is revealed from PIV measurement result.

Based on the result of the present experimental research, internal flow of fan in relation to the mechanisms of vortical and turbulent around the tip blade, acting as a major source of noise, will be conducted in the coming work.

References