Analysis of Vortical Flow Field in a Propeller Fan by LDV Measurements and LES—Part II: Unsteady Nature of Vortical Flow Structures Due to Tip Vortex Breakdown

The unsteady nature of vortical flow structures has been investigated by a large eddy simulation (LES) in a propeller fan with a shroud covering only the rear region of its rotor tip. The simulation shows that the tip vortex plays a major role in the structure and unsteady behavior of the vortical flow in the propeller fan. The spiral-type breakdown of the tip vortex occurs near the midpitch, leading to significant changes in the nature of the tip vortex. The breakdown gives rise to large and cyclic movements of the tip vortex, so that the vortex impinges cyclically on the pressure surface of the adjacent blade. The movements of the tip vortex cause the leading edge separation vortex to oscillate in a cycle, but on a small scale. The movements of the vortex structures induce high-pressure fluctuations on the rotor blade and in the blade passage. [DOI: 10.1115/1.1412566]

Introduction

Three-dimensional structures of the vortical flow field in a propeller fan with a shroud covering only the rear region of its rotor tip have been elucidated in Part I. As mentioned in Part I, the tip vortex dominating the flow field in the propeller fan presents a significant change in its nature near the pressure surface. Similar phenomenon has been reported recently in tip leakage vortices of some compressor rotors and has been found to result from the vortex breakdown. The vortex breakdown was observed in blade rows by pioneer studies of Schlechttriem and Lotzerich [1] and Furukawa et al. [2,3]. Schlechttriem and Lotzerich [1] showed by numerical simulations that the breakdown of the tip leakage vortex caused by the shock-vortex interaction occurred in a transonic axial compressor rotor. Furukawa et al. [2] found that the leakage vortex presented its breakdown even at a design point for a low-speed diagonal compressor rotor with high blade loading. Furukawa et al. [3] showed that the breakdown of the leakage vortex dominated flow fields in a low-speed compressor rotor at near-stall conditions. They also showed that the breakdown yielded substantial changes in the nature of the leakage vortex: large expansion of the vortex and disappearance of the streamwise vorticity concentrated in the vortex core. Unsteady Navier-Stokes flow simulations by Furukawa et al. [4] indicated that the spiral-type breakdown of the leakage vortex caused a cyclic and large movement of the vortex structure.

In general, the vortex breakdown is known as a highly three-dimensional and unsteady phenomenon observed in streamwise slender vortices in external vortical flow and internal swirling flow as in the leading edge vortices over delta wings, the swirling flows in a cylindrical tube and the swirling jet in combustion chambers. Studies of flow fields generated by the vortex breakdown have been reported by many researchers such as Sarpkaya [5,6], Hall [7], Leibovich [8,9], Escudier [10], Brücker and Althaus [11], Brücker [12], and Delery [13]. Although the essential mechanism of the vortex breakdown is not generalized, three types of the breakdown can be distinguished: bubble type and spiral type as well as the transition from the bubble to spiral types (double helix type). The vortex breakdown is characterized by the existence of a stagnation point near the vortex core and the reverse flow downstream of the stagnation point. It is also known that the most distinctive feature of vortex breakdown is the occurrence of the large-scale fluctuation in the vortex structure.

On the other hand, it is well known that turbulence intensity and pressure fluctuation have a close relation with aerodynamic noise generation. In the propeller fan installed in the automotive air conditioners, the turbulence intensity was highest near the rotor tip, where a tip vortex core was formed (Akaike and Kikuyama [14]). It seems that unsteady vortical flow near the rotor tip dominates the generation of noise in propeller fans.

In Part II, the unsteady nature of the vortical flow in a propeller fan is investigated by a large eddy simulation (LES). Effects of the unsteady behavior of the vortex structure on pressure fluctuation in the rotor blade passage are elucidated.

Test Propeller Fan

The present study was performed in a propeller fan with a shroud covering only the rear region of the rotor blade in the outdoor unit of room air conditioner, as shown in Fig. 5 of Part I, which consists of a condenser (heat exchanger), a propeller fan (fan rotor and shroud), and a fan driving motor.

The rotor of the fan has a design flow coefficient of 0.27 and a design static pressure coefficient of 0.22. The hub/tip ratio of the rotor with the tip diameter of 380 mm is 0.318. The rotation frequency of the rotor is 670 rpm at a design condition. The rotor blade has circular arc profile sections designed by a quasi-three-dimensional method of Inoue et al. [15] on a forced vortex operating condition and an axial inlet flow condition. The number of blades is 5, and the blade thickness changes from 4 mm (at rotor hub) to 3 mm (at rotor tip) proportionally. The blade tip section has the solidity of 0.75 and the chord length of 178 mm. Twelve
percent of the axial chord at the rear part of the rotor blade is covered by the shroud. The clearance between the shroud and the rotor tip is 5 mm (2.8 percent of tip chord).

**Nondimensional Parameters for Analyzing Vortical Flow**

To readily understand the nature of the vortex structure in the propeller fan, the vortex core identified by a semi-analytic method based on the critical point analysis (Sawada [16]) was described by nondimensional parameters: the streamwise absolute vorticity, the total pressure loss coefficients, and the normalized helicity.

The total pressure loss coefficient \( \xi_P \) is defined as

\[
\xi_P = \frac{\Omega \cdot (r c \vartheta - r_1 c \vartheta) - (P - P_1)/\rho}{U_t^2/2}
\]

where \( r \) is the radius from the axis of rotation, \( c \vartheta \) is the absolute tangential velocity, \( P \) is the total pressure, \( \rho \) is the density, \( U_t \) is the blade tip speed, \( \Omega \) is the angular velocity magnitude of the rotor, and subscript of 1 denotes the upstream of the rotor.

The streamwise absolute vorticity \( \xi_s \) is defined and normalized as

\[
\xi_s = \frac{\vec{\xi} \cdot \vec{w}}{2|\Omega||w|}
\]

where \( \vec{\xi} \) and \( \vec{w} \) denote vectors of the absolute vorticity and the relative flow velocity, respectively.

The normalized helicity \( H_n \) is defined as

\[
H_n = \frac{\vec{\xi} \cdot \vec{w}}{|\vec{\xi}| |\vec{w}|}
\]

The magnitude of the normalized helicity tends to unity in the core region of the streamwise vortex, and its sign indicates the direction of swirl of the vortex relative to the streamwise velocity component. In contrast to the streamwise absolute vorticity, distributions of the normalized helicity along the vortex core allow us to analyze the change in the nature of vortex quantitatively, regardless of the decay of the vorticity in the streamwise direction.

In the following, unsteady nature of the vortex structures in the propeller fan is analyzed by the nondimensional parameters mentioned above.

**Results and Discussion**

Unsteady behavior of the vortical flow, especially the tip vortex in the propeller fan was studied by a large eddy simulation (LES) at the design flow condition of \( \Phi = 0.27 \). By applying the periodic boundary condition, the flow field in a single blade passage was simulated using the whole grid cells of 1,341,280, which was divided into two blocks to represent the complicated configuration of the propeller fan including the shroud. The matching between block 1 and block 2 was accomplished by the inviscid and viscous fluxes across the boundary between the blocks. The details of numerical scheme, computational grid and boundary conditions were described in the Part I.

A nondimensional time step size normalized by the blade tip radius and the inlet sound speed was set to 0.05. It takes a rotor blade 32.3 nondimensional time (646 time steps) to pass through one pitch. The time resolution of 646 time steps per one blade passing, which corresponds to about 36 kHz, is sufficient to resolve the turbulence in the present propeller fan. A solution obtained by the Reynolds-averaged Navier-Stokes equations was used as an initial state of the unsteady calculation. Figure 1 shows a time history of the rotor torque nondimensionalized by its design value. The figure indicates that the unsteady flow solution has a transitional feature until about nondimensional time of \( t = 500 \). In the following, the unsteady behavior of the vortical flow in the fan is investigated by analyzing the solution for the period of 300 nondimensional time (6000 time steps) from \( t = 500 \) to \( t = 800 \) excepting the transitional state.

**Turbulence Intensity and Pressure Fluctuation.** Figures 2 and 3 show distributions of the turbulence intensity on a meridional plane shown by plane 5 in Fig. 10 of Part I, where the turbulence intensity presents the highest value. Figures 2 and 3 show results of LES and LDV, respectively. The region close to the blade surface, where the LDV measurement is impossible, is represented by a gray zone in Figs. 2 and 3. The turbulence intensity \( T_i \) is defined as

\[
T_i = \sqrt{\frac{\nu_r^2 + \nu_\theta^2 + \nu_z^2}{3 U_t^2}}
\]

where, \( \nu_r, \nu_\theta, \) and \( \nu_z \) denote the velocity fluctuation components in the radial, tangential and axial directions, respectively.

Relatively high turbulence intensity regions shown by A and B in Figs. 2 and 3 are observed close around the blade surface near the rotor tip, especially near the interference region between the tip vortex and the main flow (through flow). It is seen that the level of turbulence intensity agrees between the LDV and LES results. Although there is a little difference in the position of the tip vortex center as shown in Figs. 2 and 3, the two regions having the high turbulence intensity (A and B in Figs. 2 and 3) are in fairly good agreement between the LES and LDV results. It is found that the unsteady flow nature in the propeller fan is captured well by the present LES.

Figure 4 shows the tangentially averaged distribution of the pressure fluctuation predicted by LES. The pressure fluctuation is normalized by a dynamic pressure based on the rotor tip speed as follows:

\[
P_f = \frac{\sqrt{\rho' \nu_t^2}}{1/2 \rho U_t^2}
\]

where \( \rho' \) denotes the pressure fluctuation of the resolved field of the LES. Figure 4 indicates that there is a high-pressure fluctuation region under the tip vortex. This region corresponds to the interference region between the tip vortex and the main flow. The above implies that the tip vortex highly fluctuates with time and presents the important noise source.

In the following, the unsteady behavior of the vortex structures near the rotor tip is analyzed by the numerical results of LES.
Breakdown of Tip Vortex. Although the tip vortex core with high normalized helicity is clearly observed from the blade suction side to the midpitch in the time-averaged flow field obtained by LES, as mentioned in the Part I, it disappears near the pressure surface where the normalized helicity along the tip vortex changes rapidly. The disappearance of the tip vortex core and the rapid change in the normalized helicity imply that there are significant changes in the nature of the tip vortex near the pressure surface.
Figure 5 shows a perspective view of instantaneous vortex core structures, which is the result of LES. The vortex cores are colored with the relative velocity magnitude normalized by the rotor tip speed. Compared with the leading edge separation vortex (LSV), the relative velocity along the tip vortex (TV) is lower. Near the midpitch, the tip vortex core flow is decelerated almost to stagnation, and the tip vortex structure has a large twist. A reverse flow in the direction of the tip vortex axis appears close to the low-velocity region. This flow behavior implies the existence of a stagnation point followed by the reverse flow region in the tip vortex. The existence of the stagnation point in the vortex is the distinctive feature of vortex breakdown [Leibovich [8] and Delery [13]]. Therefore, it can safely be said that there is the onset of "vortex breakdown" near the low-velocity region in the tip vortex. It should be realized that the significant changes in the nature of the tip vortex are caused by its breakdown.

**Unsteady Nature of Tip Vortex.** Unsteady behavior of the vortex structures near the fan rotor tip is shown in Fig. 6 where the vortex cores are colored with the normalized helicity. Each instantaneous view is shown at intervals of three nondimensional time from \( t = 553 \) to 592. The tip vortex (TV) twists and turns violently with time, because its spiral type breakdown occurs near the midpitch. The normalized helicity along the tip vortex core decreases near the pressure surface. This implies that the rolling-up of the tip vortex becomes weak near the pressure surface due to its breakdown. The breakdown of the tip vortex is found to be the spiral type of the breakdown. Moreover, it is clearly observed that the unsteady nature of the tip vortex breakdown causes the unsteady interaction between the tip vortex core and the pressure surface of the adjacent blade. The movement of the leading edge separation vortex (LSV) is much smaller than that of the tip vortex.

It can be understood that an impinging position of the tip vortex on the pressure surface moves around with time, and as a result the onset position of the tip vortex also moves on the rotor tip. The onset position moves in the downstream direction from \( t = 553 \) to \( t = 568 \). At \( t = 571 \), the tip vortex core near the pressure surface disappears due to its breakdown. At the same time, the onset of tip vortex is observed clearly near the suction surface. With time, the tip vortex convects in the tangential direction until \( t = 586 \). At \( t = 589 \), it can be found that the tip vortex structure similar to one at \( t = 553 \) is observed. Like this, the cyclic movement of the tip vortex is also observed at the following time period. The cycle time of the movement is found to be 36 nondimensional time, which corresponds to 0.9 times the blade passing frequency. It should be realized that the cyclic movement of the tip vortex is a self-sustained flow oscillation caused by its breakdown.

Although the movement of the leading edge separation vortex is smaller than that of the tip vortex, the leading edge separation vortex also oscillates cyclically. Its oscillation has a close interaction with that of the tip vortex caused by its breakdown. At \( t = 553 \), the leading edge separation vortex is located close to the suction surface. It goes away from the suction surface while the onset position of the tip vortex moves in the downstream direction from \( t = 553 \) to \( t = 568 \). The leading edge separation vortex has a maximum distance from the suction surface at \( t = 571 \), when the tip vortex core disappears due to its breakdown near the pressure surface. And then, the leading edge separation vortex approaches to the suction surface again. At \( t = 589 \), the leading edge separation vortex is close to the suction surface as shown at \( t = 553 \). The cycle time of the movement of the leading edge separation vortex is also found to be 36 nondimensional times, which is the same cycle as the tip vortex.

The validity of the LES result on the unsteady flow behavior is shown through frequency analyses of fan noise and rotor torque fluctuation. Figure 7 shows a fan noise characteristic measured for the testing configuration, namely, the outdoor unit of room air conditioner with the test fan, heat exchanger, downstream grille, and a driving motor. The frequency is normalized by the blade passing frequency. Noise measurements were carried out in an anechoic chamber where background noise was kept below 18 dB(A). A dominant frequency of 0.9 times the blade passing frequency is distinctly observed in Fig. 7, which corresponds well to the cycle of the tip vortex motion as mentioned above. Figure 8 shows a spectrum analysis of the rotor torque fluctuation obtained by applying a wavelet analysis using the Morlet wavelet to the present LES result. Its power spectrum was determined by a time-averaged absolute modulus of wavelet coefficient of rotor torque fluctuation calculated by LES. In Fig. 8, a dominant frequency of 0.9 times the blade passing frequency is also observed. The experimental and numerical results on the spectrum analyses of the fan noise and the rotor torque, respectively, indicate the same dominant frequency as mentioned above. Needless to say, the variation of rotor torque is caused by a blade loading fluctuation, thus resulting from the pressure fluctuation on the rotor blade. The Blade pressure fluctuation, which has a dipole noise source, is a dominant noise source in the propeller fan operating at low Mach number. From the comparison between the experimental and numerical spectrum analyses of the fan noise and the fan rotor
torque, as shown in Figs. 7 and 8, it can be safely said that the unsteady flow behavior captured by the present LES is reliable.

Effects of Tip Vortex Breakdown on Time-Averaged Flow Field. Figure 9 shows vortex cores colored with the relative velocity magnitude normalized by the rotor tip speed (in left passage) and with the normalized helicity (in right passage) in the flow field averaged from \( r = 500 \) to 800, which is perspective view from shroud. The tip vortex core is clearly seen from the blade suction side to the midpitch, where the tip vortex convects in the tangential direction and has high normalized helicity in spite of the large movement of the tip vortex as shown in Fig. 6. Near the pressure surface, however, tip vortex core disappears because of the vortex breakdown. It should be noted that the disappearance of the tip vortex core corresponds well to the appearance of the rapid change in the normalized helicity for the steady flow simulation result by RANS shown in Part I. In the left passage in Fig. 9 the distribution of the relative velocity magnitude along the tip vortex core indicates that the flow in the tip vortex is decelerated near the midpitch, and then recovered slowly near the pressure surface.

Figure 10 shows time-averaged distributions of the total pressure loss along the vortex cores and on four planes nearly perpendicular to the tip vortex. In the total pressure loss distributions along the vortex cores, the loss production in the tip vortex (TV) is found to become higher near the midpitch (near plane III) where the breakdown of the tip vortex occurs. It is found that the high loss region is spread out to about 30 percent of span from the...
rotor tip. The large spread of the high loss region results from the fact that the large movement of the tip vortex due to the spiral-type breakdown causes its time-averaged structure to expand markedly. It is obvious that the expansion of the time-averaged tip vortex leads to a large blockage effect. The high total pressure loss concentrated around the leading edge separation vortex is decreased gradually in the streamwise direction.

Figure 11 shows time-averaged distributions of the streamwise absolute vorticity along the vortex cores and on the planes, which is presented in the same manner as Fig. 10. The streamwise absolute vorticity in the tip vortex (TV) has a large value near the suction surface and then decreases drastically along the tip vortex, thus being very small near the pressure surface. This corresponds to the fact that the tip vortex structure disappears near the pressure surface. This behavior results from the vortex breakdown. The streamwise absolute vorticity along the leading edge separation vortex core decreases gradually, and is relatively high even near the midchord, because the leading edge separation vortex has no breakdown.

Through the above analysis of the effects of the tip vortex breakdown on the time-averaged flow field, the significant changes are found in the tip vortex behavior near the rotor tip: the drastic decrease in the streamwise vorticity along the vortex core, the large expansion of the vortex and the increase in the loss production along the vortex core.

**Pressure Fluctuation Due to Tip Vortex Breakdown.** Figure 12 shows a distribution of the pressure fluctuation \( P_f \) normalized by a dynamic pressure based on the rotor tip speed, which is defined in Eq. (5). In the figure, purple isosurfaces denote the regions with high-pressure fluctuation of \( P_f = 0.07 \), and the pressure fluctuation on the rotor blade and the hub is shown by color contours. This figure also shows the vortex core structures (colored with the normalized helicity) and limiting streamlines (black lines) on the blade and hub walls for the time-averaged flow field. A large region with high-pressure fluctuation is observed under the tip vortex as shown by PF V in Fig. 12. This pressure fluctuation results from the large movement of the tip vortex caused by its breakdown. It should be realized that the high-pressure fluctuation brought about by the breakdown appears in the interference region between the tip vortex and the main stream. This region corresponds to the high-pressure fluctuation region in the time- and tangentially averaged flow field shown in Fig. 4. The region PF V in the rotor passage extends to regions PF IV and PF VI on the blade surfaces as seen in Fig. 12. High-pressure fluctuation regions PF II and PF III are caused by the oscillations of the leading edge separation vortex (LSV) and the onset of tip vortex (TV), respectively. A pressure fluctuation PF I on the suction surface is generated by a separation bubble on the suction surface near the leading edge.

Figure 13 shows distributions of the pressure fluctuation on the pressure and suction surfaces of the rotor blade. In the figure, the limiting streamlines are also shown by black lines. Outward radial flows caused by centrifugal effect are observed on the blade surfaces. On the suction surface, there is a separation line followed by an attachment line near the blade leading edge, a separation bubble is formed between the separation and attachment lines.

The high-pressure fluctuation region of PF VI is observed near the tip of the pressure surface where the tip vortex impinges cyclically because of its breakdown as shown in Fig. 6. The cyclic interaction of the tip vortex with the pressure surface causes the movement of the onset position of the tip vortex, thus resulting in the high-pressure fluctuation of PF III near the tip of the suction surface. The high-pressure fluctuation region of PF IV located near the trailing edge of the suction surface results from the unsteady interaction between the tip vortex oscillating and the main flow. The high-pressure fluctuation region of PF II is induced by the oscillation of the leading edge separation vortex interacting with the tip vortex. On the other hand, the intensity of the pressure fluctuation PF I in the separation bubble is much weak as compared with those (PF II, III, IV, and VI) caused by the oscillations of the vortex structures. It is found that the oscillations of the vortex structures caused by the breakdown of the tip vortex give rise to the high-pressure fluctuation.

**Conclusions**

The unsteady nature of the vortical flow in the propeller fan has been investigated by the large eddy simulation (LES). As a result, the relation between the pressure fluctuation on the blade surfaces and the unsteady behavior of the vortex structures has been elucidated. The results are summarized as follows:

1. The spiral-type breakdown of the tip vortex occurs near the midchord. It causes the tip vortex to twist and turn violently with time. The effects of the breakdown also cause significant changes in the time-averaged nature of the tip vortex: the drastic decrease in the streamwise vorticity along the vortex core, the large expansion of the vortex and the increase in the loss production along the vortex core.

2. The large and cyclic movement of the tip vortex is the self-sustained flow oscillation due to the vortex breakdown. The movement causes the tip vortex to impinge cyclically on the pressure surface of the adjacent blade, thus resulting in the high-pressure fluctuation near the tip on the pressure surface. The cyclic impingement of the tip vortex gives rise to the movement of the onset position of the tip vortex, leading to the high-pressure fluctuation around the onset position close to the tip of the suction surface.

3. The large movement of the tip vortex caused by its breakdown brings about the high-pressure fluctuation in the interference region between the tip vortex and the main stream. This region extends to the suction surface. The movement of the tip vortex also causes the leading edge separation vortex to oscillate in the same cycle as the tip vortex, leading to the high-pressure fluctuation near the tip in the fore part of the suction surface. However, the scale of the movement of the leading edge separation vortex is much smaller than that of the tip vortex.

4. The unsteady behavior of the tip and leading edge separation vortices dominates the pressure fluctuations in the present propeller fan. The separation bubble on the suction surface near the leading edge causes the lower pressure fluctuation, as compared with the tip and leading edge separation vortices.

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**References**


