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Numerical and experimental investigation on effects of blade tip-rake on vortex structure and aerodynamic noise of axial-flow fans in an outdoor unit of air-conditioners

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ABSTRACT

It is well known that the flow performance, efficiency, and aerodynamic noise of axial-flow fans heavily depend on the gap distance between the fan blade tip and the fan shroud. As the blade tip clearance becomes less, the flow performance increases, and the aerodynamic noise decrease. These results can be attributed to the decrease of tip vortex strength. However, the gap clearance cannot lessen below a certain critical value because of the manufacturing, installation, and operational constraints. Besides, the fan shroud generally covers the fan blade tip partially because of its installation environment. Recently, as an alternative, the tip-rake shape is introduced to solve these issues, which is generally known to weaken the tip vortex strength as the wing tip fence does in the airplane. However, the effectiveness of tip-rake is not apparent because of the additional interaction of tip rake with the fan shroud. In this paper, the effects of blade tip shape on tip vortex structure and aerodynamic noise of a cooling fan, which are used as a cooling fan in an outdoor unit of air-conditioners, are numerically and experimentally investigated. Two types of axial fans are considered: one is with blade tip-rake, and the other is without blade tip-rake. First, the flow field around the fans was predicted by solving the three-dimensional unsteady incompressible RANS equations using computational fluid dynamics techniques. Then, the validity of the numerical results is confirmed by comparing the predicted flow rates with the measured ones. The characteristics of flow field driven by the fans with and without blade tip rake are analyzed in detail, especially with an emphasis on the coherent vortex structure. Finally, the flow performance, efficiency and aerodynamic noise of axial fans are characterized according to the vortex structure whose characteristics are also closely related to blade tip shape as well as the fan shroud.
Keywords: axial-flow fans, tip-rake, tip vortex, shroud-tip vortex, aerodynamic noise, air-conditioner

1. INTRODUCTION

Air conditioners are used to control air quality in a confined space by removing heat and moisture from it. The market demands for air conditioners have continuously increased. The split type air conditioner generally consists of two units: outdoor and indoor units. The performance of the air conditioner is dominantly affected by that of the outdoor unit, which is closely related to the performance of cooling fans as well as of compressors. As the performance of the air conditioner increases, the higher cooling capacity by a fan is required, which in turn requires higher air flow and

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higher rotational fan speed. However, the increase of a fan speed may emphasize the relative importance of aerodynamic noise. The high performance and low noise fans are, therefore, essential for the air-conditioners.

The axial-flow fan is generally used as a cooling fan for the outdoor unit of an air-conditioner. Compared with the centrifugal fan, the flow structure driven by the axial-flow fan is more complex, which implies that the various design parameters are related to high performance and low noise axial-flow fans: airfoil geometry (chamber line, thickness), pitch angle, solidity, tip geometry and so on.

Fukano et al. (1) showed that the ratio of the wake width to the pitch of the blade row was the dominant factor of the turbulent noise. Fukano et al. (2) also showed that the less tip clearance improved the fan performance and reduced the noise level, effectively. Ren et al. (3) investigated the effects of shroud structure designs on a volume flow rate of axial-flow fan system in a machine room by varying its length and showed that there was the optimum length of housing for maximum volume flow rate. Heo et al. (4) improved aerodynamic and aeroacoustic performances of an axial-flow fan unit in the mechanical room of a household refrigerator by modifying its shroud structure without changing the fan blade shape. Zhao et al. (5) investigated the shapes of the tip and trailing edge of axial fan blades to reduce fan noise in an outdoor unit. Jiang et al. (6) investigated the aeroacoustics of an axial fan in an outdoor unit. Fukano's model, combined with typical computational fluid dynamics (CFD) simulation, is used to predict the broadband noise. After the predicted results were compared with the measured data, the distance to blade trailing edge is proposed as an important parameter to improve the accuracy of noise predictions in the Fukano's model. Wright et al. (7) presented the aerodynamic and acoustic properties of axial-flow fans with swept blades based on the theory of Kerschen and Envia for swept cascades. The experimental results confirmed that the swept-bladed fans show noise savings compared to the zero-sweep baseline model. Jin et al. (8) investigated the effect of sweep on the aerodynamic stall limit and aerodynamic noise source. The swept blade was found to be effective in controlling unsteady flow to improve aerodynamic stall limit and reduce noise source in rotors at off-design points. Ye et al. (9) investigated the effects of various tip structures on the flow field, losses distribution, and noise characteristics and improved fan performance by changing the blade tip structure. It was shown that the grooved blade tips improved the efficiency by reducing mixing losses between the leakage flow and mainstream, but increased the fan noise.

These studies showed that the flow performance, efficiency and aerodynamic noise of axial-flow fans heavily depend on the gap clearance between the fan blade tip and the fan shroud; as the gap distance becomes less, the flow performance increases and the aerodynamic noise decrease. These results are generally attributed to the decrease of tip vortex strength. However, it is difficult to decrease the gap clearance without limit because of manufacturing, installation, and operational constraints. Besides, the fan shroud generally cannot cover the fan blade tip fully because of its installation environment. Recently, as an alternative, the tip-rake shape is introduced to solve these issues, which is generally known to weaken the tip vortex strength as the wing tip fence does in the airplane (10). Representatively, winglet developed by Richard T. Whitcomb (11) has been used in an aircraft to reduce drag and to save fuel and cost. Also, in a marine propulsion system, the KAPPEL propeller using the tip rake was developed to increase efficiency (12).

However, the effectiveness of tip-rake is not clear because of the inevitable interaction of tip rake with the fan shroud. In this paper, the effects of blade tip shape on tip vortex structure, flow performance, efficiency and aerodynamic noise of a cooling fan, which are used as a cooling fan in an outdoor unit of air-conditioners, are numerically and experimentally investigated. Two types of axial fans are considered: one is with blade tip-rake, and the other is without blade tip-rake. First, the flow field around the fans was predicted by solving the three-dimensional unsteady incompressible RANS equations using computational fluid dynamics techniques. Then, the validity of the numerical results is confirmed by comparing the predicted flow rates with the measured ones. The characteristics of flow field driven by the fans with and without blade tip rake are analyzed in detail, especially with an emphasis on the coherent vortex structure. Finally, the flow performance, efficiency and aerodynamic noise of axial fans are characterized according to the vortex structure whose characteristics are also closely related to blade tip shape as well as the fan shroud.

2. TARGET AXIAL-FLOW FANS

The two types of axial fans considered in this study are shown in Fig. 1: one is with blade tip-rake (Model A), and the other is without blade tip-rake (Model B). These fans are used as cooling fans for an outdoor unit of split-type air-conditioners. The tip shapes between two fans are compared in detail at the three cross-sectional planes of constant azimuthal angles that are denoted by the circled numbers ①, ②, and ③ in Figs. 1 and 2.

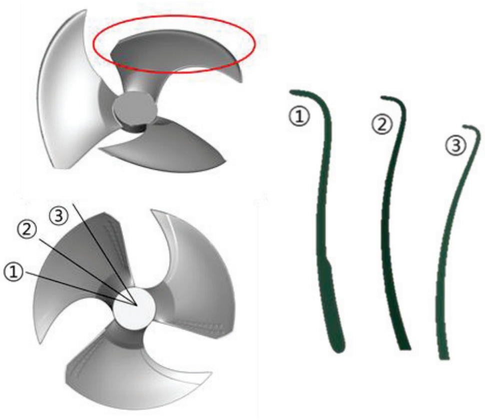


Figure 1 – Model A

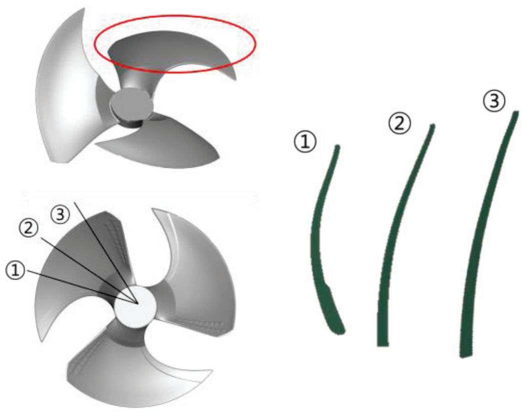


Figure 2 – Model B

3. GOVERNING EQUATIONS AND NUMERICAL METHODS

To predict the flow performance of the target blades, the following three-dimensional incompressible unsteady Reynolds-Averaged Navier-Stokes (RANS) equations are used as the governing equations:

$$\frac{\partial}{\partial x_j}(u_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(u_i) + \frac{\partial}{\partial x_j}(u_j u_i) = -\frac{1}{\rho_0}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \overline{u_j' u_i'}\right) \tag{2}$$

Eqs. (1) and (2) are numerically solved using the finite volume method based on the unstructured meshes. The k-ε RNG turbulence model is used as a closer. Numerical computations are realized using the ANSYS FLUENT. For more detailed numerical schemes used in this study, the studies (3,4) can be referred to.

4. NUMERICAL RESULTS AND DISCUSSION

4.1 Validation of numerical methods

The virtual fan performance tester is designed, as shown in Figure 3, to investigate the detailed characteristics of the flow field driven by axial fans. The rectangular ducts are set on upstream and downstream of the axial-flow fan. To simulate the experimental conditions of actual fan performance tester and thus to predict the P-Q curve of the target fan unit, the pressure difference between inlet and outlet boundary are varied.

The numerical results predicted using the virtual fan performance tester are compared with the measured one using the actual fan performance tester, which satisfies the regulations of AMCA 210-07. To improve measurement accuracy, a large chamber of 600(W)×600(D) ×1500(L) mm, five different-sized nozzles and two screens were installed. The more detailed information about the fan performance tester was provided in the preceding studies (3,4).

Figure 4 shows a comparison between two results for Model A. It is seen that the range of relative error in the volume flow rate for the two fixed pressure differences at two rotational speeds spans between 0.6% and 6.6%. This result confirms the validity of the current numerical method.

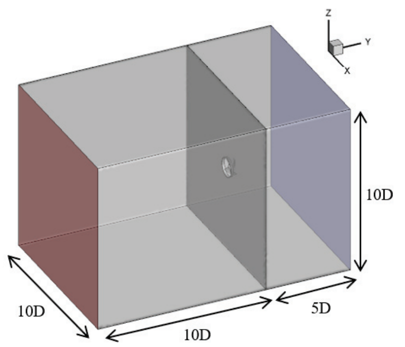


Figure 3 – Computational domain for virtual fan performance tester

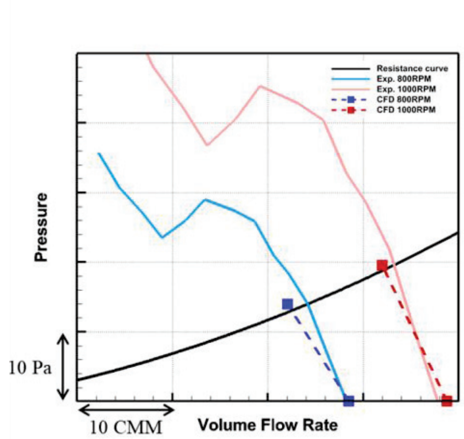


Figure 4 – Comparison of predicted volume flow rate at a given pressure difference with measured P-Q curves

4.2 Detailed flow field analysis

The predicted flow fields driven by the target fans are investigated in detail to assess the effects of blade tip rake on the flow structure. Figure 5 shows the snapshots of the velocity vectors near the blade tip on the horizontal cross-sectional plane passing the rotating center of the fan. It can be seen that the tip vortex around Model B is stronger than Model A. This result confirm that the blade tip-rake geometry reduces the tip vortex strength. Further analysis is carried out to identify the detailed vortex structure around the tip and to assess the vortex strength quantitatively.

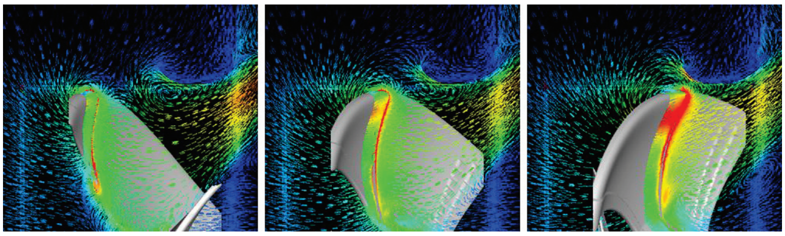


Figure 5 (a) – Model A

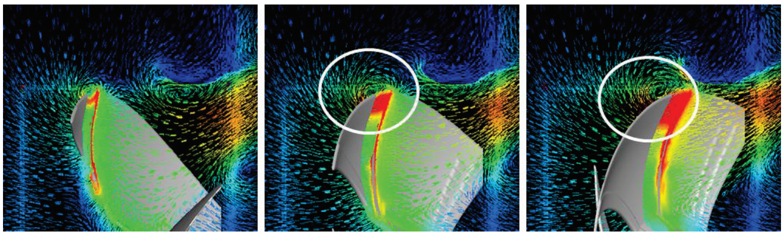
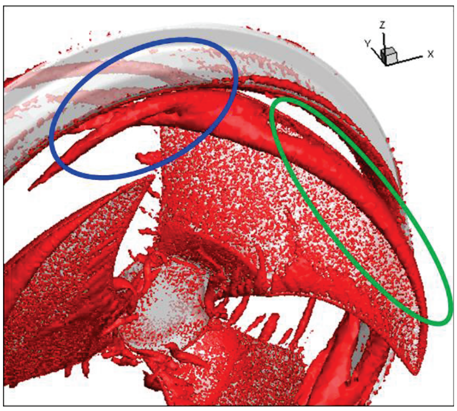
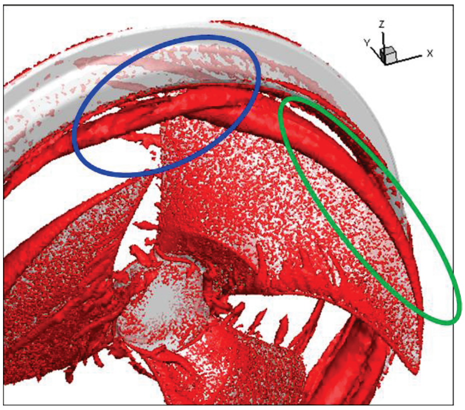


Figure 5 (b) – Model B

To identify the coherent vortex structure, Q-criterion is used as a vortex-identification criterion. Figure 6 shows the iso-contours of Q-criterion between the blade tip and the fan shroud for the two models. Two different large coherent vortex structures can be found in both models: one is well-known blade tip vortex, and the other is shroud-tip vortex which is formed along with the shroud in the tip clearance region. The blade tip vortex is generated from the leading edge, develops along with the chord of the blade tip, and interacts with the shroud-tip vortex in the gap region between the blade tip and the blade shroud. For a more quantitative comparison of vortex strength between two models, the pressure distribution around the vortex core is compared in Figure 7. It can be seen that the minimum pressure at the center of vortex core of Model B is lower than that of Model A. This implies that the stronger tip vortex forms in the flow driven by the fan of Model B. However, the pressure distributions in the gap region between the blade tip and the fan shroud are similar in two models, which means that the tip-shroud vortex is not affected by the tip rake. Figure 7 also compares the surface pressure distribution of the fan blades where the stronger tip vortex shadow can be identified in Model B than in Model A. From the fact that the surface pressure fluctuations play a role of dipole sources for aerodynamic noise, it can be inferred that the aerodynamic noise of Model B is higher than that of Model A. The averaged thrust and torque of a fan blade are computed as overall flow performance index and are listed in Table 1. Model B shows higher thrust and torque than Model A. From the fact that the thrust is directly related to the volume flow rate and the torque is related to the energy consumption, it can be expected that the volume flow rate of Model B is higher than Model A, but the efficiency of Model B is lower than Model A.

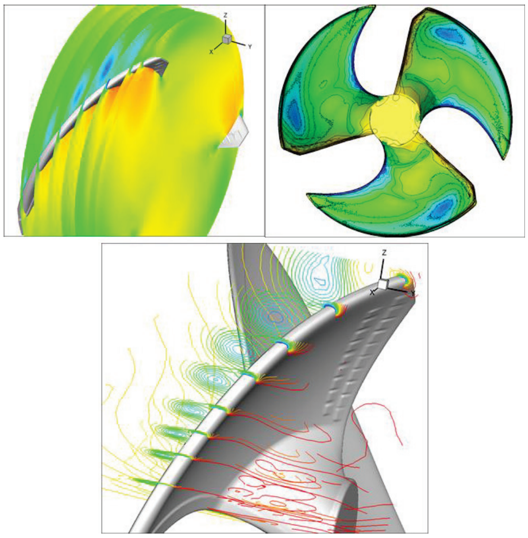


(a) – Model A

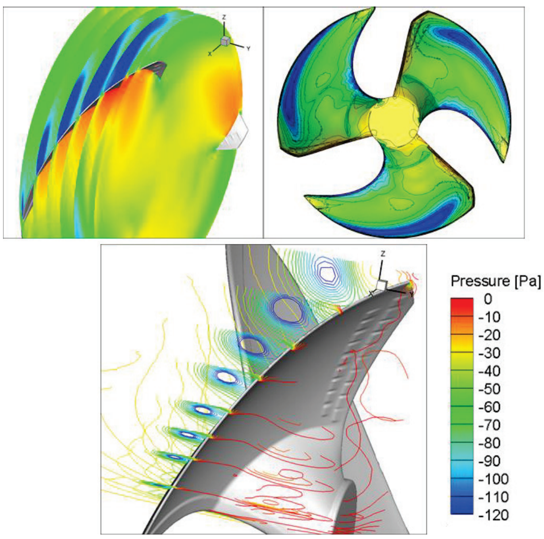


(b) – Model B

Figure 6. Iso-contours of Q criterion (Green: Tip vortex /Blue: Tip-shroud vortex)



Model A



(b) – Model B

Figure 7. Comparison of pressure distributions between two models

Table 1 – Comparison of thrust and torque between two models

Model	Thrust	Torque
A	α	β
B	1.11α	$1.13\ \beta$

5. EXPERIMENTAL ANALYSIS

To confirm the numerical results, the proto-types of Model A and Model B were manufactured, and their performances are experimentally evaluated. The results are shown in Figure 8. The volume flow rate, the sound pressure level, and the power consumption of Model A are lower than Model B. These results closely follow the numerical results presented in Section 4.

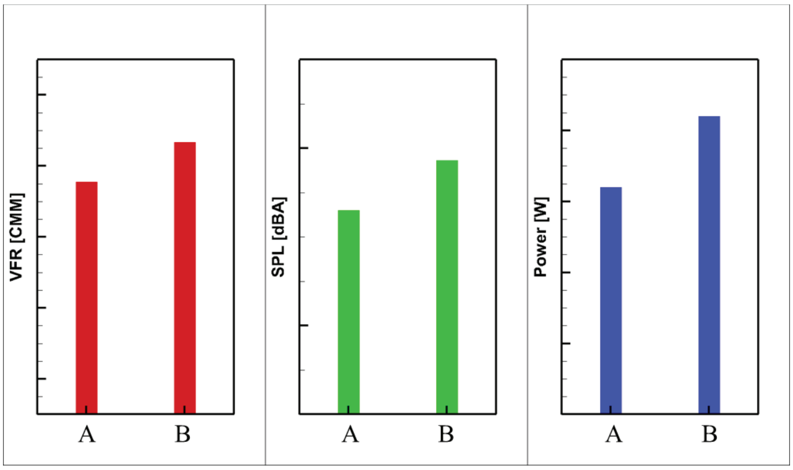


Figure 7 – Experimental results

6. CONCLUSIONS

In this study, the flow performance, efficiency, and noise of the axial fans used in the outdoor unit of the split-type air-conditioner were numerically and experimentally investigated with emphasis on the effects of blade tip-rake in association with the fan shroud. Two types of fans were considered: Model A is with tip-rake, and Model B is without tip-rake. The blade tip vortex and the shroud-tip vortex were found as the most massive coherent vortex structure in the flow driven by both fans. As expected, the strength of tip vortex was weakened by the use of blade tip rake, but the strength of shroud-tip vortex was similar in both models. The latter fact implies that the role of blade tip-rake is not effective in the blade tip clearance region between the blade tip and the fan shroud. Although the volume flow rate of Model B was higher than the Model A, the aerodynamic noise and the power consumption of Model A are lower than Model B. All of these results are confirmed by the measured data obtained from the prototypes.

This study showed that the shape of the blade tip rake located in the blade tip clearance region needs to be optimized to more improve the performance of the axial fan, which will be investigated in the next study.

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