THE NOISE PREDICTION OF AUTOMOTIVE AXIAL FAN WITH DIFFERENT BLADE SWEEP ANGLE USING THE UNSTEADY CFD ANALYSIS

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SUMMARY

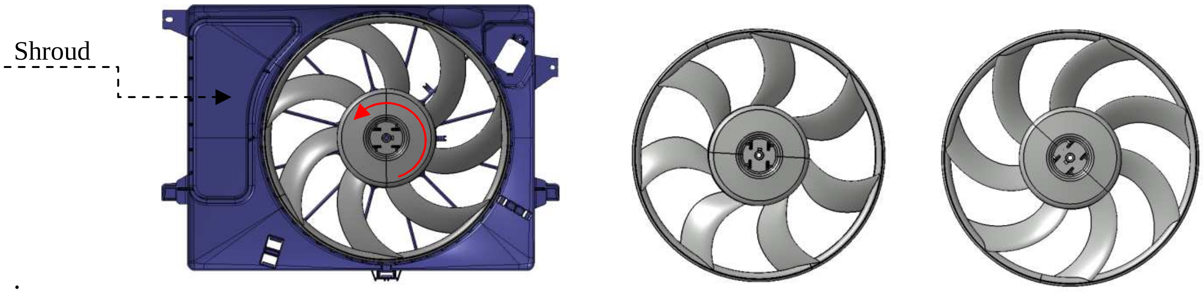
This study was conducted on automotive axial fans with the three types of swept blades: forward, backward and straight, using the three dimensional unsteady CFD analysis. The acoustic analogy by the Ffowcs Williams-Hawkings was used to predict the sound propagation in the far-field. The unsteady RANS and SST turbulence models were used for the CFD analysis. The predicted results were validated with the following experiments. The three fans with different sweep angles showed quite different performance and noise levels. Especially the overall noise of the forward swept fan showed 4 to 5 dB(A) which was lower than the straight blade and backward swept fans' at the same rotation speed. The main purpose of this study is to explain what causes the differences in performance and noise level in terms of flow characteristics, and how the sweep angle of blade affects the overall fan noise level. The corresponding setup in the CFD analysis and experiments include just cooling fans and shroud without heat exchangers.

INTRODUCTION

An automotive cooling fan is an important part in the engine room of a vehicle. By putting air through heat exchangers, it plays the key role cooling a hot engine and condensing a refrigerant for an A/C system. For this reason a number of studies have been carried out for design parameters of the axial fans to improve performance and efficiency. To do this, the prediction and optimization by using the CFD analysis have been generalized. Recently, the noise from the axial fan is becoming more and more an important factor as well as its performance. Therefore, the effort to predict a fan noise and apply the predicted result to a fan design has been done for a long time. However, predicting the noise for rotating parts such as an axial fan with an unsteady load essentially needs the 3D unsteady CFD analysis(1) and there are few analysis cases because it also would require a huge amount of computing resources and time. T. Wright and W.E. Simmons(2) explained that the sweep angle of axial fan have an important effect on efficiency and noise. Katsuhisa and Sadao(3) showed that the forward swept blade reduced the noise at the trailing edge of the blade. In this study, the 3D unsteady state CFD analysis for the three kinds of fans with different sweep, forward, backward and straight, have been carried out and tried to explain the relation between the unsteady flow characteristics and noise level. The prototype used for the analysis was made and the experiments and the CFD results were compared to validate the reliability of the prediction.

FANS

Fans used for the analysis have the diameter D=390mm, 7 blades and three different sweep angles**:** forward 45°, straight 0° and backward 45°. Each fan was set up with shroud and driven by a DC motor. All the fan blade**s** have the same design parameters such as setting angle, chord length, camber value and maximum camber position. The range of working rpm is 1800 to 1860, and the range of airflow rate is 3,000 to 3,200 m^3/h at the 12V with no resistance.



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(a) (b) (c)

Fig.1 Fans with different sweep angles

Fig.1 shows that the fans' blades have with the three different sweep angles. The (a) fan has the forward sweep angle of 45°, the (b) fan has the sweep angle of 0° and the (c) fan has the backward sweep angle of 45°. Fig.2 defines the sweep angle in this paper.

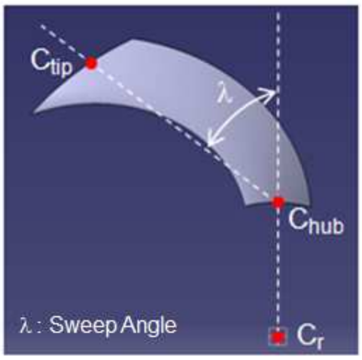
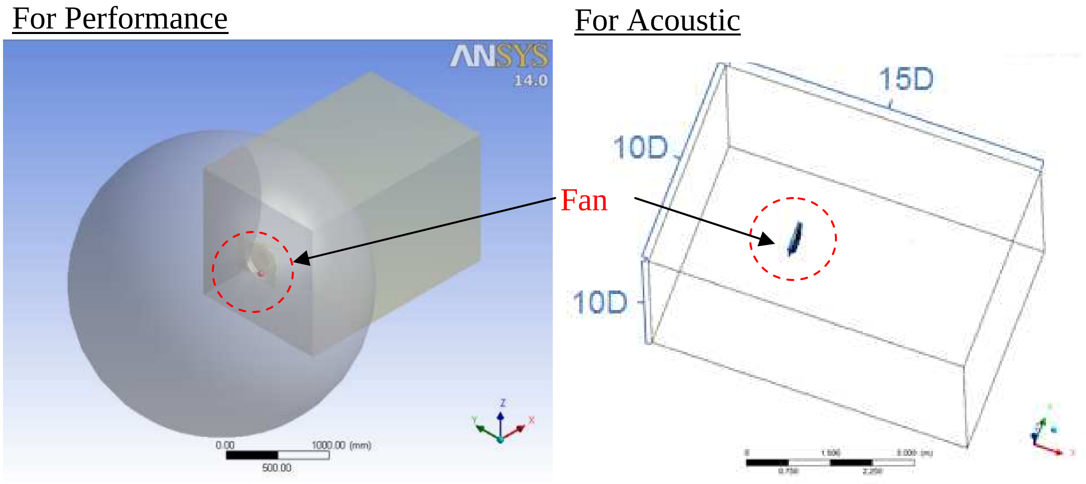


Fig.2 Definition of sweep angle

NUMERICAL ANALSIS

Computational Domains are illustrated in Fig.3. The domain for performance prediction, airflow rate and power consumption, consists of stationary and rotating volumes including fan and far field inlet volumes. The multiple reference frame method was used for the steady state analysis. The domain for the acoustic analysis and the unsteady state CFD is differently modeled to describe open space similar to the noise measurement environment. A sliding mesh was used for the unsteady state analysis. The unsteady RANS model and SST (Shear Stress Transport) model were used. The inlet and outlet were defined as an opening condition. Time step was defined considering 1 degree rotation per time step. All unsteady results were gathered after the 2nd revolution of fan. The CFD code used for this analysis is CFX.


For Performance

For Acoustic

Fig. 3 Computational domain

Table 1 indicates the data of mesh generated for the steady state analysis. The total number of elements reaches about 18 million. The generated mesh is hybrid, including tetrahedral elements and prism elements for boundary layer on the blade surfaces. The mesh for the unsteady state analysis is basically not much different from the mesh of the steady state analysis.

Table 1 Number of mesh generated

	Total	Rotating	Stationary	Far field inlet
Nodes	5,205,297	2,281,802	2,712,505	210,990
Elements	18,295,581	7,776,917	9,338,539	1,180,125

EXPERIMENT

The validation for the steady state CFD result was conducted before the acoustic analysis. Fig.4 shows the comparison of the mass flow rate which fan generated between the CFD and test. It shows that they are in a good agreement. The differences between them are -3.7 % to 2.5 %. The backward swept blade fan generates about 8 % more mass flow than the forward swept blade fan with no resistance condition of P-Q test. The measurement of noise was performed in the anechoic wind tunnel. The noise level of the fans was measured at the three positions where microphones were placed 1 m away from the center of the hub.

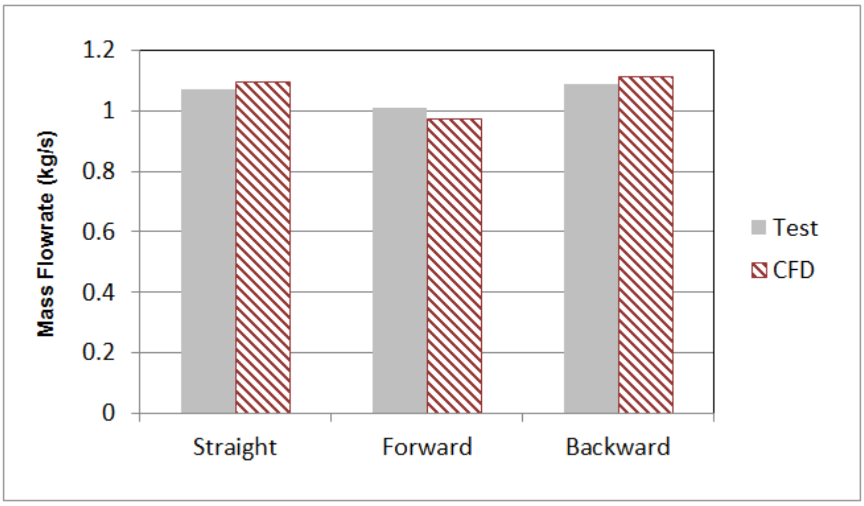


Fig.4 Comparison of massflow rate

Fig.5 illustrated the positions of the microphones for the noise measurement. By changing of the fan RPM from 1,500 to 2,000, the noise level at the three positions: observer1, observer2, and observer3 was measured simultaneously for the three types of fans.

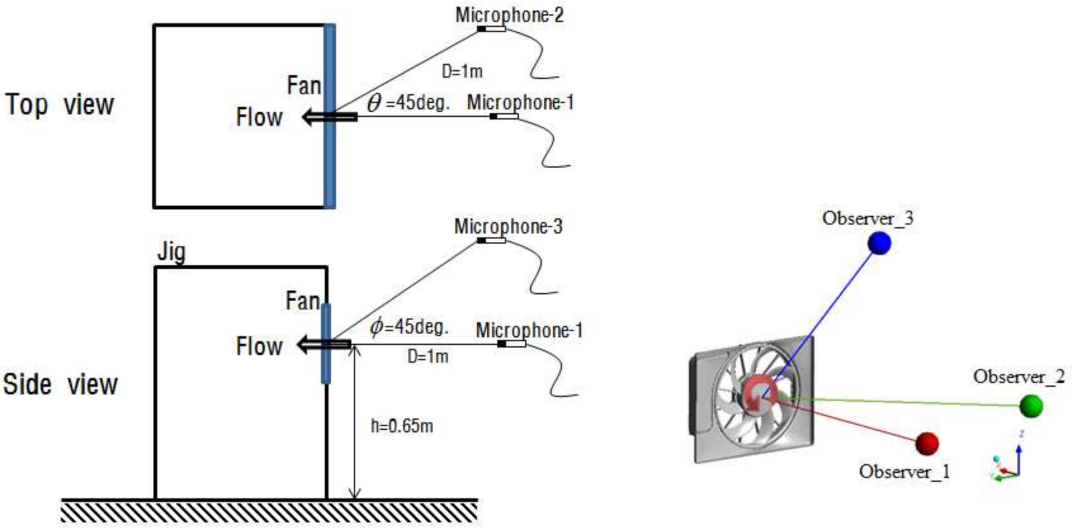


Fig.5 The position of microphones

The forward swept blade fan indicates 5 dB(A) lower noise level and the backward swept blade fan shows 1 dB(A) lower noise level than the straight blade fan at the same RPM as illustrated in Fig.6. The noise level at the three observer's positions is shown in Figure 7. It shows the noise level at the observer 1 position is the largest for all the fans.

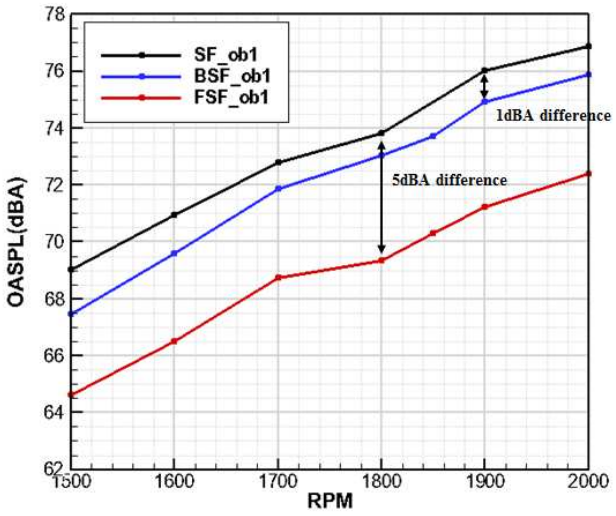


Fig.6 Noise level of fans at the observer 1 position

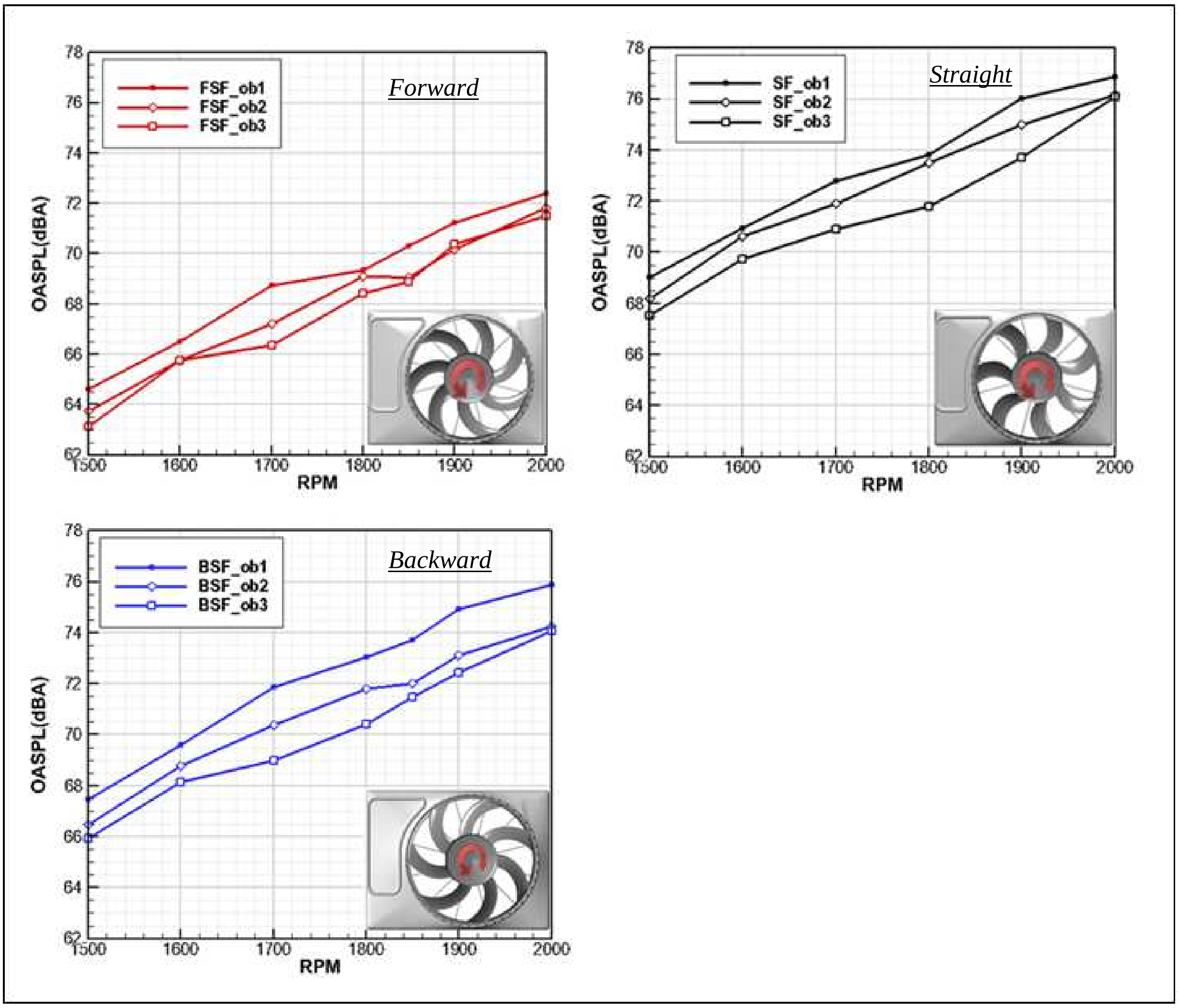


Fig.7 Noise level at the different observer position

ACOUSTIC ANALYSIS

The acoustic analogy was employed for the acoustic simulation. The acoustic source induced by flow was calculated through the unsteady CFD analysis. After that acoustic propagation to the microphone was calculated by using the in-house code based on the following the Ffowcs Williams-Hawkings equation.

$$
\begin{aligned}
\rho(\vec{x},t) = {} & \frac{1}{4\pi a_0^2} \frac{\partial^2}{\partial x_i \partial x_j} \int_V \left[\frac{T_{ij}}{r\,|1-M_r\,|} \right] dV(\vec{y}) && : \textit{quadrupole} \\
& - \frac{1}{4\pi a_0^2} \frac{\partial}{\partial x_i} \int_S \left[\frac{P_{ij} n_j}{r\,|1-M_r\,|} \right] dS(\vec{y}) && : \textit{dipole} \qquad (1) \\
& + \frac{1}{4\pi a_0^2} \frac{\partial}{\partial t} \int_S \left[\frac{\rho u_i n_i}{r\,|1-M_r\,|} \right] dS(\vec{y}) && : \textit{monopole}
\end{aligned}
$$

The equation consists of three terms of source: quadrupole, dipole and monopole. The quadrupole source is caused by the turbulence flow such as wake from the trailing edge of blade or vortex separation on the surface of the blade. The dipole is caused by steady and unsteady loads with the pressure fluctuation on the blade surface. The monopole source is named thickness noise and caused by the displacement of the air by a solid body. Generally the dipole is known as the dominant source in the automotive fan noise.

RESULT

Fig. 8 illustrates the comparison result of the overall noise level between the numerical analysis and measurements. Both of them reveal that the forward swept fan generates the lowest noise level. The overall numerical analysis indicates a good agreement with the experiment. If the ground effect is considered, it shows a better agreement with the experiment. The RPM of fans are from the P-Q test and corresponds to the RPM when a static pressure is a zero condition. Fig. 9, Fig.10 and Fig.11 shows the comparison result of the SPL distribution between the numerical analysis and the measurements. All the cases show the good agreements with the experiments except the broadband noise and some of other noise source such as a DC motor. It confirms that the 1st BPF, 2nd BPF and 3rd BPF were predicted quite accurately. Fig. 12 demonstrates the effect on fan noise by the unsteady and steady loads. It confirms the unsteady load is dominant on fan noise which also means the unsteady CFD analysis is essential to understand the flow induced fan noise mechanism. Fig. 13 is about the vorticity distribution of the fans. It shows the backward swept fan has bigger vorticity than the forward swept fan around the blade tip. Fig. 14 illustrates the flow directions by streamline through the fan blade. It suggests the flow on the backward swept blade is more concentrated toward the blade tip compared with the flow on the forward swept blade. It can be explained that this flow characteristic makes bigger vorticity and higher noise. Fig.15 shows the dp/dt (pressure fluctuation) distribution. It also points out the backward swept fan has bigger dp/dt distribution around the blade tip than the forward swept fan. It can be concluded that the backward swept blade makes the concentrated flow toward blade tip and it generates bigger vorticity, pressure fluctuation around the blade tip and it makes the fan much noisy.

CONCLUSION

The unsteady CFD analysis by using the RANS model and the acoustic analogy based on the Ffowcs Williams-Hawkings equation are used for predicting the noise of the fans which have different sweep angles: forward, backward and straight.

Through the comparison of the analysis and measurements, it indicates that the methodology in this study predicts fan noise quite accurately and needs different approach to predict broadband noise more precisely. It is expected that this method will be a very useful tool for predicting fan noise in prior to making a real prototype to evaluate its noise level.

Both of the numerical analysis and the measurements demonstrate that the backward swept fan generates higher noise than the forward swept fan. In terms of the flow characteristics and the unsteady CFD results show that the backward swept blade makes flow more concentrated on the blade tip and generates bigger vorticity, higher pressure fluctuation around it. The higher noise level of the backward swept fan can be explained by these flow characteristics.

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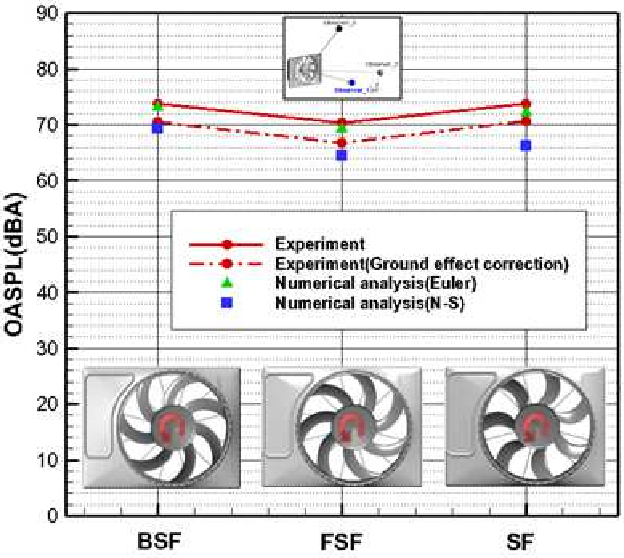


Fig.8 Comparison of noise level between numerical analysis and experiment

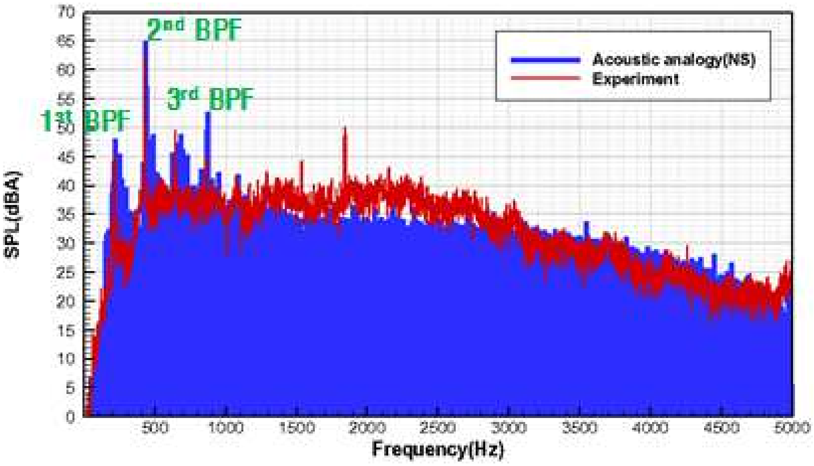


Fig. 9 Comparison of SPL between numerical analysis and experiment for backward swept fan

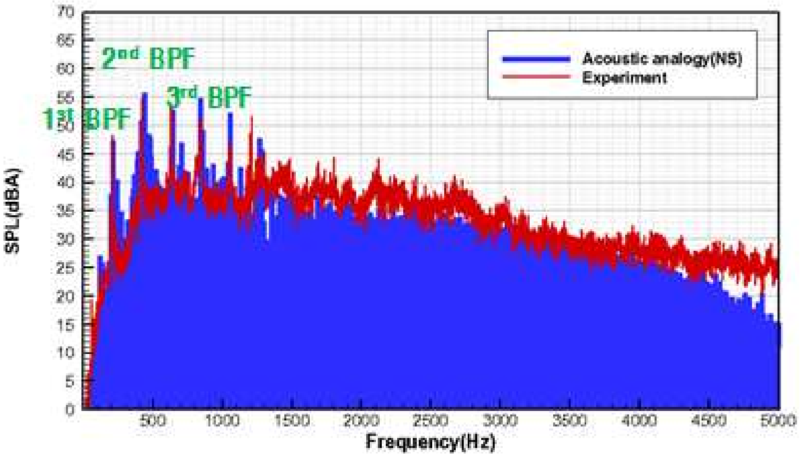


Fig. 10 Comparison of SPL between numerical analysis and experiment for forward swept fan

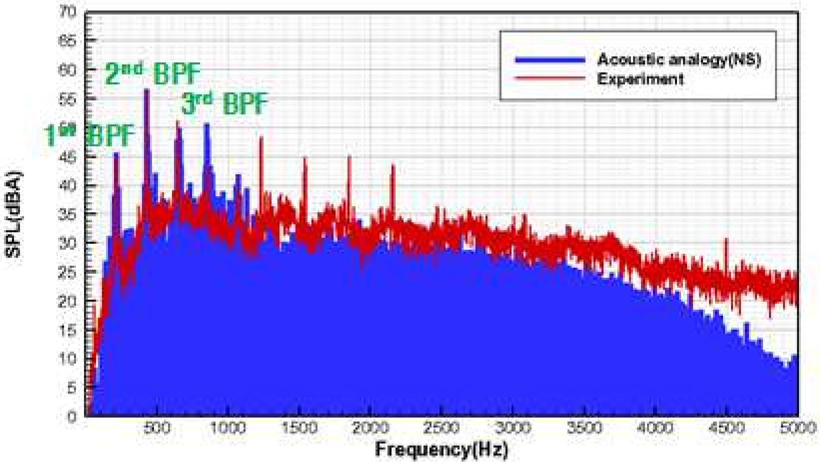


Fig. 11 Comparison of SPL between numerical analysis and experiment for straight fan

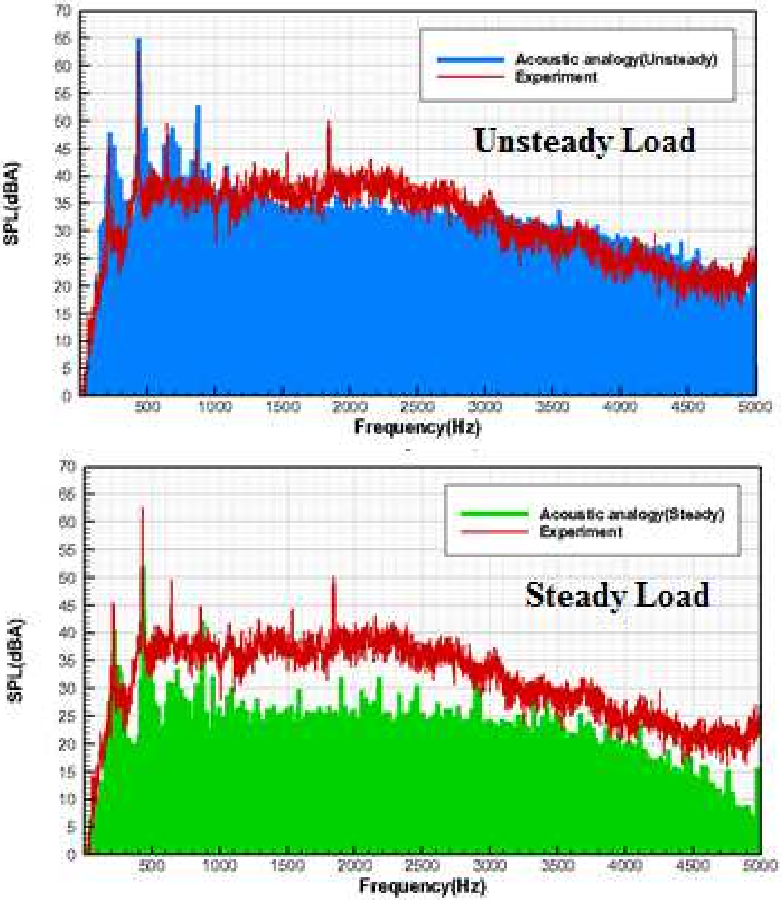
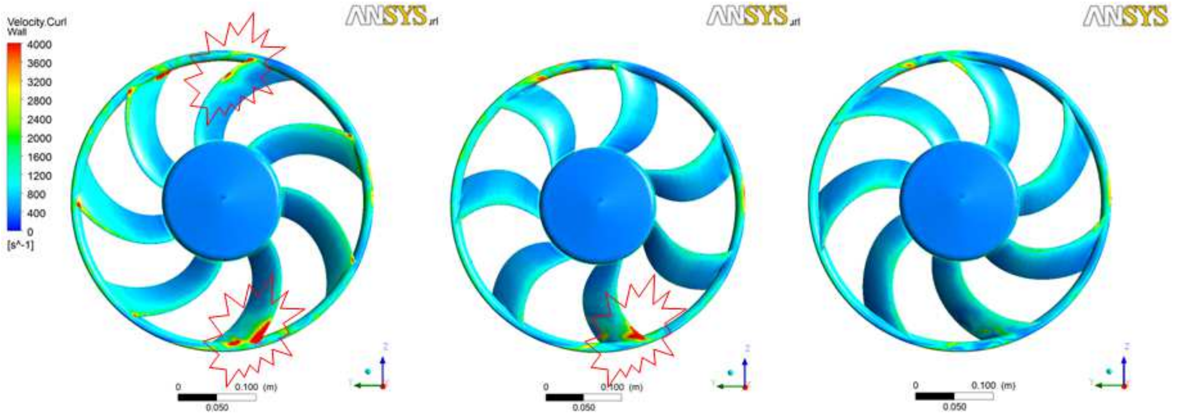
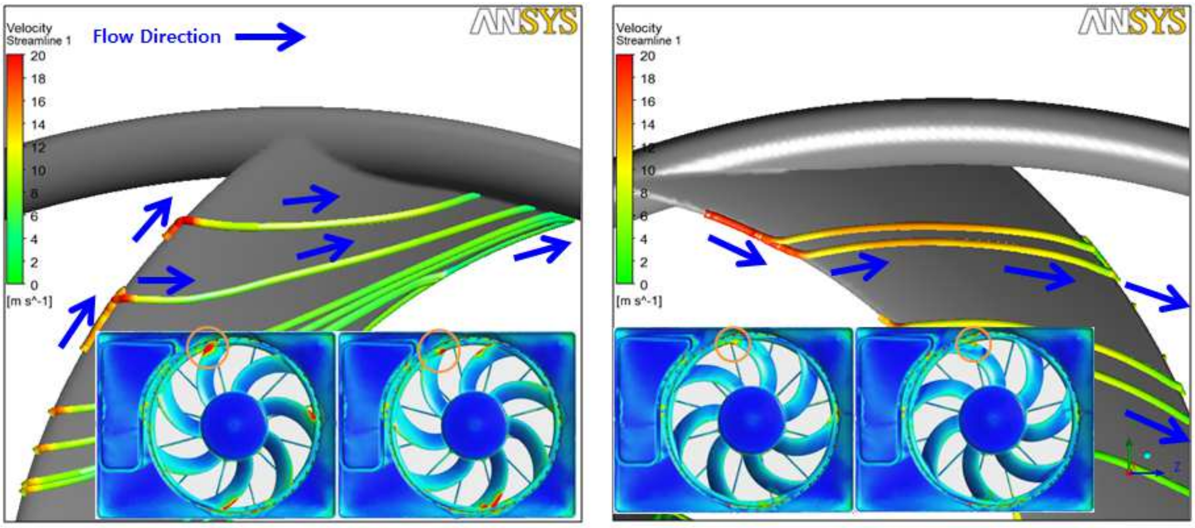


Fig.12 Acoustic effect by unsteady and steady load



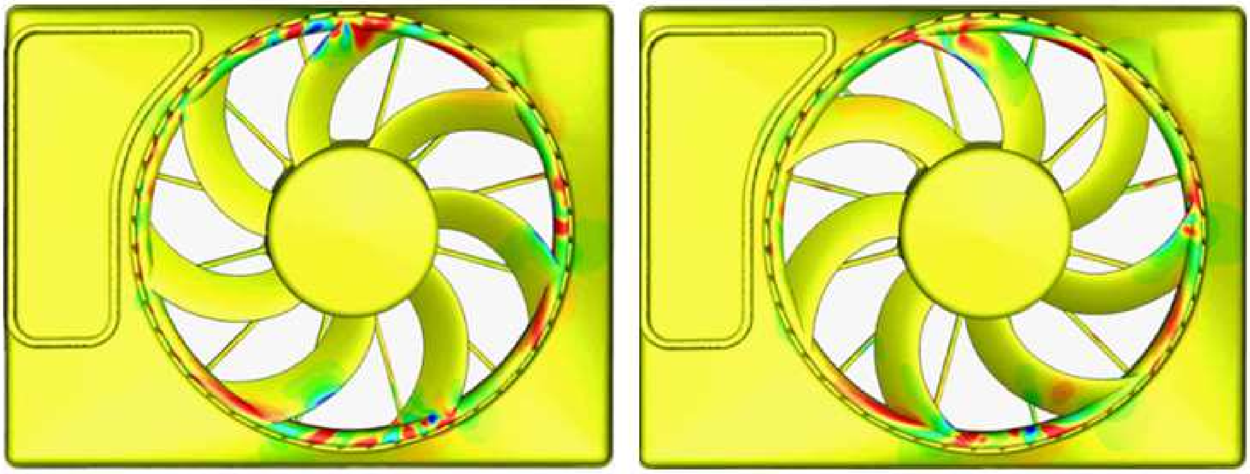
BSF SF FSF

Fig.13 Vorticity distribution of fans



Backward Swept Fan(BSF) Forward Swept Fan(FSF)

Fig.14 Velocity streamline of backward and forward swept fans



Backward Swept Fan(BSF) Forward Swept Fan(FSF)

Fig. 15 dp/dt distribution of backward and forward fans