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An Aeroacoustic Comparison of Centrifugal Fans with Backward-curved and Airfoil Blades

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ABSTRACT

This paper addresses a noise comparison of centrifugal fans, with backward-curved blade and backward-inclined airfoil blade, by using computational aeroacoustics. Flow fields over simplified models are examined under specific system resistance and sound pressure levels are calculated with Ffowcs Williams-Hawkings acoustic analogy. For backward-curved blade, flow separation occurs at the leading edge; strong vortex sheets are generated and propagated downstream; and pressure fluctuation is increased. To attenuate unsteady acoustic sources, airfoil blade based on four-digit NACA has been implemented and then vortex shedding is suppressed and sound pressure level is decreased significantly. Over the actual experiment, air flow rates and sound pressure levels are measured, validating the analysis accuracy.

Keywords: Noise, Fan, Centrifugal
I-INCE Classification of Subject Number: 14

1. INTRODUCTION

Electrical machines are consuming 53 % of electricity worldwide and crucial concerns of industrial use motors are with increase of cooling performance and power density. Due to the flexibility of design and manufacturing, backward-curved (BC) blade centrifugal fans are commonly used for the motor cooling, as shown in Fig. 1. However, sound pressure level of BC blade could exceed the noise limit at applications of high speed and large dimension and then we might be enforced to select airfoil (AF) blade fans, as a last resort.

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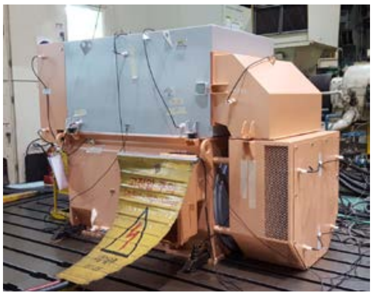
Here, we introduce computational fluid dynamics (CFD) and computational aeroacoustics (CAA) to investigate flow structures and sound pressure levels of BC and AF blades. Over the actual experiment, air flow rates and sound pressure levels are measured, validating the analysis accuracy.



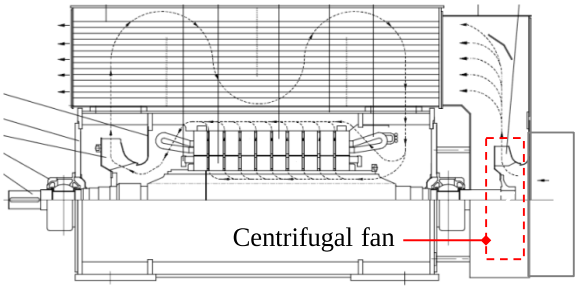


Figure 1. Totally enclosed air to air cooled (TEAAC) induction machine and sectional drawing.

2. METHOD

2.1 Numerical Details

Fig. 2 shows analysis model, boundary condition, and domain size of the centrifugal fan. To save numerical cost, geometric change from housing to cooling pipe—inducing pressure drop— are converted to analytic resistance that is proportional to square of velocity. The resistance is defined at a circular plane located at upstream. Inlet and outlet boundary conditions are stagnation and static pressure constant and then air flow rate of the fan is determined at equilibrium between resistance and performance. Reference frame is adapted to a region enveloping the fan. Reynolds number based on tip velocity and radius is 1.4 million, as shown in Table 1. Rotating speed of the machine is 1800 rpm. Time advance is corresponding to 1.0 degree rotation for a step and maximum CFL number is 32 on the trailing edge. SST k-omega detached eddy simulation (DES) using wall function is selected and maximum normal grid size is lower than 48 in wall coordinate.

Sound pressure level at 1 meter distance from the shaft is calculated with Ffowcs Williams-Hawkings acoustic analogy and Dunn-Farassat_Padula_1A formulation is adapted with loading components on blade surfaces except shroud and stationary parts, meaning that sound pressure level from CAA is issued under free field.

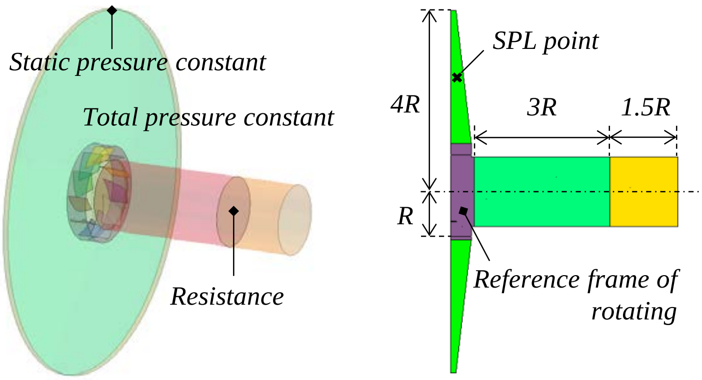


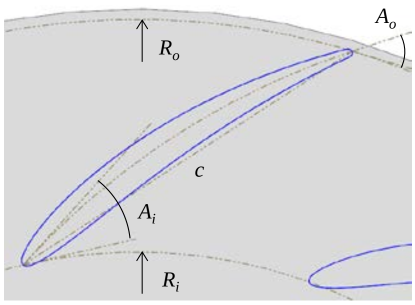
Figure 2. Analysis model, boundary condition, and domain size for computational fluid dynamics and aeroacoustics.

Table 2 shows dimension of BC and AF blade fans: remarkable changes are that camber and thickness are increased for high-lift and anti-stall.

Table 1. Numerical details for computational fluid dynamics and aeroacoustics.

List	Symbol	Value
Reynolds number	$\mathrm{Re} = 2\pi N \cdot {R_o}^2/v$	1.4 million
Rotating speed	N	30 (rps)
Hydraulic resistance		149 (kg/m^7)
Turbulence model		SST (menter) k-omega detached eddy
Gird distribution		0.4~8 (mm)
Grid distribution	$y^+ = yu^*/v$	Max. 48
Grid number		8 million
Time step		1.0E-5 (s)
Acoustic analogy		Ffowcs Williams-Hawkings
FW-H formulation		Dunn-Farassat_Padula_1A

Table 2. Dimension of BC and AF blade fan.
(*non-dimensionalized by R_o, **non-dimensionalized by C)

Dimension	BC	AF	Illustration
${R_o}^*$	1.0	1.0	
${R_i}^*$	.746	.685	
A_o (degree)	35	35	
A_i (degree)	35	35	
Width, W^*	.448	.323	
Chord length, C^{**}	1.0	1.0	
Camber**	.05	.065	
Camber position**	.5	.5	
Thickness**	.0221	.0947	e.g. AF blade

2.2 Experiments

Flow rates and sound pressure levels of BC and AF fans are measured at an actual application. Velocities are measured at 40 points for right and left inlets with the turbine flow meter. Sound pressure levels are measured at 4 points at 1 meter distance from the motor—drive end (de), non-drive end (nde), right, left— with microphones.

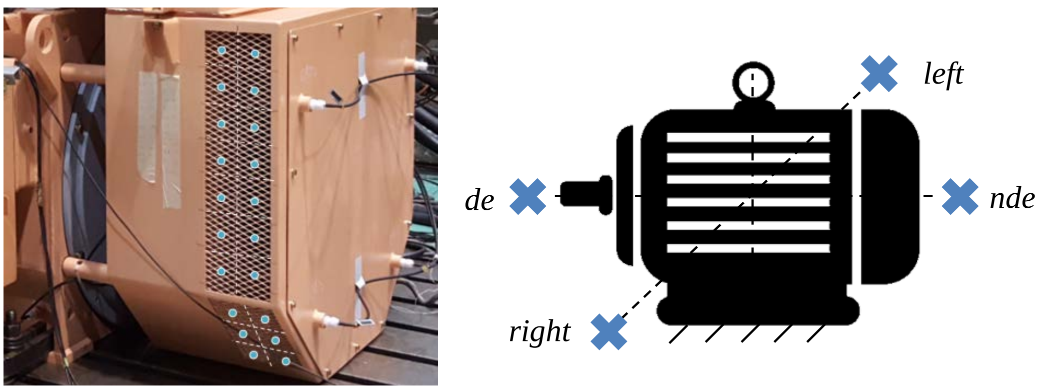


Figure 3. Measuring points for velocity (left) and sound pressure level (right).

3. RESULT

3.1 Flow Field

Fig. 4 shows a comparison of velocity vectors between BC and AF blades. For BC blade, flow separation occurs at the leading edge; vortices are generated and propagated; low pressure region is developed over suction side; fan efficiency is deteriorated; and pressure fluctuation is increased, as shown in Fig. 5 After applying AF blade, flow separation is delayed to the trailing edge; vortex is suppressed; and fluctuation is attenuated. It is expected that radiation and propagation of noise from the blade would be decreased.

Calculated flow rate of AF blade is equal to BC blade quantity and measured flow rate of BC blade is in a good agreement with calculation of BC blade, as shown in Table 3.

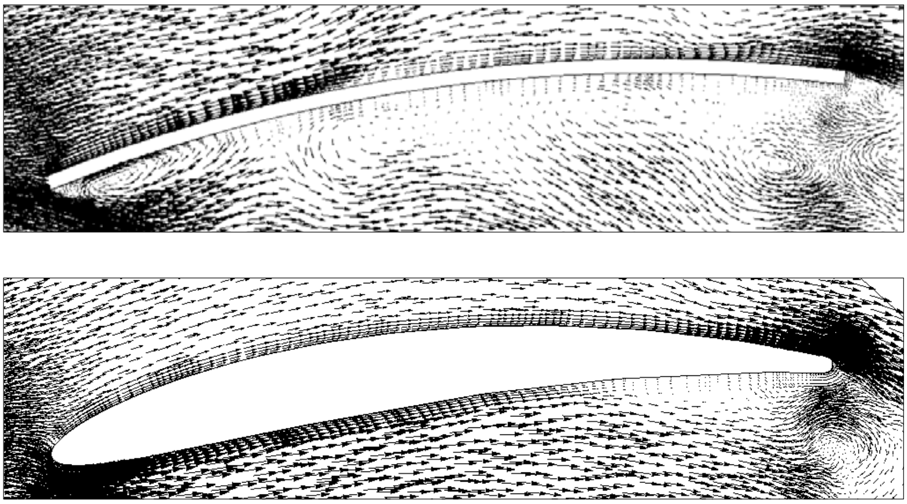


Figure 4. Velocity vector of BC and AF blade fan.

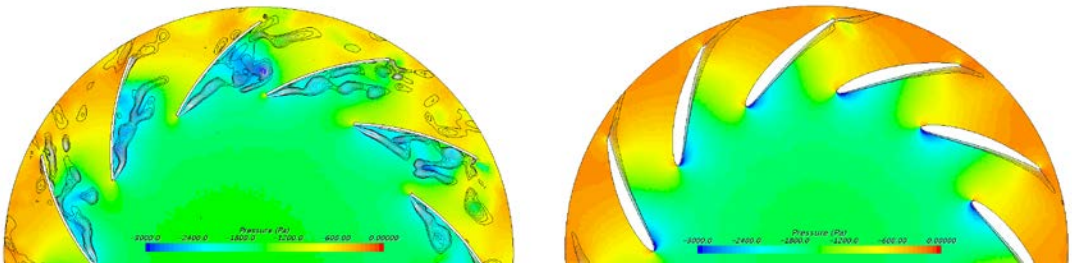


Figure 5. Iso-line of axial vorticity and pressure contour of BC and AF blade fan.

Table 3. Air flow rate from analysis and experiment of BC and AF blade fan.

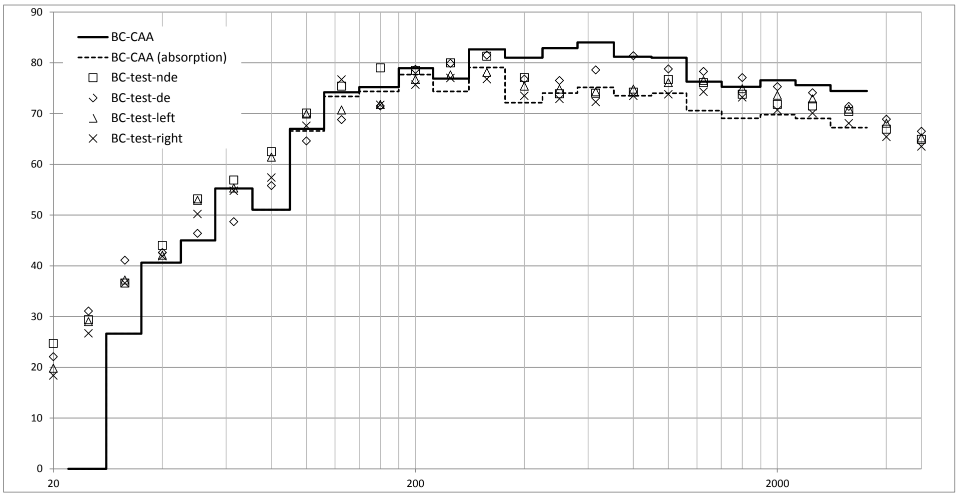
Method	CAA		Experiment	
Blade	BC	AF	BC	AF
Flow rate (m^3/s)	3.38	3.30	3.39	-

3.2 Acoustics

Comparing to BC blade, sound pressure level of AF blade is decreased at domain of blade passing frequency, as shown in Table 4, and then overall sound pressure levels of BC and AF blades are 91.5 and 89.4 dB(A), respectively. At an actual

Table 4. Sound pressure level from analysis and experiment of BC and AF blade fan.

1/3 octave band (Hz)	A-weighted sound pressure level (dBA)												Absorption coefficient, α (50t poly urethane)
	CAA				Experiment								
	raw data		corrected w/ α		BC				AF				
	BC	AF	BC	AF	nde	de	left	right	nde	de	left	right	
12.5					10	13	7	4	1	30	1		
16.0					19	15	12	11	9	36	9	10	
20.0					25	22	20	18	21	41	24	22	
25.0					29	31	29	27	23	47	25	24	
31.5	27	28	27	28	37	41	37	37	34	52	34	35	
40.0	41	32	41	32	44	43	42	42	44	54	41	40	
50.0	45	34	45	34	53	46	53	50	49	58	48	49	
63.0	55	40	55	40	57	49	55	55	51	59	53	54	
80.0	51	48	51	48	63	56	61	57	59	61	56	57	
100.0	67	45	67	45	70	65	70	68	67	64	62	62	0.09
125.0	74	53	73	53	75	69	71	77	71	70	71	72	0.17
160.0	75	70	74	69	79	72	72	72	71	68	68	68	0.18
200.0	79	71	78	70	79	79	77	76	73	75	70	71	0.25
250.0	77	71	74	68	80	80	78	77	73	76	71	69	0.44
315.0	83	79	79	75	81	82	78	77	76	77	76	74	0.56
400.0	81	75	72	66	77	77	75	74	74	74	71	73	0.87
500.0	83	79	74	70	74	77	75	73	71	73	70	70	0.87
630.0	84	80	75	72	74	79	74	72	68	75	71	70	0.87
800.0	81	80	74	73	74	81	75	74	69	79	73	73	0.83
1000.0	81	78	74	71	77	79	76	74	73	77	73	72	0.80
1250.0	76	82	71	76	76	78	77	74	71	74	81	75	0.73
1600.0	75	78	69	72	74	77	75	73	68	71	76	71	0.76
2000.0	77	79	70	72	72	75	74	71	69	71	69	68	0.79
2500.0	76	72	69	65	72	74	73	70	65	68	67	66	0.78
3150.0	74	71	67	64	70	71	71	68	64	65	66	65	0.81
4000.0	71	72	64	65	67	69	68	65	61	62	63	62	0.79
Overall	91.5	89.4	84.9	82.0	84.8				82.0				0.09



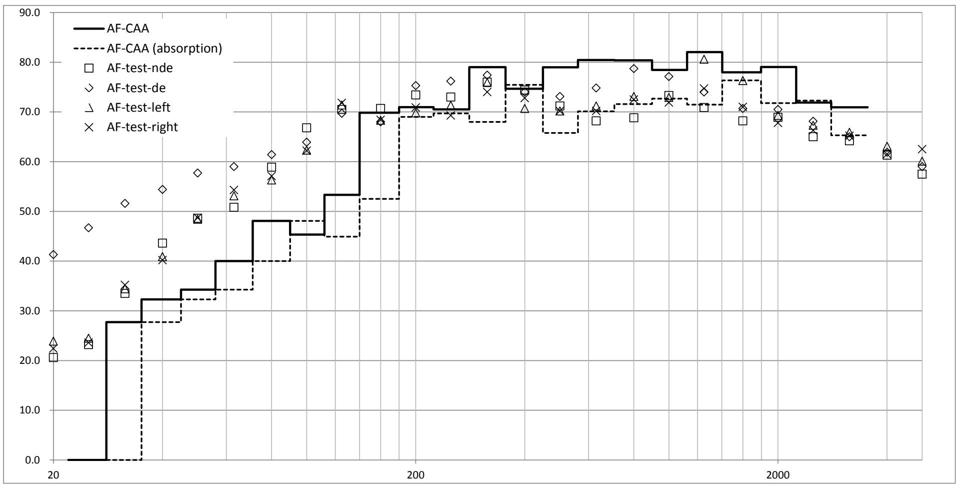


*Figure 6. Comparison of s*ound pressure level between analysis and experiment.

application, sound absorber of 50 thickness poly-urethane is attached inside the fan housing. After considering this absorption coefficient, overall sound pressure levels of BC and AF blades are 84.9 and 82.0 dB(A), respectively, and these are in good agreements with experimental measurements.

4. CONCLUSION

We investigated flow structures and sound levels of backward-curved (BC) blade and airfoil (AF) blade centrifugal fans, used for cooling of the electrical machine, by using computational fluid dynamics and computational aeroacoustics. In a case of BC blade, flow separation occurred at the leading edge and vortices were propagated to suction side of the blade. After substituted to AF blade based on 4-digit NACA, flow separation was delayed to the trailing edge and vortices were suppressed. As a result, sound pressure level of AF blade plummeted at domain of blade passing frequency and then overall sound pressure level of AF blade was decreased by 2.1 dB, comparing to BC blade. Air flow rates of BC and AF blades were sustained.

After considering the absorption coefficient, overall sound pressure levels of BC and AF blades were calculated to 84.9 and 82.0 dB, respectively. From the actual application, overall sound pressure levels of BC and AF blades were measured to 84.8 and 82.0 dB, respectively, showing good agreements with the analysis quantities.

5. REFERENCES

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