NOISE GENERATION MECHANISM AND NOISE REDUCTION DESIGN ON BI-DIRECTIONAL RADIAL FAN

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SUMMARY

The bi-directional radial fan with the blade provided to the radial direction is used for cooling of the electric motor which rotates in both directions. Increase of the fan noise at a high rotation speed becomes a problem. But it isn't known where the fan noise source is, the suitable blade shape for the bi-directional radial fan has not be found yet. In this paper, the position of the fan noise source is calculated using Computational Aero-Acoustics (CAA), blade shapes which enable fan noise reduction were proposed. The effect was confirmed through the experiment, bi-directional radial fan shape which enables maintaining airflow rate and reducing fan noise could be created.

NOMENCLATURE

BPF	Blade Passing Frequency	CAA	Computational Aero Acoustics
CAD	Computer Aided Design	CFD	Computational Fluid Dynamics
d	fan diameter	DES	Detached Eddy Simulation
M	Mach number	Re	Reynolds number
SPL	Sound Pressure Level	SST	Shear Stress Transport

INTRODUCTION

Motor which rotates both clockwise and counterclockwise is used for traction motor of the train, traction motor of the elevator and industrial motor. Bi-directional radial fan is applied to these motors so that the same cooling capability can be obtained whichever direction it rotates. Wind is sucked from inner circumference side of the fan, and its direction is changed by 90 degrees by a main plate. Since the bi-directional radial fan generates vorticity by shearing the air at the edge of the blade, it generates the broadband noise. On the other hand, in the axial fan, the turbofan, and the sirocco fan, the fan noise source is specified and low noise fan shape is proposed by various analyses [1-3]. Since the rotation direction is specified, the optimal blade shape is investigated and generation of vorticity is suppressed. In contrast, there is little research on the bi-directional radial fan, it is not specified where are the main sound sources. Conventionally, the various blades were manufactured and the low noise fan blade was qualitatively chosen by the experiment [4]. Although Computational Aero-Acoustics (CAA) is commonly used in recent years, it is not yet concretely clear what kind of flow caused fan noise generated by the bi-directional radial fan.

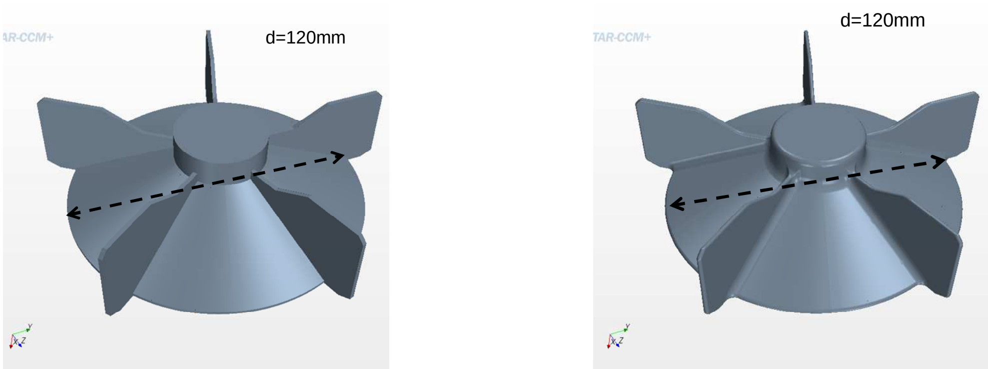
In this paper, the separation of flow which is the feature of the flow generated by the bi-directional radial fan was focused on, the effect of the rounded edge which controls separation of flow was confirmed by CAA and measurement. Furthermore, the influence of the blade inner circumference side which is acquired as a new knowledge was compared by using five kinds of blade, and the relation between airflow rate and sound pressure level (SPL) was estimated by analysis. As a result, it was able to clarify the fan shape by which SPL can be reduced while maintaining the airflow rate. This paper introduces the noise generation mechanism and presents low noise blade shape of the bi-directional radial fan.

Figure 1: Bi-directional radial fan of the industrial motor (without fan cover)

INVESTIGATION OF THE NOISE SOURCE

Analytical objects and analytical conditions

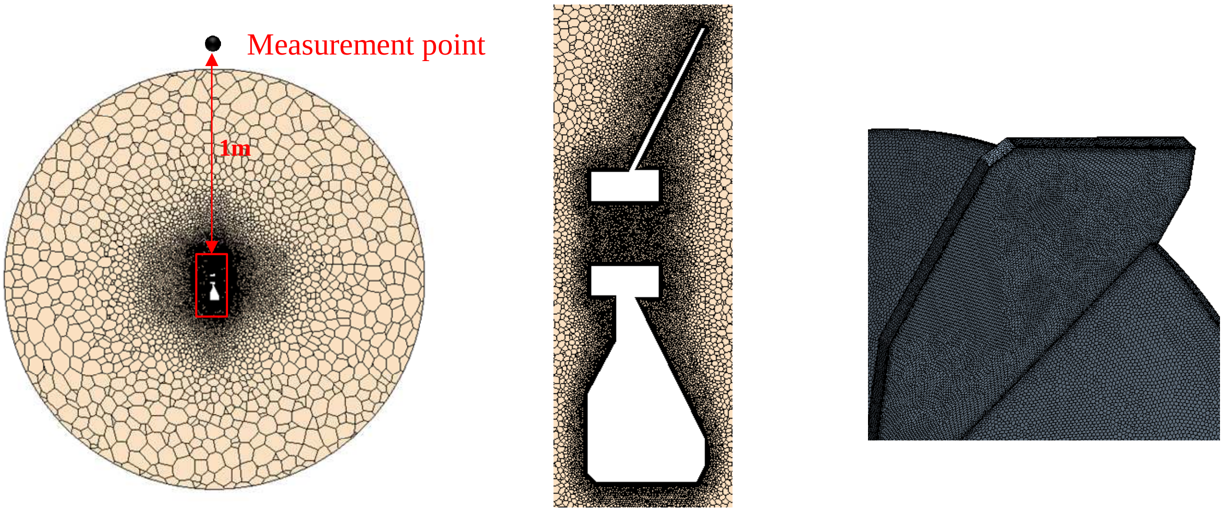
In order to investigate about the separation of flow which is the feature of the bi-directional radial fan, the fan used by the industrial motor was analyzed. The fan models are shown in Fig. 2. Since vorticity which generates by the separation of flow at the blade edge is the noise source, the blade with rounded edge is compared with the one without rounded. The fan made of resin with the five blade used so far was the analytical fan model. The diameter of the main plate which supports a fan blade is 120 mm.



Without rounded With rounded

Figure 2: Alalytical (fan model)

A CAA model is shown in Fig. 3. The sphere of radius of 900 mm was the analysis area, so the flow or pressure of the circumference of the fan is not influenced by the boundary. Since a pressure boundary has influence of reflective in this case, the no reflection boundary is used there. Furthermore, the surface mesh of the fan is subdivided into 0.5 mm cell size in order to analyze the minute fluctuating pressure. Thereby the Y+ on the fan surface is set to five or less, it was confirmed that mesh division is sufficient for acoustic analysis. The numbers of mesh element is about 7 million.



Analysis area Detail of the mesh near the fan Surface mesh of the fan

Figure 3: CAA model for bi-directional radial fan

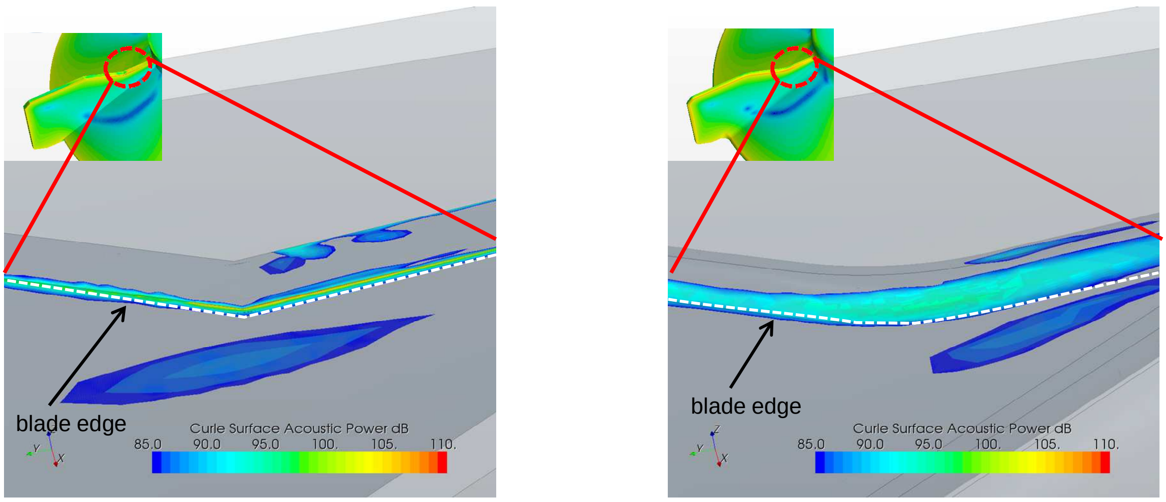
Next, the analysis methods used by acoustic analysis are shown in Table 1. The commercial flow code star-ccm+ ver8.04 is used for aero-acoustic analysis based on Lighthill theory [5, 6]. As acoustic model, dipole sound source is calculated by Curle analogy [7], quadrupole sound source is calculated by Proudman analogy [8] for steady state analysis, and sound propagation is calculated by Ffowcs William-Hawkings analogy [9] for unsteady analysis. Since rotation speed is 1800 rpm and the number of blade is five, blade passing frequency (BPF) is $1800/60\times5=150\,Hz$. At 1800rpm, the fan peripheral speed is $\pi\times0.12\times1800/60=11.3\,m/s$, and a Mach number is $M=11.3/340\approx0.03$. If the representative speed is defined by peripheral speed of the fan and representative length is defined by diameter of the one, Reynolds number is about $\mathrm{Re}=11.3\times0.12/1.55\times10^{-4}\approx1\times10^{4}$. The turbulence model used for unsteady analysis is k-omega SST for detached eddy simulation (DES) [10]. The same turbulence model is used for steady analysis so that those are correlated respectively. In the wall function, all y+ treatment which is expressed with one function from viscous sublayer to turbulent boundary layer is used [11]. In order to treat acoustic generation, ideal gas which is considered compressibility is treated. The time step in unsteady simulation is set to 2.0×10^{-5} in consideration of the less than one in courant number. The calculated frequency range is set less than 5000 Hz taking into account the analysis result of the past experimental data.

Table 1: analysis methods

Analytical method	Steady	Unsteady
Acoustic model	Curle (dipole), Proudman (quadrupole) analogy	Ffowcs William-Hawkings analogy
Rotation speed [rpm]	1800	
Blade passing frequency [Hz]	150	
Turbulence model	$k-\omega$ SST	DES (RANS : $k-\omega$ SST)
Wall treatment	All y+ treatment	
Fluid property	Ideal gas (compressible)	
Time clause	N/A	Second order
Convection term scheme	Second order	Second order
Time step [s]	N/A	2.0×10^{-5}
Estimate frequency [Hz]	Less than 5000	
Number of mesh	About 7 million	

Analysis results

The dipole sound sources (Curle) on the edge of the blade root are shown in Fig. 4. The range to display is set to 85~110 (dB) in order to make visible the dipole sound sources which generates on the corner of the blade. Although the dipole sound source has generated at the blade edge without rounded, it has spread on the rounded part of the blade with rounded, and peak value of the dipole sound source is reduced.



Without rounded With rounded

Figure 4: Dipole sound sources of the blade edge

In order to analyze the generation part of the dipole sound source in detail, the one along the edge line on the blade was compared on the graph. Dipole sound source comparison on the blade edge is shown in Fig. 5. The position on the blade is standardized from 0 to 1.

The value with rounded is lower than the one without rounded near the root of the blade. The maximum value of 82 dB is seen in the root portion of the blade without rounded. Since wind is sheared by the blade when it flows to between blades from axial direction, the root of the blade is the part which noise tends to generate. On the other hand, the value without rounded is lower than those with rounded near the periphery of the blade. This is because the flow direction of the wind is the radial direction in this part, so the flow is not disturbed rather than the one with rounded.

There is the maximum value of the blade without rounded, so the noise reduction effect in the one with rounded is confirmed. Moreover, it turned out that the noise sources are the edge of the blade, especially the root of the one.

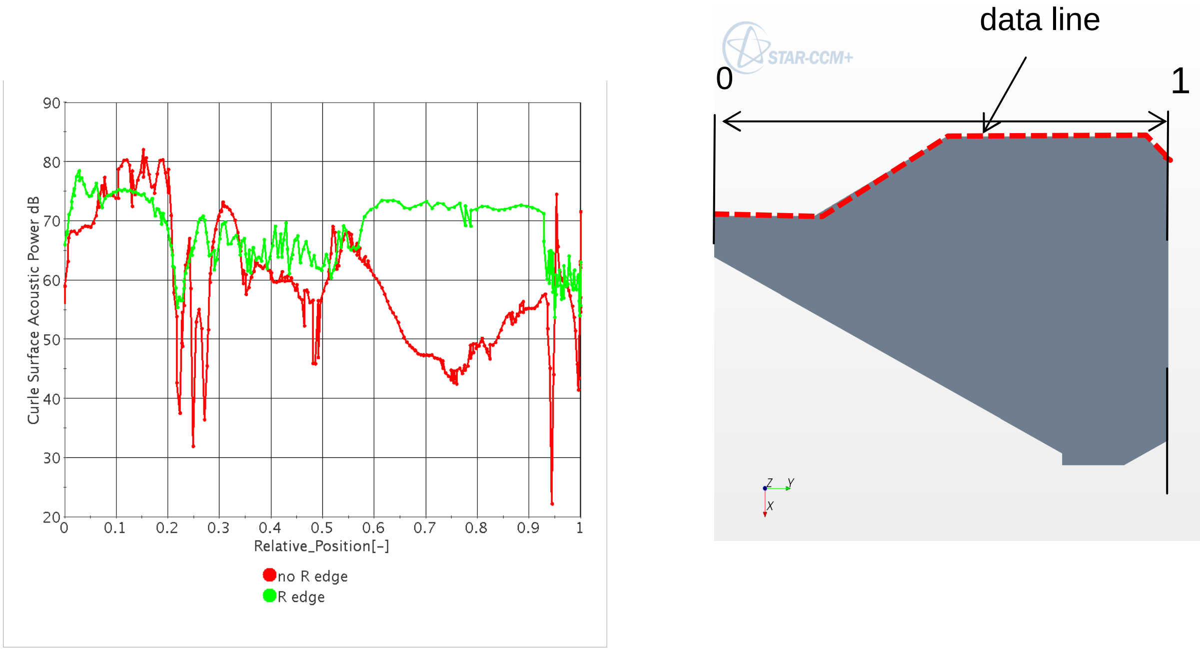


Figure 5: Dipole sound source along the blade edge

Next, quadrupole sound source along the edge line on the blade are compared on the graph. Comparison of the quadrupole sound source on the blade edge is shown in Fig. 6. Since the quadrupole sound source generates not on the surface of the blade but in space, the line for evaluation is separated from the edge of the blade by 1 mm. Moreover, the value lower than 0 is set to 0.

Also in this case, the difference appears notably near the root of the blade. In the blade with rounded edge, the quadrupole sound source value is mostly zero and the effect of decreasing turbulence generated by separation of flow was confirmed.

As mentioned above, it was shown clearly that the bi-directional radial fan noise source was the edge of the blade. Moreover, it was obtained as new knowledge that the root portion of the blade is important as a fan noise source.

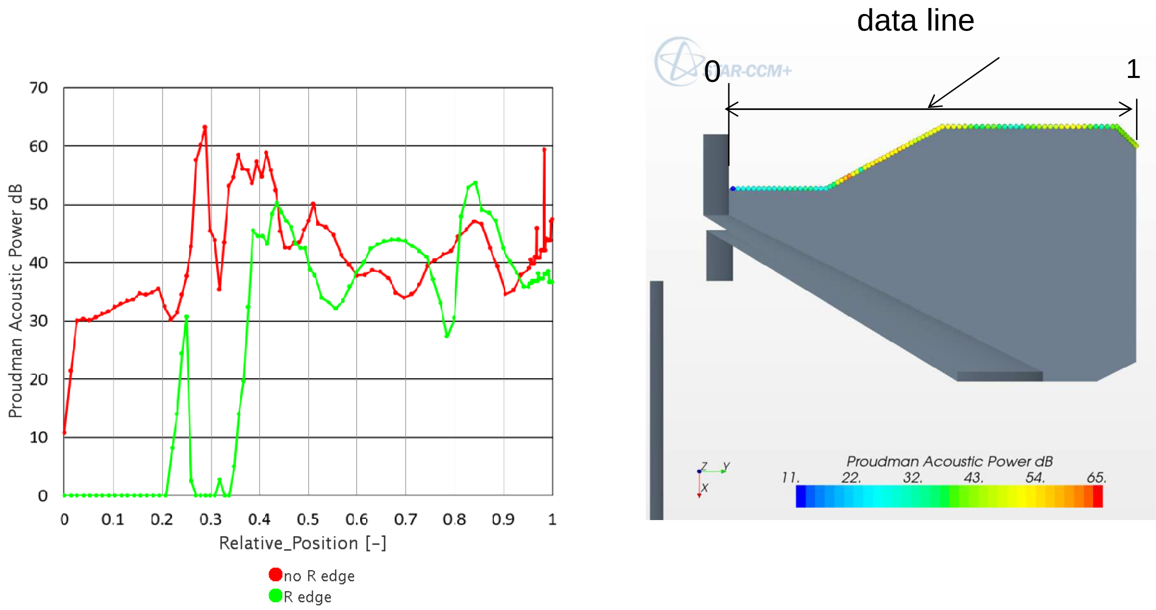


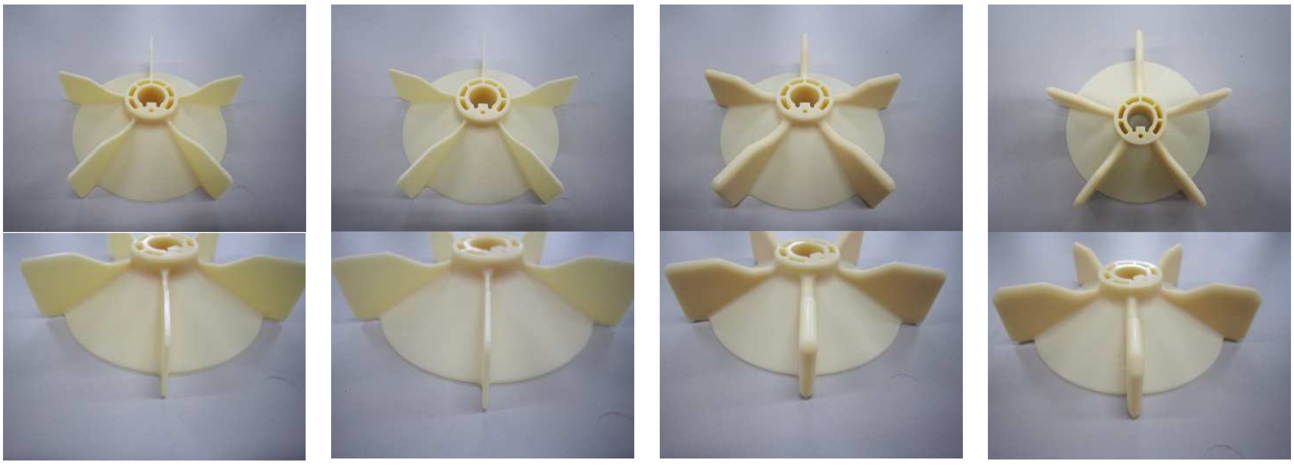
Figure 6: Quadrupole sound source along the blade edge

Measurement result

In order to confirm the result obtained in analysis, the rotary device with which the only fan noise is measured was manufactured. The state where the device is installed in the semi-anechoic room is shown in Fig. 7. The height of rotation axis is 1-m from a floor, so turbulent flow near the floor is controlled. Since the drive section is covered with the case stacked the sound absorbing material on the inside wall, motor sound and bearing rotation one do not emit outside from the case. Moreover, in order that rotational vibration doesn't transmit to the support stand, a vibration control materials are installed at the connection parts. Through these measures, when only the shaft is rotated at 2000 rpm without the fan, it was confirmed that the background noise is about 29 dB(A). The measurement fan noise is about 43 dB at 1800 rpm, and since it is separated from the background noise by 10 dB or more, the device performance which measures only fan noise is sufficient. In order to associate the measurement with the analysis, the microphone is set at three positions (Radial 1, Axial, and Radial 2) which away 1-m from the fan. There is only equipment inside the semi-anechoic room, and measurement is carried out from the outside of it. The motor was rotated using by direct current power supply, checked the rotational situation with the Web camera installed in the semi-anechoic room. In 1000~2000 rpm, rotation is increased at a time by 200 rpm, and noise is measured for 20 seconds each time. Since the average number of times is set to be 20 times, the noise component is removed.

Figure 7: Measurement environment in the semi-anechoic room

As a result of simulation for investigating low noise blade, four kinds of fans, which have the blade without rounded edge, with rounded one, with large rounded one, and with large ellipsoid rounded one, were manufactured. The fans for measurement are shown in Fig. 8. The blade itself is made from ABS resin and is cutting work. Thereby, the fan controlled the surface roughness was made in the state where it is maintained strength. Especially the shape of rounded edge designed by CAD is simulated accurately.



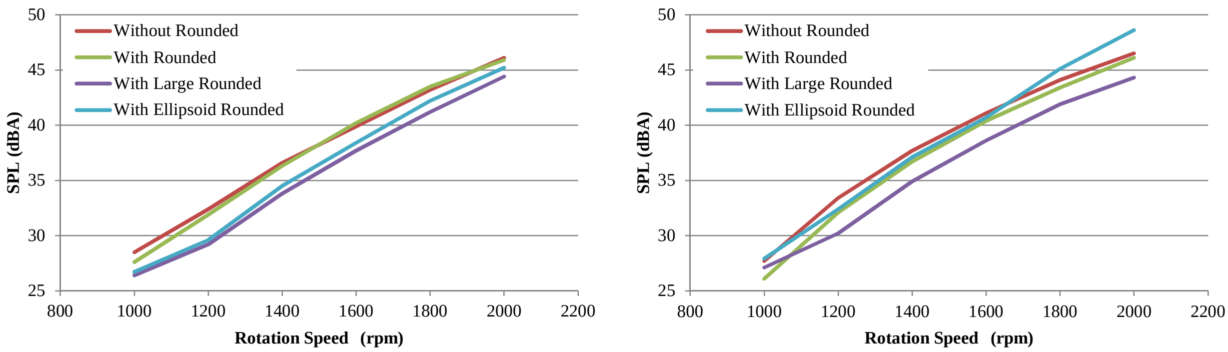
(a) Without rounded (b) With rounded (c) With large rounded (d) With ellipsoid rounded

Figure 8: The blades for measurement

In four kinds of blade shape, the relations between the SPL in expressed in dB(A) and rotation speed at each measurement position are shown in Fig. 9. In the radial direction, the blade with rounded was decreased by about 1 dB(A) in the low-speed region and was equivalent at 1600 rpm or more as compared with the blade without rounded. In the axial direction, SPL is reduced by about 1 dB(A) in the high-speed region, and by about 2 dB(A) in the low-speed region. It was confirmed the effect of the blade with rounded edge by measurement too.

The blade with large rounded can be decreased by about 3 dB regardless of rotation speed. Moreover, although SPL decreased by 1~3 dB in the blade with ellipsoid rounded edge fan, SPL increased rather than the blade without rounded edge fan from 1600 rpm at the Axial direction. Because the elliptical fan was not able to process elliptical shape perfect in the case of cutting work.

It was confirmed that the blade with large rounded edge fan was possible to decrease the fan noise by the measurement and the analysis. However, a possibility that the airflow rate was decreased is also considered. From now on, we will clarify by investigation of measurements and analysis.



(a) Radial direction (b) Axial direction

Figure 9: Noise level comparison

Next, the frequency characteristic in measurement and CAA was compared. Frequency characteristic comparison is shown in Fig. 10. The frequency characteristics which has peak near 1000 Hz in measurement, near 1200 Hz in analysis are acquired respectively. Although a little difference was seen by peak frequency, the nearly equivalent result was obtained. The validity of analysis has been confirmed.

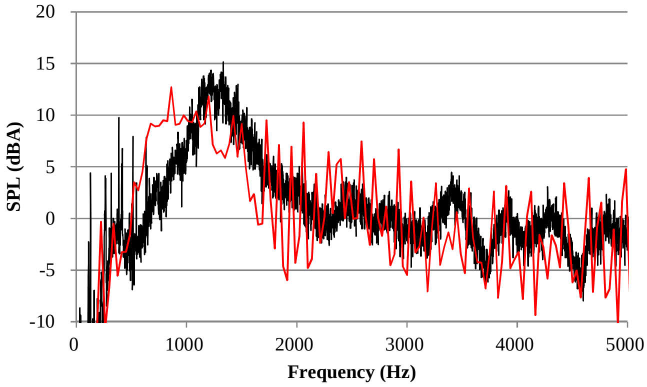


Figure 10: Frequency characteristic comparison of measurement and CAA

DESIGN FOR LOW NOISE BI-DIRECTIONAL RADIAL FAN

Investigation of the low noise blade

Since the inner circumference side of the blade is predicted to generate the noise source, five kind of blades in which inner circumference blade shape differs were investigated. The five kind of analytical fan models are shown in Fig. 11. All of five kinds of blades have the same areas respectively. The No.1 blade is connected to the boss part with the simple rectangle, the No.2 blade is cut the part on the inner circumference side in the rectangle, the No.3 blade is cut the inner circumference side in the triangle, the No.4 blade is cut the inner circumference side in the circle, the No.5 blade is cut the inner circumference side in the ellipse. The measurement point of the noise in the CAA simulation is set to the position which away 1-m from the fan in the radial direction.

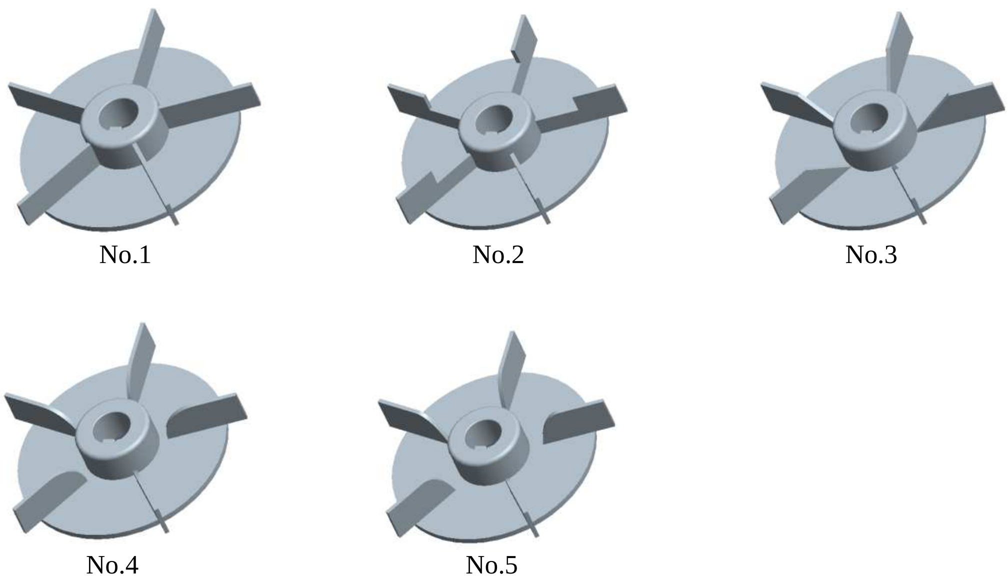
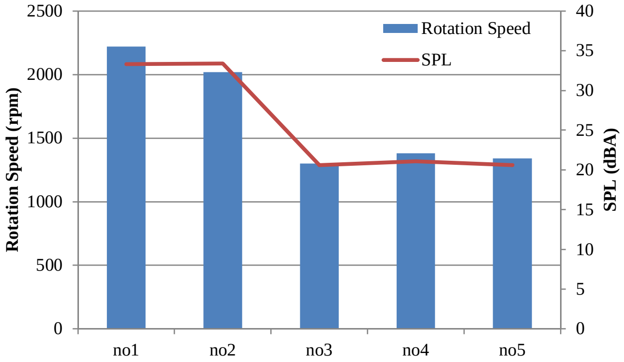
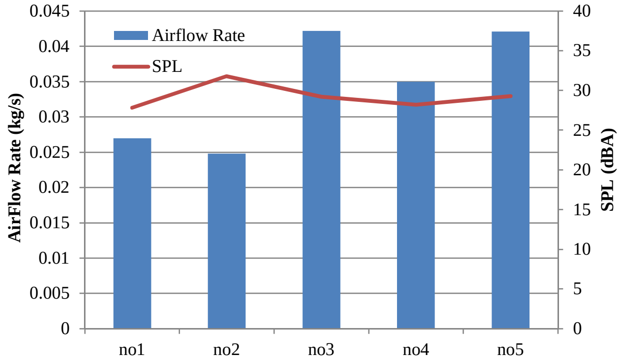


Figure 11: Five kinds of Analytical fan models

The relation between airflow rate and SPL in the same rotation speed (1800 rpm), and the relation between rotation speed and SPL at the same airflow rate (0.03 kg/s) are shown in Fig. 12. Moreover, comparison of the dipole sound source in No.1 and No.3 is shown in Fig. 13. At the same rotation speed, it turns out that the airflow rate of No.1 and No.2 connected to the boss part is less than the others. On the other hand, although the airflow rate increases No.3, No.4, and No.5, there is little increase of the SPL. Moreover, while rotation speed increases No.1 and No.2 at the same airflow rate, No.3, No.4, and No.5 have few increases rotation speed with low SPL. This is because wind is sheared by the blade inner circumference side when the wind is absorbed between blades, as shown also in the contour figure of Fig. 13. Since it becomes the noise source and the flow is obstructed by rotation of the blade, the airflow rate is also suppressed. Therefore, in order to make compatible increase of the airflow rate and reduction of the SPL, the blade cut the inner circumference side is effective.



(a) Same rotation speed



(b) Same airflow rate

Figure 12: Airflow rate, rotation speed and SPL of each blade

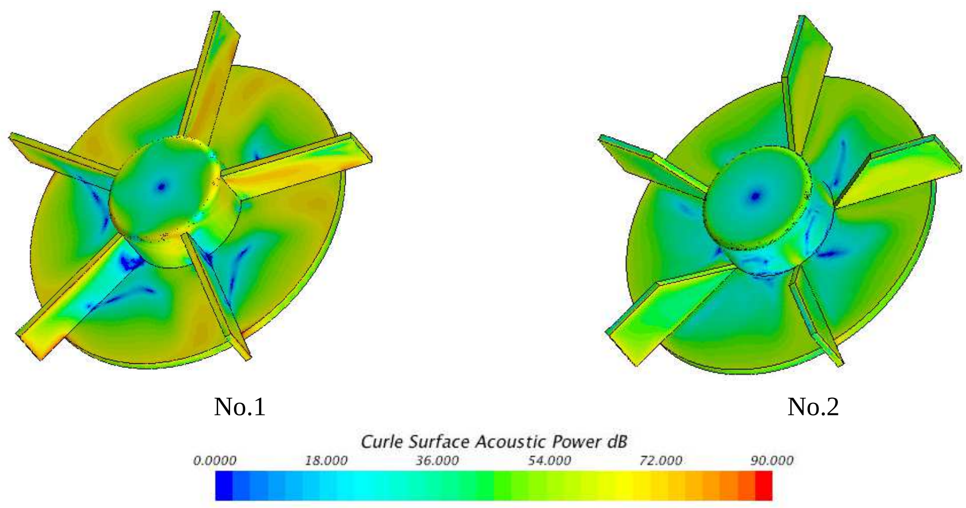


Figure 13: Dipole sound source comparison

CONCLUSION

The main noise sources of the bi-directional radial fan which rotates in both directions were clarified, and it was able to be shown clearly that noise reduction becomes possible by preparing the blade with rounded edge. Moreover, it turned out that the inner circumference side of the blade is one of the main noise sources. It was shown that coexistence of increase of the airflow rate and reduction of the SPL is possible to control the blade shape.

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