Experimental investigation of the flow- and sound-field of low-pressure axial fans with different blade stacking strategies

Florian Zenger*, Andreas Renz1, Stefan Becker1

Abstract
In this study we investigated the impact of different fan blade stacking strategies on the flow-field and the sound-field of low-pressure axial fans. For this, we considered two fans with single-type fan blade skew (backward and forward) and two fans with combined-skewed fan blades (with backward-skew on the inner part of the fan blade and forward-skew on the outer part of the fan blade; and vice versa) and otherwise identical design parameters. We assessed the aerodynamic and acoustic properties on basis of laser Doppler anemometer measurements and beamforming evaluations using a virtual rotating microphone array.

We found that the contribution of several fan blade regions to the overall sound emission is differently expressed, depending on the applied fan blade skew. We also observed a strong impact of the different types of fan blade skew on the flow field, in particular on the flow properties on the suction side. Furthermore, we linked flow-phenomena to several sound generation mechanisms. These findings provide a better understanding of the interrelations between the flow-field and the sound-field in axial fans.

Keywords
Turbomachinery aeroacoustics — Axial fan — Blade stacking — Blade skew
1Institute of Process Machinery and Systems Engineering, Friedrich-Alexander University Erlangen-Nürnberg, Erlangen, Germany
*Corresponding author: ze@ipat.fau.de

INTRODUCTION
Low-pressure axial fans are used in a variety of commercial applications. Design optimizations focus on the one hand on the fan aerodynamics and on the other hand on the fan acoustics. These two characteristics strongly correlate with each other, i.e. the flow-field has a strong impact on the sound emission of axial fans. The flow field in modern low-pressure axial fans is strongly influenced by the applied fan blade skew, which is a combination of fan blade sweep and fan blade dihedral [1, 2]. The effect of fan blade skew on the flow- and sound-field is discussed in the following course. Thereby, a distinction is drawn between broadband, narrowband and tonal sound components.

Broadband sound Broadband sound in axial fans is generated by boundary layer noise, trailing edge noise and by turbulence ingestion noise (leading edge noise). [3, 4, 5]

Boundary layer noise is dependent on the boundary layer parameters, in particular on the boundary layer thickness. Fan blade skew influences the boundary layer development (under the assumption of otherwise identical design parameters). On backward-skewed fan blades the boundary layer thickness is increased compared with unskewed fan blades as the fluid will move further outwards and therefore travel a longer path before reaching the trailing edge. Accordingly, the boundary layer thickness is decreased for forward-skewed fans which leads to a lower source strength of boundary layer noise. [3, 4, 5]

The level of trailing edge noise is (amongst other parameters) governed by the velocity perpendicular to the trailing edge \( \nu_\perp \) [6, 7, 8]. This is obvious when looking a trailing edge noise prediction models, e.g. in [9, 10, 11, 12, 13, 14]. Depending on the trailing edge shape, in particular the trailing edge curvature, \( \nu_\perp \) is in- or decreased. Consequently, the source mechanism contribution is influenced [6].

Turbulence ingestion noise in axial fans is dependent on the inflow turbulence intensity \( Tu \) and the integral length scale \( \Lambda \) of the flow field upstream of the fan. The emitted sound is enhanced with increasing inflow turbulence intensity. If the fan blade chord length \( l_c \) is smaller than the integral length scale \( \Lambda \) a fluctuating airfoil loading is induced. If the fan blade chord length \( l_c \) is larger than or equal to the integral length scale \( \Lambda \), local areas with pressure fluctuations develop on the fan blade leading edges. Both phenomena are an effective broadband sound source. [15, 16]

Narrowband sound Narrowband tip noise that arises from flow phenomena in the tip gap region of low-pressure axial fans is dependent on the flow field during the blade passage [17, 18, 19, 20, 21]. Due to the application of fan blade skew, the radial equilibrium condition often is no longer valid, leading to an additional radial velocity component \( \omega_\perp \) [3, 22]. If all design parameters except the fan blade skew are identical (blade profile, loading distribution, chord lengths,
stagger angles, etc.), the direction of this radial velocity component solely depends on the type of fan blade skew. Thereby, backward-skewed fan blades induce a radial outwards directed velocity component whereas forward-skewed fan blades induce a radial inwards directed velocity component [22, 23, 1, 24, 25]. Owing to the different impact on the flow field, forward-skewed fan blades weaken the tip vortex formation [26, 27, 28, 24], which also leads to reduction of narrowband tip noise.

Tonal sound Fan blade skew is an effective measure for decreasing unsteady blade forces, i.e. unsteady loading noise. Using unskewed fan blades, each part of the blade interacts with the inflow at the same instant, especially if the fan blade leading edge geometry coincides with the radial direction. For skewed fan blades, the peak load is reduced as different parts of the fan blade interact with the inflow at different times. [4, 29]

The interaction is further dependent on the type of fan blade skew, i.e. forward- or backward-skewed. The blade tip sections of forward-skewed fans are known to change the blade loading at the fan blade tip. Hence, the meridional velocity at the suction side $c_m$, is increased in the tip region and decreased in the hub region compared with unskewed fans. The opposite applies to backward-skewed fans. [30, 31, 22, 32, 33]

1. MICROPHONE ARRAY METHOD

A microphone array method using a virtual rotating microphone array [34, 35, 36, 2] was used for localizing sound sources on the investigated fans. With this method, the recorded microphone signals are transformed into a frame virtually rotating with the same rotational speed as the investigated axial fan. Therefore, the microphones needed to be arranged on one or more rings, coaxial to the fan’s rotational axis. The virtual rotating data were then obtained by linear interpolation of the stationary microphone data. Using this method, the application of frequency domain beamforming with subsequent deconvolution is possible.

Beamforming relies on the evaluation of phase shifts from discrete focus points $x_f(i)$, defined as

$$x_f(i) := \begin{pmatrix} (x_f)_{i,1} \\ (x_f)_{i,2} \\ (x_f)_{i,3} \end{pmatrix} \text{ for } i = 1 \ldots F,$$  

with the number of focus points $F$, to an array of microphones $x_m(j)$, defined as

$$x_m(j) := \begin{pmatrix} (x_m)_{j,1} \\ (x_m)_{j,2} \\ (x_m)_{j,3} \end{pmatrix} \text{ for } j = 1 \ldots M,$$  

with the number of microphones $M$, which finally yields a sound map [37, 38].

In the frequency–domain beamforming, the cross–spectral matrix (CSM) is evaluated, which is obtained using Welch’s method [39]. For this, let $p \in \mathbb{R}^{M \times N}$ be a matrix with microphone signals in a virtual rotating frame, with the number of data samples $N$. Each data set $p^{(j)}$, with

$$p^{(j)} := \begin{pmatrix} p_{j,1} \\ \vdots \\ p_{j,n} \end{pmatrix} \text{ for } j = 1 \ldots M \text{ and } n = 1 \ldots N, \quad (3)$$

is divided into $K$ sections, onto which a window function and then a fast Fourier transform (FFT) are applied. For each frequency $f$ in the corresponding frequency vector $f \in \mathbb{R}^{N_{FFT}}$, with the number of discrete Fourier transform points $N_{FFT}$, the FFT result is stored in $N_{FFT}$ matrices $X(f) \in \mathbb{C}^{M \times K}$. By averaging cross spectra of data sets, the CSM $C(f) \in \mathbb{C}^{M \times M}$ is obtained (Equation 6) [40, 38, 41].

In Equation 6, $X(f)$ is the complex conjugate of $X(f)$. The delay-and-sum beamformer output $b^{(f)} \in \mathbb{C}^F$ is then calculated via [37, 42]

$$b^{(f)} = h^{(f)} C(f) h^{(f)\dagger} \text{ for } f = 1 \ldots N_{FFT}, \quad (4)$$

with $\cdot^\dagger$ indicating a Hermitian matrix. Equation 4 involves steering vectors $h^{(f)} \in \mathbb{C}^{F \times M}$. In this work, formulation III in Sarradj [42] was used, with

$$h^{(f)}_{ij} = \frac{1}{r_{i,ij} r_{0,ij} \sum_{l=1}^{M} 1/r_{i,il}^2} e^{-j(k_n (r_{i,ij} - r_{0,ij})},$$

for $f = 1 \ldots N_{FFT}$, $i = 1 \ldots F$ and $j = 1 \ldots M$. \quad (5)

In Equation 5, $k$ is the wave number, $r_i$ the distance from the focus point to the microphone and $r_0$ the distance from an arbitrary reference point to the microphone.

For improving the resolution and dynamic range of the beamformer output, deconvolution algorithms are used. In this process, point spread functions (PSFs) are determined and replaced by single points or narrow-width beams. [43, 44, 45]

In this study, the CLEAN-SC deconvolution algorithm [43] was used, which estimates PSFs on the basis of correlated parts of the beamformer output. For a deconvoluted sound map, only the maxima of the correlated parts are considered.
2. EXPERIMENTAL SETUP

In total four different fans were investigated, which differed in the applied blade skew, i.e. fan blade sweep and dihedral (refer to [1, 2] for angle definitions). The sweep angle $\lambda$ was varied along the radius individually for each fan to yield a distinctive fan blade skew. The applied sweep angles of all fans are shown in Figure 1. The dihedral angle was adapted to minimize the axial installation space incorporated by the respective fan. The following fans were investigated:

- Fan B with backward-skewed fan blades,
- Fan F with forward-skewed fan blades,
- Fan FB with forward-skew on the inner part and backward-skew on the outer part of the fan blade and
- Fan BF with backward-skew on the inner part and forward-skew on the outer part of the fan blade.

The fan blades are shown in Figure 2. Each fan had nine fan blades, an outer diameter of $d_{fan} = 495$ mm, a hub diameter of $d_{hub} = 248$ mm, a tip gap of $t_{tip} = 2.5$ mm and a similar blade loading distribution. They were designed for a volume flow rate $V = 1.4$ m$^3$/s and a total-to-static pressure difference $\Delta p_{ts} \in (140$ Pa, $170$ Pa).

For obtaining spectra from different portions of the fan blades, beamforming sound maps were integrated over different regions corresponding to the fan blade leading edges (LE), the fan blade surfaces (BS), the fan blade trailing edges (TE) (Figure 2) or the whole focus grid (FG).

![Figure 1. Fan blade sweep angles $\lambda$ of the investigated fans.](image1)

The aerodynamic and acoustic investigations were carried out in a standardized inlet test chamber according to ISO 5801 [46] (Figure 4). The chamber was built as an anechoic room with absorbing walls, ceiling and floor. The test fans were installed in a short duct with an inlet bellmouth upstream of the fan and a diffuser downstream of the fan (Figure 4).

2.1 Microphone array and integration regions

The microphone array consisted of 12 1/2 inch microphones and 64 1/4 inch microphones. The 64 1/4 inch microphones were arranged with equidistant spacing on a ring with a diameter $d_{array_l} = 1.8$ m (large array) and a distance of 750 mm to the fan hub (Figure 3). Accordingly, the 12 1/2 inch microphones were installed on a ring with a diameter $d_{array_s} = 0.37$ m (small array) and a distance of 480 mm to the large array (Figure 3).

![Figure 3. Schematic representation of the microphone array setup.](image3)

2.2 Flow-field

The flow-field with was measured on the suction side and on the pressure side of the fans with a laser Doppler anemometer (LDA) [47, 48]. The LDA system included a 2-component LDA...
probe. The measurement positions were chosen, so they had a distance of either 10 mm upstream of the fan blade leading edges or 10 mm downstream of the fan blade trailing edges (Figure 5).

As the fan blade geometry varied for the four investigated fans, the measurement positions were adapted individually. For obtaining fluid mechanical properties in meridional, circumferential and radial direction \((c_m, c_u\) and \(c_r\)), two different measurement setups on the suction side as well as on the pressure side were necessary (Figure 5). The results in Section 3 are presented by means of phase-locked ensemble-averaged values. For this, the bin size was 2°.

Only a finite measurement time was practical for each measurement point of the LDA measurements. The measurement uncertainties can be assessed under the assumption of a Gaussian normal distribution \([49]\) by \([50]\)

\[
c_j = \bar{c}_j \pm 1.96 \sqrt{\frac{c_j'^2}{N_m}}, \tag{7}
\]

with the number of samples \(N_m\). This implies that each single value \(c_j\) is with a probability of 95 % (95 % confidence level) within the given range. The measurement uncertainties for each velocity component are shown in Table 1.

![Figure 5. Schematic representation of the LDA measurement positions.](image)

Table 1. LDA measurement uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>suction side</th>
<th>pressure side</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_m)</td>
<td>(\bar{c}_m \pm 0.05 \text{ m/s})</td>
<td>(c_m = \bar{c}_m \pm 0.02 \text{ m/s})</td>
</tr>
<tr>
<td>(c_u)</td>
<td>(\bar{c}_u \pm 0.02 \text{ m/s})</td>
<td>(c_u = \bar{c}_u \pm 0.01 \text{ m/s})</td>
</tr>
<tr>
<td>(c_r)</td>
<td>(\bar{c}_r \pm 0.07 \text{ m/s})</td>
<td>(c_r = \bar{c}_r \pm 0.02 \text{ m/s})</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

The aerodynamic characteristic curves are shown for the whole fan operating range. In contrast, averaged sound pressure spectra, sound maps as well as flow-field properties are presented for the design volume flow rate \(\dot{V} = 1.4 \text{ m}^3/\text{s}\).

3.1 Characteristic curves

The aerodynamic characteristic curves are shown in Figure 6 and 7. The total-to-static efficiency was calculated according to

\[
\eta_{ts} = \frac{\dot{V} \Delta p_{ts}}{M_s 2 \pi n}, \tag{8}
\]

with the shaft torque \(M_s\) and the rotational speed \(n\).

In general, the progressions of the total-to-static pressure difference \(\Delta p_{ts}\) and the total-to-static efficiency \(\eta_{ts}\) are strongly dependent on the type of fan blade skew. Qualitatively, the curves for the fans B and FB, and also F and BF,
which leads to more pronounced tonal components.

In contrast to fans F and BF, very dominant subharmonic narrowband components occur for the fans B and FB. This is again associated with flow phenomena in the tip region. In the tip region, coherent flow structures develop that interact with the fan blade leading edges. As these coherent flow structures are rotating themselves with a slightly scattered angular velocity, narrowband humps arise that do not correspond to the BPF \([19, 17, 21]\). Forward-skewed fans are known to weaken the tip vortex formation \([27, 28, 24]\), hence this sound generation mechanism is suppressed for the fans F and BF at the considered operating point.

For \(f > 1\) kHz, the spectra consist mainly of broadband components. In contrast to the low-frequency part, fans B and FB feature lower sound pressure levels than fans F and BF. The radiated sound is expected to be generated by pressure fluctuations beneath the turbulent boundary layer. Trailing edge noise can be assessed with the velocity component perpendicular to the trailing edge \([7, 8, 10, 11]\). Owing to the convex trailing edge shape of forward-skewed fans, this velocity component is increased compared with backward-skewed fans with a concave trailing edge shape \([6, 52]\). Lower sound pressure levels for the fans B and FB than for the fans F and BF hint at trailing edge noise being the relevant sound source mechanism in the high-frequency range. This is discussed further on the basis of sound maps and integrated sound pressure spectra.

### 3.3 Beamforming sound maps

Beamforming sound maps are evaluated in third-octave bands. They are further processed to yield integrated spectra of different regions on the fan blades. In this section, only sound maps of one third-octave band with the center frequency \(f_c = 2.5\) kHz are showcased (Figure 9). In general, the sound sources are located in the outer part of the fan blade as there is a higher circumferential velocity. For the fans B and FB, the sound sources in Figure 9 are located near the fan leading edges, but sources for the fans F and BF are shifted towards the fan blade trailing edges. The source levels for the fans B and FB are lower than for the fans F and BF. This is in accor-
dance with the sound pressure spectra in Figure 8, which also show increased values for the fans F and BF above $f = 2$ kHz. The contributions of different fan blade regions to the overall sound emission are discussed in the next section on the basis of integrated sound pressure spectra.

### 3.4 Integrated spectra

The integrated sound pressure spectra for the different fans are shown in Figures 10 – 13. Thereby, the blade surface and trailing edge integration regions were consolidated (BS+TE).

For all fans, sound from the leading edge integration regions is dominant for most part of the considered frequency range. The integrated spectra of this specific region nearly correspond to the integrated spectra of the whole focus grid (FG).

For the fans F and BF even greater differences occur between these integration regions with differences of $10 – 20$ dB. Hence, for the fans F and BF leading edge noise is less dominant compared to the fans B and FB.
3.5 Interrelations between the sound-field and the flow-field

In Figures 14 and 15, plots of the phase-locked ensemble-averaged velocity values for \( \dot{c}_{m}, \dot{c}_r \) and \( \dot{c}_u \) on the suction side (index 1) and on the pressure side (index 2) are illustrated. Thereby, the contour represents the meridional velocity \( \dot{c}_m \) and the vector field the plane velocity components \( \dot{c}_r \) and \( \dot{c}_u \). Additionally, plots of the phase-locked ensemble-averaged turbulent kinetic energy on the suction side \( \dot{k}_1 \) are shown in Figure 16.

In general, the flow field is governed by the fan blade angular position. An alternating pattern of regions with high and low meridional velocity is observed. The pattern is more pronounced on the fan suction side than on the pressure side, as on the pressure side, the flow field is driven by a strong circumferential velocity component \( \dot{c}_u \), owing to the fan rotation.

On the suction side, a \( \dot{c}_{m1} \) maximum is observed in the outer blade span region for the fan F (and to some extent for the fan BF), while near the fan hub, \( \dot{c}_{m1} \) is decreased. Compared with the fan F, no pronounced \( \dot{c}_{m1} \) maximum in the outer blade span region occurs for the fans B and FB.

The blade tip sections of forward-skewed fans are known to change the blade loading at the fan blade tip [30, 22, 32, 33, 26]. Owing to the increase in the meridional velocity \( \dot{c}_{m1} \) at the outer blade sections, the averaged relative flow angle \( \beta_\infty \) is increased. This also affects the angle of attack \( \alpha_s \).

As the stagger angle \( \gamma \) is only dependent on the fan blade geometry, \( \gamma \) is independent of the velocity diagrams, i.e. \( \gamma = \text{const} \). Consequently, the angle of attack \( \alpha_s \) is reduced by the growing relative flow angle \( \beta_\infty \). This further leads to a reduction in lift and blade loading. The opposite applies to backward-skewed fans. This un-/uploading effect explains the \( \dot{c}_{m1} \) distribution for the different fans in Figure 14.

The flow field in the tip region of the fans B and FB is substantially different, compared with the fans F and BF. The resulting in-plane velocity vector of \( \dot{c}_r1 \) and \( \dot{c}_u1 \) is no longer directed against the circumferential direction but is oriented in circumferential direction (Figures 14(a) and 14(c)). This is associated with the uploading effect and its impact on the flow field in the tip gap region, due to the applied backward-skew [26, 53]: The pressure gradient between the suction side and the pressure side is increased, which leads to an intensified

![Figure 14](image)

**Figure 14.** Phase-locked ensemble-averaged distribution of the meridional velocity \( \dot{c}_{m1} \) (contour) and the mean plane velocity components \( \dot{c}_r \) and \( \dot{c}_u \) (vector-field) on the suction side of the fans B (a), F (b), FB (c) and BF (d).
tip gap flow. This is obvious in Figures 14(a) and 14(c): As the meridional velocity $\tilde{c}_{mz}$ is reduced in the tip region, the flow in meridional direction is reduced and accelerated in the circumferential direction. Only a reduced through-flow is possible in the tip region, hence the flow field swerves towards lower radii. From the plots of the turbulent kinetic energy in Figure 16, it is obvious that an intensified gap flow leads to higher $\tilde{k}_1$ values in the tip region for the fans B and FB compared with the fans F and BF. The interaction of the backflow with the fan blades creates a distinctive narrowband hump in the acoustic spectrum (Figure 8).

The values of the meridional velocity on the pressure side $\tilde{c}_{mz}$ in Figure 15 are decreased again for the fans B and FB, compared with the fans F and BF. In contrast, the values of circumferential velocity $\tilde{c}_{uz}$ are increased. Similarly to the pressure side, the intensified tip gap flown, as indicated by high $\tilde{k}_1$ values in Figure 16, leads to these phenomena.

4. CONCLUSION

The flow- and sound-field of four axial fans with single-type blade skew (backward and forward) and combined blade skew (backward-forward and forward-backward) were investigated experimentally with focus on interrelations between the sound radiation and the flow properties.

The aerodynamic characteristic curves showed that the general progression of the pressure coefficient and the efficiency is mainly dependent on the type of skew in the outer part of the fan blade (for otherwise identical design parameters except of the fan blade skew). In the typical operating range, forward- and backward-forward-skewed fans had an extended operating range towards lower volume flow rates and a higher efficiency compared with backward- and forward-backward-skewed fans.

The sound pressure spectra revealed very pronounced subharmonic narrowband humps for the fans with backward-skew in the outer part of the fan blade, which are the main reason for the higher overall sound pressure levels of these fans. The spectra were again dependent on the type of fan blade skew in the outer part of the fan blade, with hardly any differences for single-type- and combined-skewed fans.

The integrated spectra showed that the main contribution to the overall sound emission above $f = 1$ kHz is trailing edges noise. This effect was more pronounced for the fans F.
and BF, i.e. with forward-skew on the outer part of the fan blades.

LDA measurements on the suction side showed that the more pronounced trailing edge noise for the fans F and BF compared with the fans B and FB can be caused by higher flow velocities in the tip region, as there is less influence from the tip gap flow on the flow-field on the suction side than for the fans with backward-skew on the outer part of the fan blades (fans B and FB). For the fans B and FB, flow phenomena in terms of a reduced meridional velocity and increased turbulent kinetic energy values in the tip region were identified that are associated with a subharmonic narrowband sound emission, originating from the tip region.

**Figure 16.** Phase-locked ensemble-averaged distribution of the turbulent kinetic energy $\tilde{k}_1$ (contour) on the suction side of the fans B (a), F (b), FB (c) and BF (d).

**REFERENCES**


Experimental investigation of the flow- and sound-field of low-pressure axial fans — 10/11


