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THREE-DIMENSIONAL STRUCTURE OF SEPARATED AND VORTICAL FLOW IN A HALF-DUCTED PROPELLER FAN

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ABSTRACT

Three-dimensional structure of separated and vortical flow field has been investigated by numerical analysis on a half-ducted propeller fan. Complicated flow phenomena in the fan were captured by the Reynolds-averaged Navier-Stokes flow simulation (RANS) and a vortex structure identification technique based on the critical point theory.

The flow field around the fan rotor is dominated by the tip leakage vortex. The tip leakage vortex starts to be formed near the blade mid-chord and grows nearly in the tangential direction without vortex breakdown. In the rotor passage, the high vorticity flow around the tip leakage vortex core is impinging on the pressure surface of the adjacent blade. It is expected that the behavior of the tip leakage vortex plays a major role in characteristics of the fan noise.

INTRODUCTION

Propeller fans have simple structure and can be possible to achieve the high flow rate. For this reason, propeller fans with half-ducted shroud covering only the rear region of their rotor tips are widely used as cooling fans in the outdoor unit of split room air-conditioners and in the cooling unit of engine block on automobiles. The half-ducted propeller fans are closely operated near our domiciliary life. Recently, they need compactness, low noise and high performance characteristics. However, it is difficult to develop these propeller fans by conventional and heuristic techniques.

Therefore, grasping the details of vortical flow structures in the propeller fans is very important to reduce fan noise and enhance fan efficiency. Specially, investigations of flow structure in the propeller fans have been performed with numerical and experimental analyses to reduce the fan noise. It has been found that the noise of propeller fan can be controlled by the tip leakage vortex that develops in the tangential direction and impinges on the tip region of the pressure surface of the adjacent blade by Jang et al [2001]. They also performed the analysis on the frequency characteristic of the fluctuating pressure on the rotor blade [2003]. The analysis showed that the noise of propeller fan is closely related to the unsteady behavior of the tip leakage vortex.

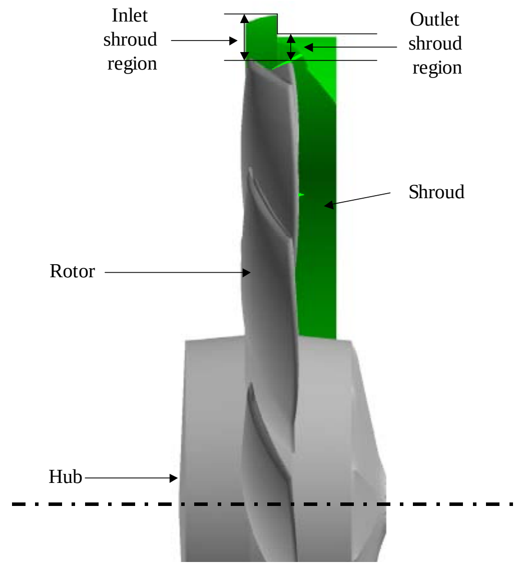
In the present study, three-dimensional structure of separated and vortical flow fields has been investigated by numerical analysis on a half-ducted propeller fan. Complicated flow phenomena in the fan were captured by the Reynolds-averaged Navier-Stokes flow simulation (RANS). The vortex structure is visualized with the vortex identification technique based on the critical point theory.

TEST FAN

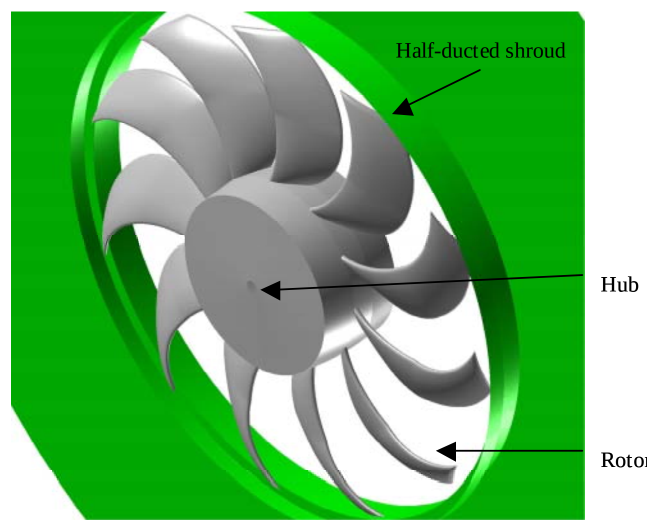
The present investigation was performed on a half-ducted propeller fan with the clearance between the shroud and the blade tip shown in Fig.1. It has the design flow rate coefficient ϕ of 0.214. The number of blades is 11, the blade diameter is 320.0mm, the hub diameter is 120.0mm, and the tip clearance is 13.5mm on the inflow side of blade and 5.5mm on the outflow side of blade. The flow rate coefficient ϕ is defined as follows:.

$$\phi = Q/(\pi(1-\upsilon^2)R^2U_t) \quad (1)$$

where Q, υ, R and U_t denote the flow rate, the hub-tip ratio, the blade radius and the tip velocity, respectively. In the present study, the flow structure in the propeller fan is analyzed at the design flow rate. According to the prior studies, the propeller fan noise is controlled by the tip leakage vortex impingement on the adjacent blade. Therefore, it is very important to understand the complex vortical flow fields in the fan rotor to design low noise fan.



(a) Meridional view



(b) Perspective view

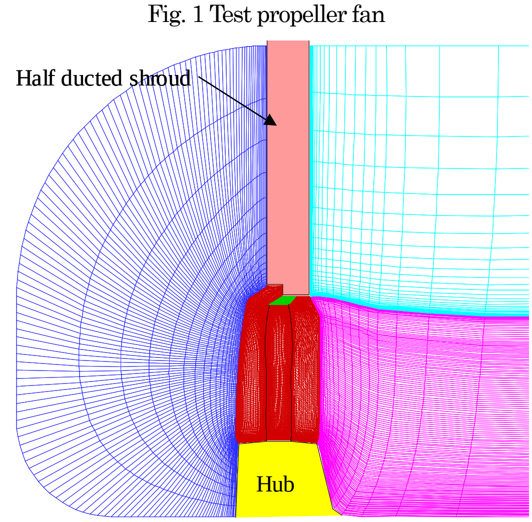
Fig. 1 Test propeller fan

NUMERICAL SCHEME

In the present numerical simulation, the compressible three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations were solved by an implicit unfactored upwind relaxation scheme [Furukawa et al., 1992, 1995]. The flow field was simulated in the relative frame of reference rotating with the rotor. The compressible Navier-Stokes equations were discretized in space using a cell-centered finite volume formulation. In order to capture the vortical flow structure sharply, the inviscid fluxes were evaluated by a high-resolution upwind scheme based on a TVD formulation [Furukawa et al, 1991] where a Roe's approximate Riemann solver of Chakravarthy [1986] and a third-order accurate MUSCL approach of Anderson et al. [1986] with the Van Albada limiter [Van Albada et al, 1982] were implemented. The viscous fluxes were determined in a central differencing manner with Gauss's theorem. Simultaneous equations linearized in time were solved by a point Gauss-Seidel relaxation method using no approximate factorization. And the eddy viscosity is estimated by the k-ω two-equation turbulence model [Wilcox et al, 1988].

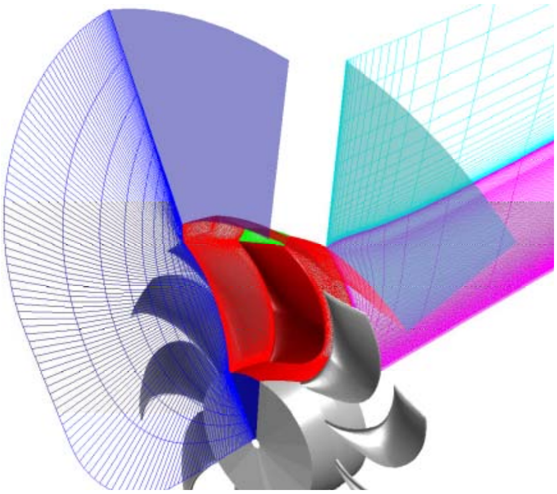
COMPUTATIONAL GRID SYSTEM

A computational grid system is composed of H-type and O-type girds from upstream region to downstream region. As shown in Fig. 2, the computational domain was divided into 5 blocks. The shape of inflow region is adopted as hemisphere to express opening to atmosphere. And the shape of outflow region is reproduced as cylinder shape that is indicating the duct of cylinder shape. O-type grid is applied to the clearance region between the shroud and the blade tip. As shown in table 1, the computational cells are concentrated on block1 region where the rotor blade region was latticed. Because this region is the most important field to understand complicated vortical flow in the fan.



(a) Meridional view

Fig. 2 Computational grid



(b) Perspective view

Fig. 2 Computational grid

Table. 1 Computational cells

	Flow direction	Span direction	Pitch direction	The number of computational cells
Pitch of fan	137	138	40	756,240
Clearance	57	22	8	10,032
Inflow	17	138	40	93,840
Outflow1	27	138	40	149,040
Outflow2	27	30	40	32,400

IDENTIFICATION METHOD OF VORTEX CORE

To understand the vortex structure in the complex vortical flow field of the propeller fan, a vortex identification method by Sawada [1995] is adopted. This method based on the critical-point theory [Perry and Chong, 1987]. In the Sawada's method, assuming that a local velocity field can be linearly parameterized in a tetrahedral cell, and streamline equations are analytically integrated on the cell. As a result, the obtained streamline expression provides the possibilities of vortex core in the cell. If the vortex centerline crosses the cell, the line segment inside the tetrahedral cell is regarded as the fraction of the vortex core. According to this method, it is possible to visualize the vortex core in the whole computational cells. To analyze the nature of vortex quantitatively, the normalized helicity [Levy et al. 1990] is investigated along the vortex core. The normalized helicity is useful to investigate the nature of vortices: for example detecting the vortex breakdown region and the stagnation point in the vortex core, as shown in compressor rotor flow fields by Furukawa et al. [1999]. The normalized helicity H_n is defined by the following equation.

$$H_n = (\vec{\xi} \bullet \vec{\omega}) / (|\vec{\xi}| \bullet |\vec{\omega}|) \tag{2}$$

Here, $\vec{\xi}$ and $\vec{\omega}$ denote vectors of the absolute vorticity and the relative flow velocity, respectively. The normalized helicity is equivalent to the cosine of the angle between the absolute vorticity and the relative flow velocity. Therefore, if the value of formula (2) is being ± 1 in the computational region, it shows that the core of longitudinal vortex exists on that region.

RESULTS AND DISCUSSTIONS

Tangentially-Averaged Flow Field

Figure 3 shows meridional streamlines in the tangentially-averaged flow. At the inflow tip blade region, the strong radially inward flow is observed. The large vortical flow near the blade tip trailing edge corresponds to the tip leakage vortex. It is clearly seen that the tip leakage vortex has the large blockage effect on the flow near the rotor tip. A small separation vortex is formed on the hub surface. However, the separation vortex is reattached in front of the blade region. The separation on the hub is suppressed by the large blockage effect of the tip leakage vortex. It is founded on the principle that the flow field around the fan rotor is dominated by the tip leakage vortex.

Figure 4 shows a span wise distribution of the inlet axial velocity at the rotor leading edge. The inlet axial velocity is normalized by the rotating velocity of the blade tip. The vertical axis of the Fig. 4 is the non-dimensional span height. As shown in Fig.4, the inlet axial velocity is low near the rotor tip. The large blockage effect caused by the tip leakage vortex suppresses the acceleration of the inlet flow near the rotor tip.

Figure 5 shows a span wise distribution of the inlet relative flow angle at the rotor leading edge. The inlet relative flow angle $\beta[^\circ]$ is defined as

$$\beta = \tan^{-1}\left(\frac{W_{1\theta}}{W_{1m}}\right) \tag{3}$$

where $W_{1\theta}$ and W_{1m} denote the components of the inlet relative and meridional velocity, respectively. The inlet relative flow angle is higher than 60° along the whole span. Especially, the inlet flow angle increases near the tip leakage vortex region where the large blockage effect caused by the tip leakage vortex makes the inlet axial velocity low as shown in Fig. 4. Near the hub, the inlet relative flow angle becomes very high, because the separation of the hub wall boundary layer takes place as shown Fig.3.

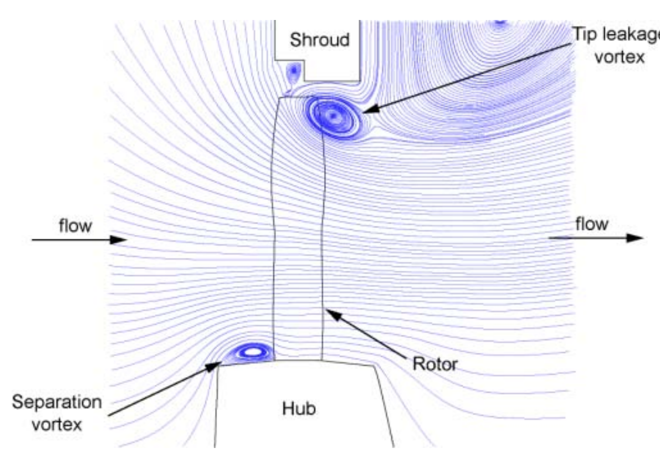


Fig. 3 Meridional Streamline in tangentially averaged flow

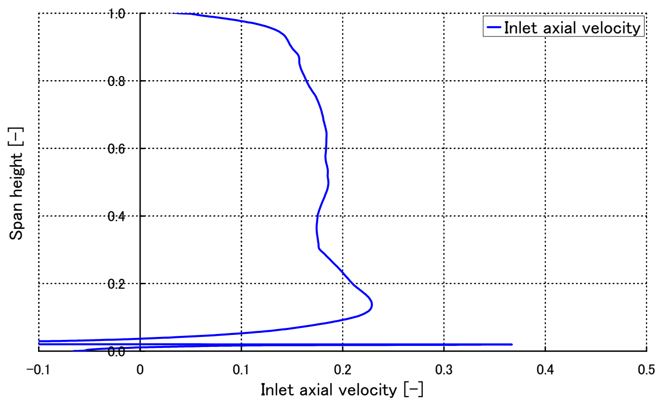


Fig. 4 Inlet axial velocity distribution in tangentially averaged flow

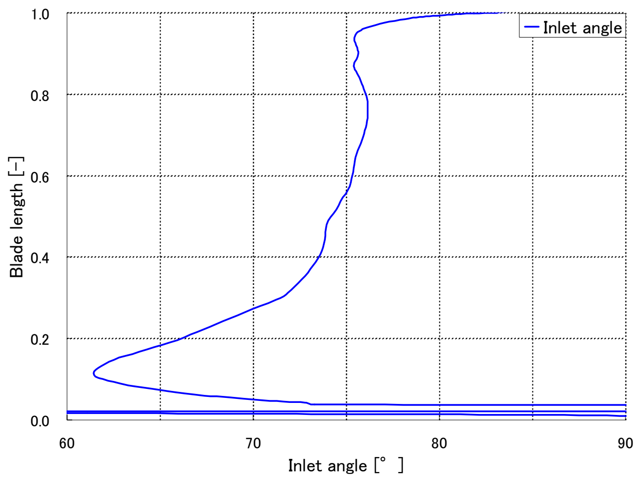
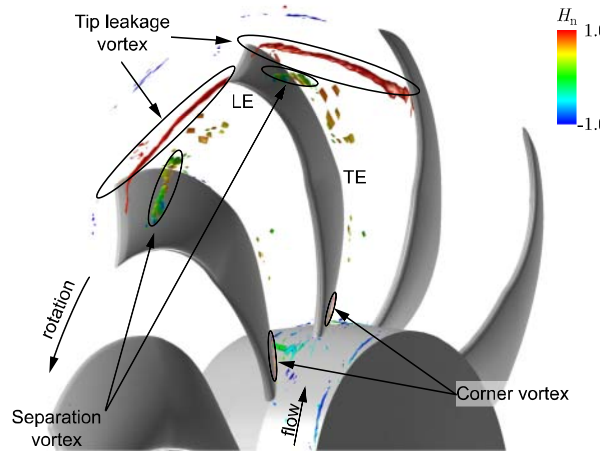


Fig. 5. Inlet relative flow angle distribution in tangentially averaged flow

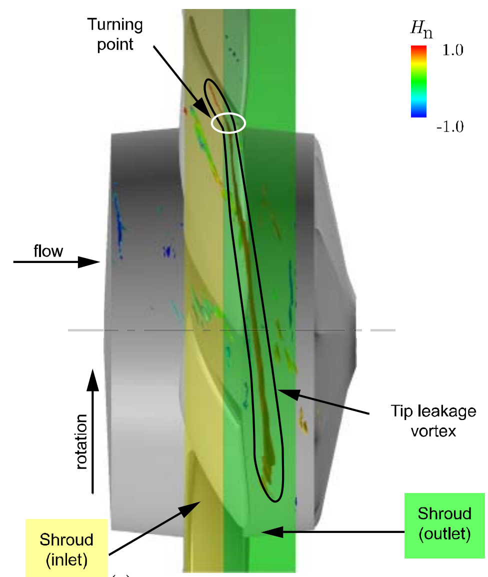
Three-Dimensional Separated and Vortical Flow Structure

Figure 6 shows three-dimensional vortex structures in the fan rotor. In the figure, the color on the vortex structures shows a distribution of the normalized helicity: Red and green denote the normalized helicity of unity and zero, respectively. The normalized helicity is about unity (red) along the tip leakage vortex, which means that the tip leakage vortex is strongly rolled up from its inception position to the downstream direction. It is founded that the inception point of the tip leakage vortex is located near 50 percent tip chord on the suction surface. And then the tip leakage vortex develops in the almost tangential direction. A separation vortex is observed near the tip leakage vortex on the suction surface. This separation is caused by the large inlet relative flow angle near the tip, as shown in Fig. 5. However, the tip leakage and separation vortices don't interact with each other because the separation vortex develops in the almost flow direction.

As shown in Fig. 6 (b), the trajectory of the tip leakage vortex turns at the boundary between the inlet and outlet regions of the shroud, where the tip clearance changes as shown in Fig. 1 (a). The tip leakage vortex develops along the suction surface as far as the boundary of the inlet and outlet shroud regions. Downstream of the boundary, however, the tip leakage vortex develops in the almost tangential direction. This behavior of the tip leakage vortex can be explained by the interaction with the tip leakage vortex and the shroud wall, as shown in figure 7. The induced velocity to the tip le-



(a) View from flow direction



(b) View from radial direction

Fig. 6 Vortex structure

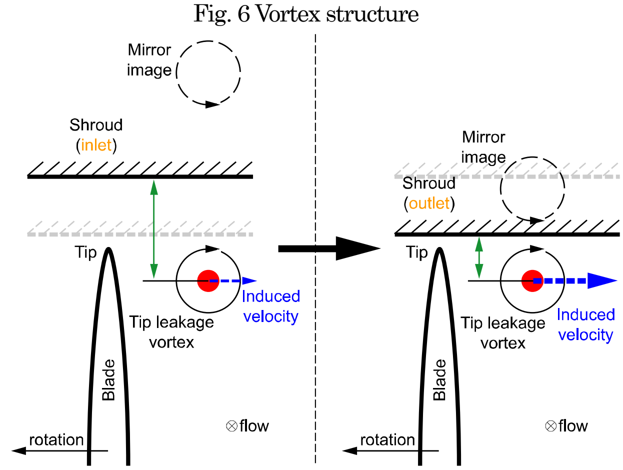


Fig. 7 Interaction between tip leakage vortex and shroud wall

akage vortex caused by its mirror image depends on the distance between the vortex and the shroud wall. In this viewpoint, it can be explained why the trajectory of the tip leakage vortex core is changed in the tangential direction.

Figure 8 shows the vortex structures and limiting streamlines on the blade suction surface. It is found that the limiting streamlines near the blade tip region develops in the almost radial direction by the swirl effect of the tip leakage vortex. It is clearly seen that a separation line is formed near the tip, which corresponds to the separation caused by the large inlet relative flow angle.

Figure 9 shows distributions of the absolute vorticity on cross sections perpendicular to the tip leakage vortex. The absolute vorticity is normalized by the angular velocity of the rotor. The tip leakage vortex core does not directly interfere with the pressure surface of the adjacent blade. However, it is found that the high value region of absolute vorticity around the vortex core is impinging on the pressure surface. This behavior of the vortical flow may cause the fan noise.

CONCLUDING REMARKS

The vortical flow field in a half-ducted propeller fan has been investigated by the compressible Reynolds averaged Navier- Stokes simulation based on the k-ω two-equation turbulence model. The following conclusions are obtained.

For the half-ducted propeller fan, the flow field around the rotor is dominated by the tip leakage vortex. The tip leakage vortex starts to be formed near the blade mid-chord and grows nearly in the tangential direction. In the blade passage, the high vorticity flow around the tip leakage vortex core is impinging on the pressure surface of the adjacent blade. It is expected that the behavior of the tip leakage vortex plays a major role in characteristics of the fan noise.

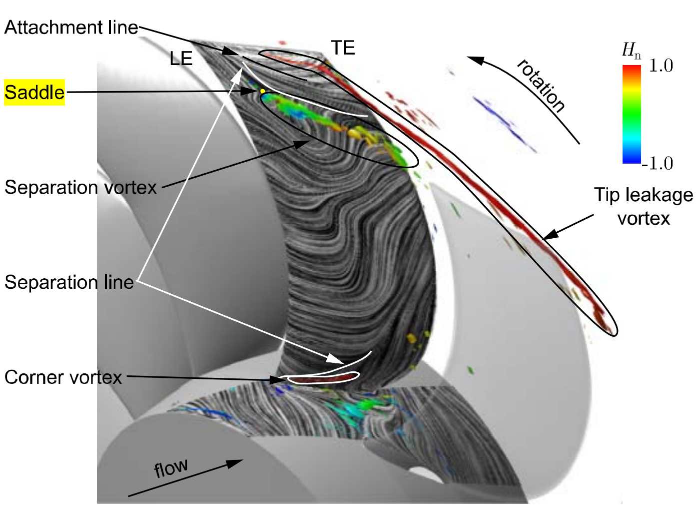


Fig. 8 Limiting streamline

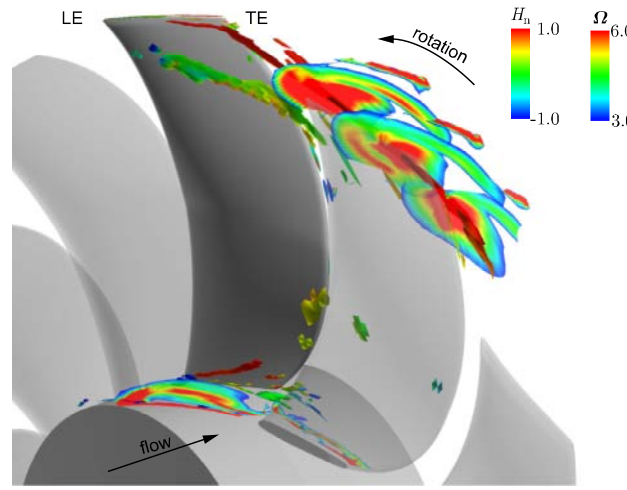


Fig. 9 Distribution of absolute vorticity

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