Tonal and broadband noise attenuation of an axial flow fan with forward and backward swept blades

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Abstract

A swept blade is one of the efficient ways to control unsteady flow and passively attenuate the noise radiated from an axial flow fan. Herein, an experimental study was conducted to investigate the effect of the blade sweep on the acoustic characteristics of an axial fan system operating under system resistances at an anechoic chamber facility. The noise level and fan performance of the axial fans with forward-swept, backward-swept, and straight blades were systematically measured using an acoustic fan tester, which can simultaneously measure them at various system resistance conditions. The variations in the overall A-weighted sound pressure levels (OASPLs) as a function of the static pressure and air flow rate, and acoustic spectra at the specific operating conditions were examined. The results showed that the forward-swept blade has superior aerodynamic and acoustic performance in a wide range of operating conditions to the other blades, except for the high system resistance corresponding to rotating stall conditions. In conclusion, the use of a forward-swept blade can achieve noise level reductions of 2–4 dBA under system resistance conditions since the amplitude of tonal noise associated with blade passing frequency is decreased.

Keywords: Axial fan, System resistance, Acoustic fan tester, Swept blade, Noise reduction

1. Introduction

Swept blades are effective in controlling unsteady flow to reduce the noise levels of axial fan systems. Many researchers have attempted to design more advanced blades that can improve the aerodynamic performance and reduce the noise levels of axial fan systems [1, 2]. Smith and Yeh [3], and Lewis and Hill [4] investigated the effects of sweep and dihedral angles on the performance of axial fans using the swept cascades and actuator disk theory, respectively. Vad [5, 6] discussed the advantages of swept blades, focusing on the major aerodynamic phenomena related to the improvement of efficiency and performance and extension of stall-free operating range. Bamberger and Carolus [7] suggested an optimal low-pressure axial fan that can maximize efficiency and minimize noise emission by modifying the sweep angle of the blade. Moreover, several studies have shown the potential applications of swept blades in attenuating tonal noise radiated from axial flow fans [8–11]. Schulten [12, 13] showed that the leaned or swept vanes can be exceptionally effective in reducing noise resulting from the interaction of rotor wakes and a stator. Hanson [14] theoretically investigated the influence of the geometrical shape of a propeller on far-field harmonic noise and showed the acoustic benefit of swept blades. Wright and Simmons [15] also demonstrated that the swept blade is effective for attenuating the dominant noise source. Carolus and Beiler [16, 17] discussed the noise reduction mechanism of swept blades in detail. Agboola and Wright [18] numerically studied the change in the radial velocity profile depending on the blade sweep directions that contribute to reducing axial fan noise. Dierke [19] found installation effects on propeller noise due to the collision of propeller tip vortex to the swept-wing equipped with a Coanda flap.

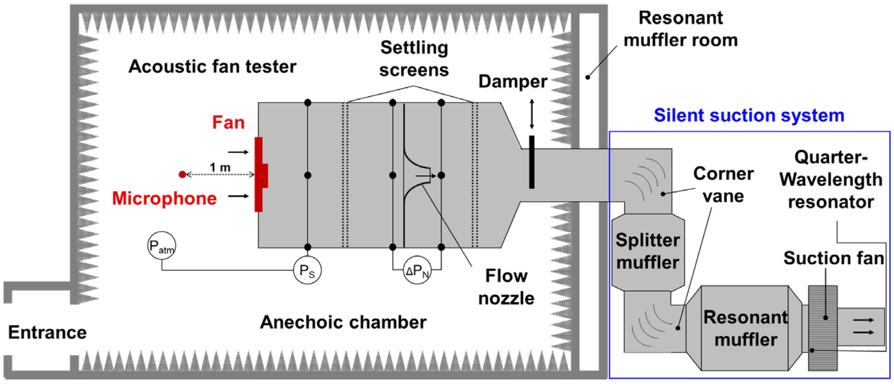
The noise levels generated by three different axial fans with the straight, forward-, and backward-swept blades were examined experimentally with a focus on the position of the noise source [20–22]. Mohammed and Raj [23] first conducted an experimental study on forward-swept blades with different sweep angles. The measurements showed that forward-swept blades operate more efficiently than unswept blades, particularly at low air flow rate conditions. Moreover, the blade stall was delayed, and the negative effect due to the radially outward boundary layer flow at the tip region was alleviated by the forward sweep. Some studies have reported that the forward-swept blade can provide better aerodynamic performance over a broad range of operating conditions than other blade configurations, such as straight and backward-swept blades [24–27]. Hurault *et al*. [28] found that forward-swept blades also can decrease the magnitude of the radial velocity component, whereas backward-swept blades tend to increase it. In addition, Zenger *et al*. [29, 30] showed that the forward-swept blade is an efficient way to mitigate a turbulence ingestion noise generated because of distorted inflow turbulence.

An axial fan usually operates under the system resistance conditions caused by the complex components behind the rotating blades. However, to our best knowledge, very few studies have attempted to measure the aerodynamic noise emitted from the axial fan systems and address the blade sweep effect at the system resistance condition. In our previous study [31], the effects of blade sweep on the acoustic characteristics of the axial fan system were investigated in the free-field condition through numerical and experimental approaches. The main purpose of this study is to examine the effect of the blade sweep on the acoustic characteristics of axial fans operating under the system resistances. We used the acoustic fan tester installed in an anechoic chamber and measuring equipment that is capable of simultaneously measuring the fan performance and noise at system resistance conditions. The noise measurements on the three different configurations of the blades used in the previous study [31], including straight, forward-, and backward-swept blades, were compared, and the sweep effects are discussed in detail.

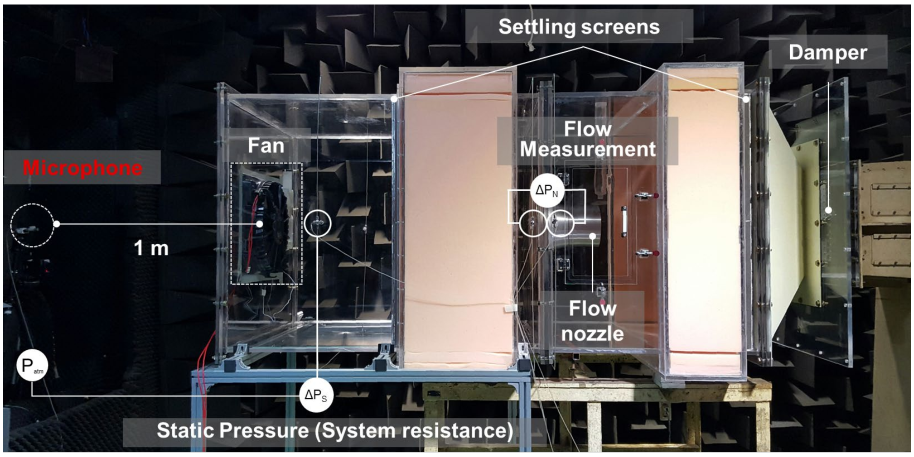
2. Experimental setup

2.1 Acoustic fan tester

An acoustic fan tester [32] installed in an anechoic chamber facility is used to measure the noise levels of the cooling fan with swept blades operating at the system resistance conditions. Fig. 1 shows the schematic and experimental environment of the facilities for the noise measurement system consisting of the semi-anechoic chamber, acoustic fan tester, and measuring equipment. The experiment facilities were constructed per the AMCA 210-99 standard [33]. The acoustic fan tester with dimensions of 1 (W) × 2.4 (L) × 1 (H) m is located in the anechoic chamber with dimensions of 6 (W) × 5 (L) × 4 (H) m. The anechoic chamber was built surrounding the test section to provide a non-reflecting condition and minimize background noise. The anechoic chamber was constructed as a room using a concrete wall of 0.2 m thickness and fiberglass sheets of 0.1 m thickness. The saw-tooth-shaped sound absorbers in the anechoic chamber were designed using fiberglass wedges with dimensions of 0.2 × 0.2 × 0.4 m to maintain a low cut-off frequency of 180 Hz. The background noise in the anechoic chamber is less than 20 dBA. A silent suction system is located outside the anechoic chamber to allow airflow to exit quietly, and the system resistance is controlled by a throttle damper and silent suction fan. The rotational speed of the axial fan mounted on the electric motor is controlled by the current and voltage of the DC power supply (UP-3050, 30V-50A) and measured using a tachometer (UT-372). The static pressure P_s is measured by a pressure scanner (DSA-3217), which is connected to the ring of the four pressure taps located at the center of each of the four-plenum walls. The sampling rate of the static pressure signal is 0.5 kHz/channel, with a long-term system accuracy of ±0.05% full scale. The air flow rate passing through the fan is measured by a standard air flow nozzle. The fan noise is measured using a half-inch free-field microphone (Brüel & Kjær 4190). The microphone has a nominal sensitivity of 50 $mVPa^{-1}$, with a dynamic range of 14.6–146 dB, and a flat frequency response of 20 kHz. The sensitivity of the microphone is validated using a B&K model 4231 sound calibrator. The measured sound pressure signals are acquired using an NI DAQ-4431 24-bit digitizer and amplified by a B&K Nexus 2690. The stationary microphone is located on the upstream centerline of the fan, with an axial distance of 1 m per the ISO 7779 standard [34].



(a)

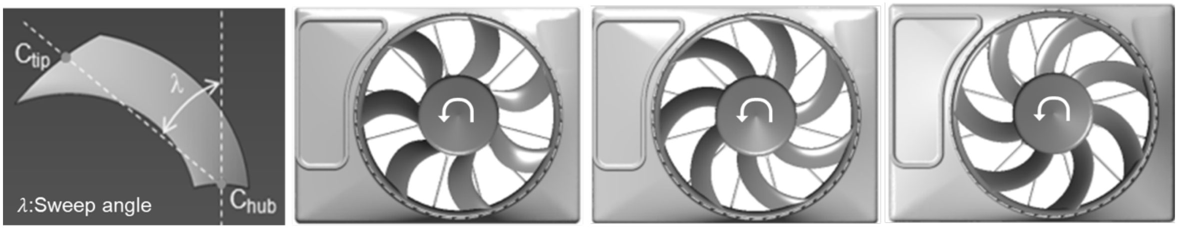


(b)

Fig. 1. Experimental apparatus for measuring the performance and noise of an axial fan at system resistance: (a) schematic diagram, and (b) experimental environment in an anechoic chamber [32]

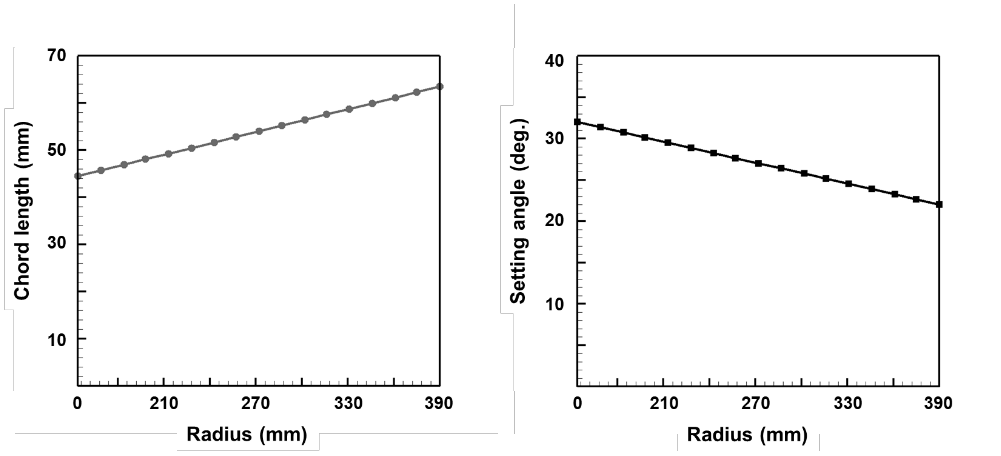
2.2 Geometry of swept blade

The definition of sweep angle and the geometries of straight, backward-, and forward-swept blades are illustrated using the shrouded fan in Fig. 2. The sweep angle is defined as the angle between the line connecting the rotating center (C_r) to the midpoint of the chord line of the blade hub (C_{hub}) and the line connecting the midpoint of the chord line of the blade tip (C_{tip}) to the midpoint of the chord line of the blade hub (C_{hub}), as shown in Fig. 2(a). In addition, the forward- and backward-swept blades are determined based on the direction of the sweep angle. The rotational direction of the fan blade is counter-clockwise when viewed from the front. Fig. 2(b) shows that the straight blade has no sweep angle. The hub–tip line of the forward-swept blade has a sweep angle of 45° along the rotating direction, whereas that of the backward-swept fan has a sweep angle of 45° along the counter-rotating direction, as presented in Figs. 2 (c) and (d), respectively. The cross-sectional shape of the fan blade is a modified NACA 4-series airfoil. The planform geometry of the fan blade can be defined in terms of the chord and setting angle distributions, as shown in Figs. 3(a) and (b). The chord length increases linearly from 44.5 mm at the hub to 63.5 mm at the tip, and the setting angle decreases linearly from 32° at the hub to 22° at the tip. This setting angle includes the effective angle of attack and the incident angle of the local relative wind. The axial fan is made up of a hub with a diameter of 154 mm, seven blades, and a rotating ring [35, 36] connecting the blades with a diameter of 390 mm. The straight and swept blades were designed to examine the noise characteristics of the fans depending on the sweep direction.



(a) (b) (c) (d)

Fig. 2. Geometries of shrouded fan with blades: (a) definition of sweep angle, (b) straight blade, (c) forward-swept blade, (d) backward-swept blade



(a) (b)

Fig. 3. Planform shape of fan blade: (a) chord length distribution, and (b) geometric setting angle distribution

2.3 Non-dimensional performance curve

One of the most valuable pieces of information supplied by fan manufacturers is the fan performance curve. This curve illustrates the relationship between the air flow rate (Q) passing through the fan and the static pressure (P_s), where static pressure is the physical meaning of the system resistance generated at various air flow rates. The static pressure and air flow rate can be defined as non-dimensional parameters using Eqs. (1) and (2), where ρ is the air density, N_{rps} is the rotational speed, and d is the diameter of the axial fan.

$$\phi = \frac{Q}{N_{rps} d^3} \quad \text{Eq. (1)}$$

$$\psi = \frac{P_s}{\rho N_{rps}^2 d^2} \quad \text{Eq. (2)}$$

Figure 4 shows the non-dimensional performance curve of the shrouded fan with straight blades. Note that the x-axis in Fig. 4 indicates the non-dimensional air flow rates (ϕ), and the y-axis denotes the non-dimensional static pressure (ψ), which is the system resistance acting on the rotating blades. The fan performance was measured under the various fixed rotational speed conditions to verify the repeatability of our proposed method. The measured data using the acoustic fan tester were compared with the reference data [37] obtained from the Hanon Systems' conventional fan tester facility, which was constructed according to the ISO 5801 standard [38]. The performance curves as a function of the non-dimensional parameters follow similar trends, although the rotational speed of the blades is different. Moreover, the measurements are in close agreement with the reference data, indicating that our acoustic fan tester can provide reliable and reproducible data of the performance measurement of a shrouded fan.

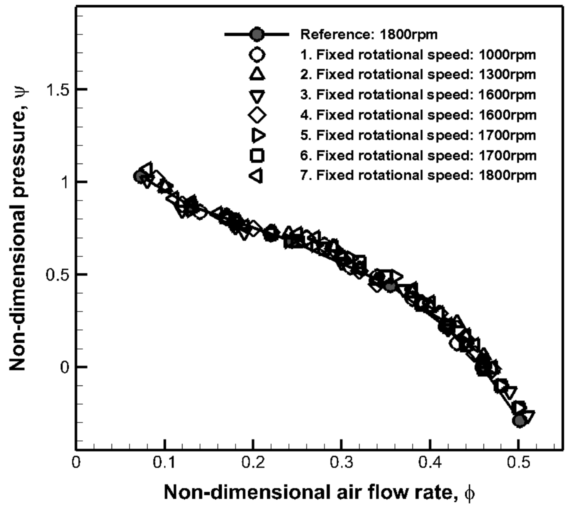
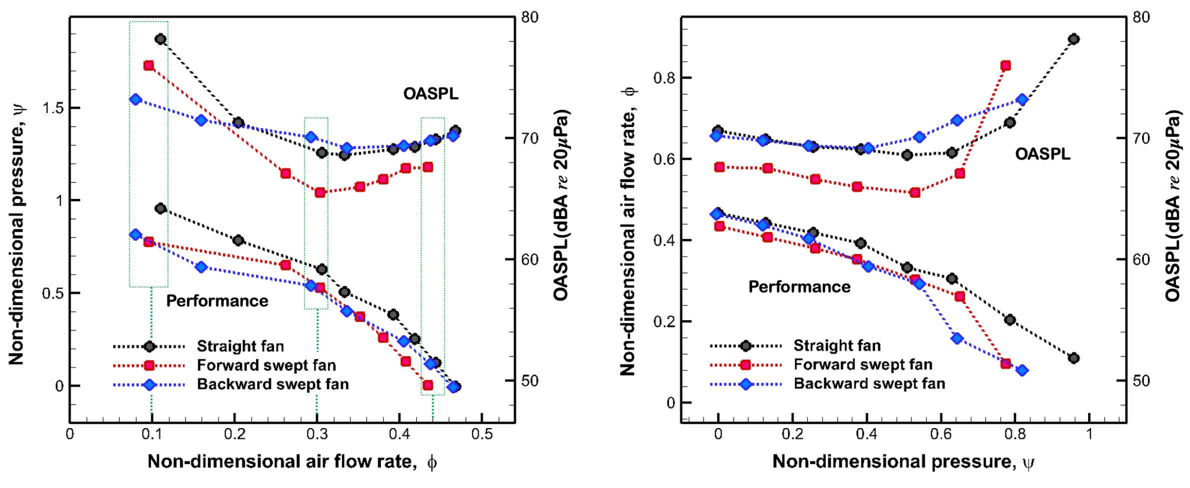


Fig. 4. Non-dimensional performance of the axial fan with straight blades at various fixed rotational speeds

3. Results and discussion

The aerodynamic and acoustic characteristics of the axial fan system depend on the sweep direction of the blade and the operating environment. The main focus of this study is to offer an extensive investigation of the effect of blade sweep direction on the performance and noise levels of axial fan systems under operating system resistance conditions. The acoustic fan tester was used to measure and compare three metrics, namely the system resistance, air flow rate, and noise level. Changes in the performance and overall A-weighted sound pressure levels (OASPLs) (re: 20 μPa) with the straight, backward-, and forward-swept blades were investigated at the fixed rotational speed of 1,700 rpm.

Figure 5 shows the non-dimensional aerodynamic performance curve and noise characteristics of axial fans with three different blades operating at the fixed rotational speed of 1700 rpm. The performance varies depending on the blade sweep geometry; it is necessary to compare fan noise under the same performance conditions. However, it is not easy to compare it under the same conditions because the static pressure and air flow rate must be considered simultaneously. Therefore, to compare the noise on the same criteria, each noise comparison was conducted based on the flow coefficient and pressure coefficient. Fig. 5(a) shows the aerodynamic and acoustic performance as a function of the air flow rate. The x-axis indicates the non-dimensional air flow rate induced by the shrouded fans under the system resistances. The left y-axis indicates non-dimensional static pressure for the results located at the bottom of the figure, whereas the right y-axis shows the OASPLs at each operating point of the fans for the results located at the top of the figure. It can be observed that the OASPLs of the forward-swept blade are lower than those of the straight and backward-swept blades for $\phi > 0.2$ conditions. Fig. 5(b) depicts the variation in the air flow rate and noise levels of three different blades depending on the static pressures. The x-axis indicates the non-dimensional static pressure, corresponding to the system resistance acting on the rotating blades. The left y-axis indicates the non-dimensional air flow rate, whereas the right y-axis shows the OASPLs according to the static pressure. It is also observed that the OASPLs of the forward-swept blade are lower than those of the straight and backward-swept blades for $\psi < 0.7$ conditions. In conclusion, it is found that the forward-swept blades can reduce the noise levels by approximately 2–4 dBA for most operating conditions, except for $\phi < 0.2$ and $\psi > 0.7$ conditions, where rotating stall occurs owing to the high system resistance. The forward-swept blade geometry reverses the direction and decreases the magnitude of the radial velocity component [28], which is one of the main contributing mechanisms for reducing the noise in low-speed axial fans, as reported by Agboola and Wright [18]. In addition, the tangential component of the velocity of the forward-swept blade is lower than those of the others [27], which can be considered one of the important contributing mechanisms for reducing the noise by alleviating the shed vortex interaction between the blade tip and rotating ring. Therefore, the forward-swept blade has better performance than other blades reported in the literature [21, 28].

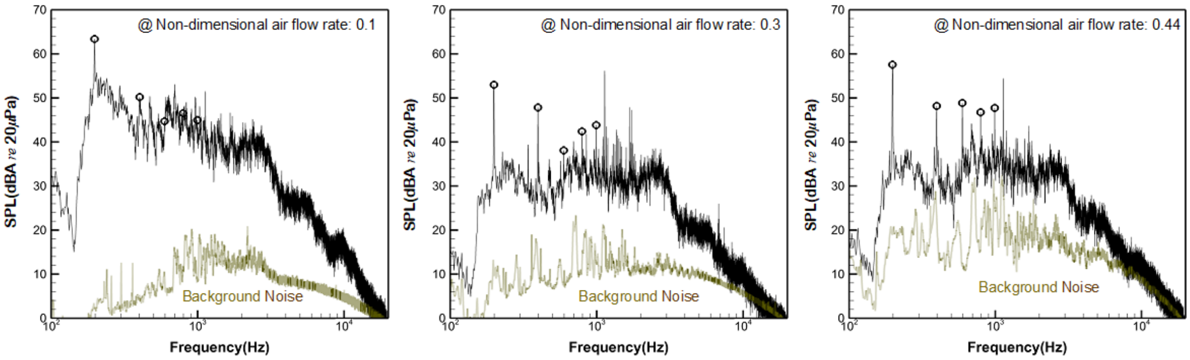


(a) (b)

Fig. 5. Comparison of the performance curves and OASPLs of the axial fan with three different blades

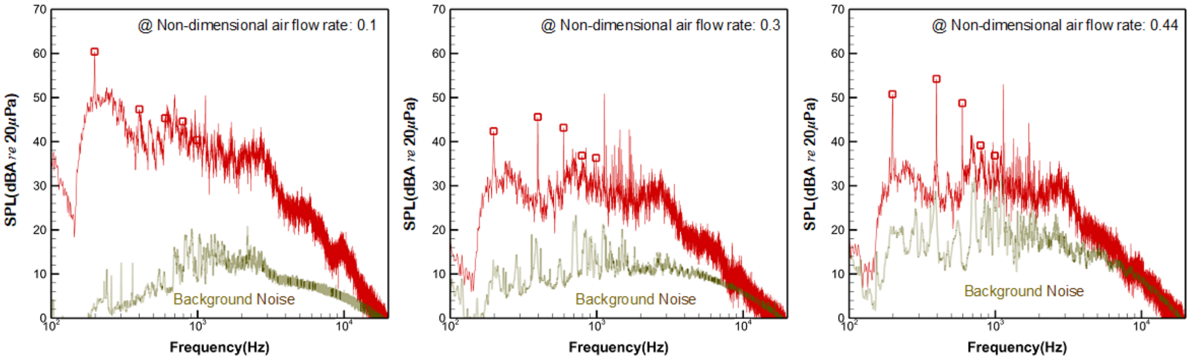
Figures 6−8 show the sound pressure spectra of the axial fan with three different blades at the air flow rate coefficients of $\phi = 0.1$, 0.3, and 0.44. Noise spectra weighted to A-value scales were presented in decibels to analyze discrete tonal and broadband noise. The symbols in the figures represent the discrete tonal noise associated with blade passing frequencies (BPFs). Other tonal components indicate motor noise [31]. The measured background noise at air flow rate (ϕ) of 0.1, 0.3, and 0.44 were compared with the spectra of fan noise since their levels depend on the flow rate through the installed flow nozzle. The signal-to-noise ratios (SNR_{dB}), the differences between the measured fan noise and the background noise, are more than 25 dB, 16 dB, and 13 dB for the air flow rate of 0.1, 0.3, and 0.44, respectively. The dominant noise is the discrete tonal noise at the operating conditions of ϕ = 0.3 and ϕ = 0.44. The measurements show that the tonal noise of the forward-swept blade is lower than that of the straight blade, as shown in Figs. 6(b), 6(c), 7(b), and 7(c), whereas the tonal noise of the backward-swept blade is similar to that of the straight blade, as shown in Figs. 6(b), 6(c), 8(b), and 8(c). It can be observed that the amplitude of tonal noise associated with BPFs tends to increase with increasing air flow rate for the three different blades in the air flow rate coefficient range of $0.3 < \phi < 0.44$.

However, the 1st BPF noise and broadband noise components increase significantly at the air flow rate coefficients of $\phi \leq 0.1$ or the static pressure coefficients of $\psi \geq 0.8$, as shown in Fig. 5(a). In particular, Figs. 6–8(a) showed that the noise levels of the straight blade are higher than those of the forward- and backward-swept blades at ϕ = 0.1. In addition, both 1st BPF noise and its surrounding broadband noise are significantly increased owing to the rotating stall, as reported by Zhang *et al.* [39]. This phenomenon is similar to the blade vortex interaction (BVI) noise due to the interaction between the trailing vortex and the leading edge of the following blade [40]. The blade sweep geometry can typically reduce the BVI noise of a helicopter in descent flights [41]; however, it depends on the operating conditions [42]. It was reported that the trailing vortex from a generated forward-swept shape tends to flow inside the hub and is likely to impinge upon the leading edge of the blade following it, as the shed vortex cannot flow downstream owing to high system resistance, i.e., high static pressure [18, 28]. Herold *et al*. [20] found substantial sound pressure sources at the leading edge of a forward-swept blade in high system resistance. Therefore, this investigation showed that the forward-swept blade has excellent aerodynamic and aeroacoustic performance in general operating conditions but adverse properties at the high system resistance of $\psi > 0.7$.



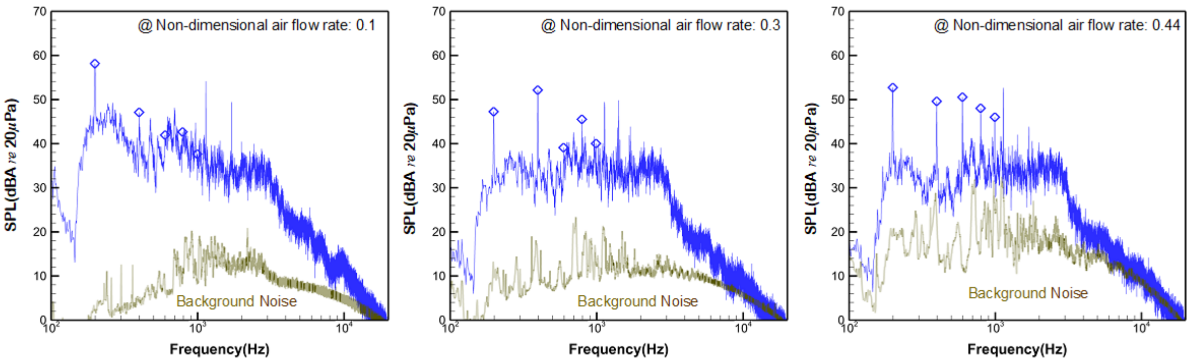
(a) (b) (c)

Fig. 6. Sound pressure spectra of axial fan with straight blade: (a) $\phi = 0.1$, (b) $\phi = 0.3$, and (c) $\phi = 0.44$



(a) (b) (c)

Fig. 7. Sound pressure spectra of axial fan with forward-swept blade: (a) $\phi = 0.1$, (b) $\phi = 0.3$, and (c) $\phi = 0.44$



(a) (b) (c)

Fig. 8. Sound pressure spectra of axial fan with backward-swept blade: (a) $\phi = 0.1$, (b) $\phi = 0.3$, and (c) $\phi = 0.44$

4. Conclusion

The main focus of this study was to investigate the use of swept blades for passive noise alleviation on axial fan systems. The acoustic characteristics of three shrouded axial fans with forward-swept, backward-swept, and straight blades were studied through an acoustic fan tester under various system resistances. An experimental investigation was conducted to measure the fan performance and noise simultaneously using the acoustic fan tester. An attempt was made to uniquely compare the noise and performance of the fans logically according to the various system resistances.

We found that the axial fan with the forward-swept blades had approximately 2–4 dBA less OASPL than other fans under most operating conditions ($0 < \psi < 0.7$ and $0.2 < \phi < 0.44$). At the air flow rate coefficients of $\phi \leq 0.1$ or the static pressure coefficients of $\psi \geq 0.8$, the tonal noise associated with 1st BPF and its surrounding broadband noise increased significantly owing to the rotating stall. In particular, the forward-swept blade had substantially higher noise than others at the same static pressure coefficient of $\psi = 0.8$. This phenomenon can be explained by the fact that the trailing vortex generated from forward-swept blades has the trend to flow inside the hub and is likely to impinge upon the leading edge of the blade following it, as the shed vortex cannot flow downstream owing to high system resistance. In conclusion, it was found that forward-swept blades can reduce the aerodynamic noise and increase the fan performance of an axial fan in a wide range of operating conditions; however, it has adverse properties at the rotating stall at the high system resistance of $\psi > 0.7$. From these comparison results, both the fan performance and noise characteristics change based on the blade sweep. Hence, it is important to consider the design point value and the operating condition when designing the fan and blade sweep.

Declaration of competing for interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science, ICT & Future Planning (NRF-2017-R1A5A1015311 and NRF-2021R1C1C1010198).

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