Impact of Different Aerodynamic Optimization Strategies on the Sound Emitted by Axial Fans

Konrad Bamberger\(^1\) and Thomas Carolus\(^2\)

\(\textit{Institut für Fluid- und Thermodynamik, Universität Siegen, Paul-Bonatz-Str. 9-11, 57068 Siegen, Germany}\)

The correlation between the aerodynamic design strategy and the sound emission of low pressure axial fans is investigated by a case study. The four fans investigated are equal in terms of total-to-static design point, rotational speed, diameter, and tip clearance, but different regarding hub size and blade geometry. One fan (the baseline) is designed using the analytical blade element momentum method whereas the other fans are optimized by stationary CFD simulations embedded in an evolutionary optimization algorithm. Three different target functions are applied: Maximization of total-to-static and total-to-total efficiency at design point, and maximization of operating range. The distinction between the two efficiencies addresses two competing effects: While the fan optimized with respect to total-to-total efficiency has the lowest secondary flow effects, its aerodynamic load required to fulfill the same total-to-static pressure rise is higher. The characteristic curves of each fan are measured on a chamber test rig to validate the CFD results. The acoustic investigations are conducted in a semi-anechoic chamber. It is found that optimization with respect to total-to-total efficiency, i.e. minimization of losses, leads to the lowest sound power levels around the design point at low Mach numbers while the design optimized with respect to total-to-static efficiency is superior at high Mach numbers. The fan optimized with respect to operating range is loudest at the design point, but this observation inverses when moving to off-design flow rates. It is concluded that none of the design strategies can be recommended purely from an acoustical point of view and that there always is a trade-off between noise, power consumption, operating range, and development cost.

Nomenclature

| Symbols | \begin{align*} D & = \text{fan diameter} \\
| - | L_W & = \text{sound power level} \\
| - | Ma & = \text{mach number} \\
| - | P & = \text{power} \\
| - | S & = \text{tip clearance} \\
| - | T & = \text{time} \\
| - | \dot{V} & = \text{flow rate} \\
| - | \dot{V} & = \text{flow rate} \\
| - | a & = \text{speed of sound} \\
| - | c & = \text{chord length} \\
| - | d & = \text{max. thickness (of NACA airfoil)} \\
| - | f & = \text{frequency or max. camber (of NACA airfoil)} \\
| - | n & = \text{rotational fan speed} \\
| - | p & = \text{pressure} \\
| - | w & = \text{relative flow velocity} \\
| - | x & = \text{coordinate along airfoil chord} \\
| - | z & = \text{number of blades} \\
| - | \alpha & = \text{angle of attack or acoustic exponent} \\
| - | \phi & = \text{flow coefficient} \end{align*} |
I. Motivation and Objectives

The main objectives in the design of axial fans are high energy efficiency and low noise emission over a large operating range. However, present optimization efforts mainly focus on efficiency whereas noise is often neglected. This originates from the immense difference between prediction of aerodynamic performance and sound in terms of computational cost. Sound prediction by means of computational aeroacoustics (CAA) is generally conducted in two steps. Firstly, the acoustic sources, i.e. the unsteady pressure fluctuations on the fan blade are computed by transient computational fluid dynamics (CFD). Subsequently, the acoustic propagation is computed, e.g. using the Ffowcs Williams and Hawkings' analogy. This approach was taken by Reese who compared the accuracy in terms of acoustic source prediction of four distinct unsteady CFD methods: URANS, SAS, DES, and LES. The best results were obtained by LES (large eddy simulation), but this method was also most time consuming and required approx. 2600 CPU-hours. Due to the high computational cost, optimization loops with repeated geometrical adjustments and computation of the corresponding sound emission is not feasible. In contrast, stationary (time-averaged) CFD solutions such as Reynolds-averaged Navier-Stokes (RANS) simulations are often sufficient for the aerodynamic optimization. On top of that, the requirements regarding computational grid fineness are much lower in that case.

As a consequence of the huge differences regarding computational cost, it is desirable to estimate the impact of distinct aerodynamic optimization strategies on the sound emission without need for time consuming CAA. The aim
of this work is to investigate the impact of four aerodynamic design strategies on the sound radiated by a low pressure axial fan. The four methods are

1. Straight forward utilization of blade element momentum method (subsequently called “BEM”)
2. Optimization regarding total-to-static fan efficiency ($\eta_{ts}$) at the design point (subsequently called “OTS”)
3. Optimization regarding total-to-total fan efficiency ($\eta_{tt}$) at the design point (subsequently called “OTT”)
4. Optimization regarding total-to-static fan efficiency over a large operating range (subsequently called “OOR”)

The blade element momentum method is based on the two dimensional flow analysis at distinct radial positions. A detailed discussion how this method can be applied in axial fan design is given by Carolus. The advantage of this method is the analytical formulation which leads to short development time and requires almost no resources. In case of an essentially two dimensional flow in the blade passages, reasonable accuracy can be obtained by predicting lift and drag of each radial airfoil section, e.g. using XFOIL as suggested by Carolus and Starzmann. The main limitation is the inability to consider complex secondary flow effects which can only be resolved by CFD. CFD results are often precise enough to be coupled with optimization algorithms. The evolutionary algorithm implemented for this work was inspired by the work of Thévenin and Janiga as well as Nelles. Evolutionary algorithms belong to the class of global optimization methods which is a major advantage as compared to gradient based methods. The main bottleneck is the slow convergence and the large number of function evaluations required.

A collection of optimization work in the context of turbomachinery can be found in the notes of the von Karman Institute lecture series 2000-07. The presence of several examples with 2D optimization of airfoils illustrates the main problem of CFD-based optimization – the computational cost of each function evaluation. This can e.g. be overcome by adjoint methods (examples collected by Thévenin and Janiga) or simply by relatively coarse computational grids. To avoid increased uncertainties, grid independency studies are usually recommended. Good experience with optimization work using a relatively coarse grid (around 500,000 nodes) was made in an earlier study by the authors of this work.

The three optimization targets of this work address different practical requirements. The total-to-total efficiency considers the real total-to-total pressure rise from a plane upstream of the fan (“1”) to plane downstream of the fan (“2”):

$$\eta_{tt} = \frac{\dot{V} \Delta p_{tt}}{P}, \text{ where } \Delta p_{tt} = p_2 - p_1$$

(1)

However, this optimization target only makes sense when the dynamic part of $p_2$ is recovered by guide vanes and diffusers. Otherwise, the kinetic energy at the fan exit is lost and the total-to-static efficiency determines the power consumption of the fan:

$$\eta_{ts} = \frac{\dot{V} \Delta p_{ts}}{P}, \text{ where } \Delta p_{ts} = p_2 - p_1$$

(2)

In some applications it is necessary to consider not only the design point but an extended operating range. Each of these three requirements is supposed to have acoustic benefits and drawbacks. Optimization regarding total-to-total efficiency is concerned with the reduction of aerodynamic losses that originate from secondary flows or flow separation. These flow phenomena are known to be effective sound sources and it is expected that noise can be reduced by increasing $\eta_{tt}$. This is also confirmed by the aforementioned study. However, in most applications the blade load is determined by the total-to-static pressure rise that is required. The minimum blade load can then only be obtained by optimizing with respect to $\eta_{ts}$. Consequently, there are two competing effects which must be weighted up. In contrast, the impact of optimization with respect to operating range can easily be estimated. There will be a loss in peak efficiency but an increase at other operating points. It can be assumed that this leads to compromised acoustic properties at the design point but less noise at off-design. It is the aim of this work to quantify these effects.

Upon the design work, the characteristic curves of each fan is simulated and measured on a chamber test rig. Eventually, the acoustic performance of the four fans is measured in an anechoic chamber. The performance is analyzed regarding the overall sound power level ($L_{W,o}$) at the design point over fan speed, the overall sound power level over flow rate, and acoustic spectra. The definition of the specific sound power level is based on the Madison law

$$P_{\text{ac}} \sim u_{\text{op}}^m D^2.$$  

(3)
where \( P_{ac} \) is the acoustic power, \( u_{tip} = \pi n D \) is the rotational tip speed. Dimensional analysis as suggested by Starzmann\(^{10}\) yields

\[
L_{W,\text{spec}} = L_W - 10 \log \left( \frac{u_{tip}^3 D^2 \rho M a^{\alpha-3}}{P_0} \right)
\]  

(4)

where the acoustic reference power is assumed to be \( P_0 = 10^{-12} \) W. The Mach number is defined as tip speed of the fan over the local speed of sound \( (a) \).

\[
Ma = \frac{u_{tip}}{a}.
\]  

(5)

Generally, the speed of sound is a function of air conditions (e.g. temperature, moisture, density). Given the conditions determined prior to the measurements, we here assume \( a = 343 \) m/s.

II. Methodology

A. Fan design strategy

All fans are designed for the flow coefficient \( \phi = 0.2 \) and the total-to-static pressure coefficient \( \psi_{ts} = 0.18 \) which are defined as usual in a turbomachinery context:

\[
\phi = \frac{\dot{V}}{\pi \frac{3}{4} D^3 n}
\]  

(6)

\[
\psi = \frac{\Delta \rho}{\pi \frac{2}{2} D^3 n^2 \rho}
\]  

(7)

This is a typical operating point for low pressure axial fans which is within the proposed band in Cordier’s diagram. The fan designed with the blade element method is designed using the method suggested by Carolus and Starzmann\(^{4}\). NACA sections are used for the blade and the lift and drag of each section is predicted by XFOIL. Airfoils with low drag-to-lift ratio are selected to obtain high efficiency and an impeller that is representative for good state-of-the-art fans.

The geometry of the fans to be optimized are described by 25 parameters listed in Table 1. The hub-to-tip ratio \( \nu = D_h / D \) is quite significant. It is the most powerful parameter to influence exit losses but also has a significant impact on \( \eta_t \) and on the selection of the other parameters. The optimized designs also use NACA sections that are described by the maximum camber \( (f) \), position of maximum camber \( (x_f) \), maximum thickness \( (d) \), and position of maximum thickness \( (x_d) \). All of these parameters are normalized with the chord length \( (c) \). Formulas to compute the corresponding blade shape can be found in reference\(^{11}\). The section parameters are varied at hub, midspan, and shroud with polynomial interpolation in between. The design flow rate \( (\phi_d) \) is required to compute the relative inflow velocity. The blade sweep angle \( (\lambda) \) is applied in that direction and also varied at hub, midspan, and shroud. Furthermore, this flow component is required to determine the blade stagger angle which deviates from the inflow direction by the angle of attack \( (\alpha) \). Given these quantities a huge variety of potential blades can be realized. Nevertheless, the parameters are physically interpretable representing an advantage over optimization strategies in which the fan geometry is changed based on a set of control points.

The outer diameter \( (D) \) and the rotational speed \( (n) \) are constant throughout the optimization and hence the Reynolds number. Scaling up the fans would merely require a Reynolds number correction as e.g. discussed by Pelz\(^{12}\). In the present design process the diameter is \( D = 0.3 \) m and the fan speed is \( n = 50 \) s\(^{-1}\). The tip clearance is excluded from the optimization as the dependency between increasing tip clearance and increasing sound emission was proven in many previous studies. It is kept very small \( (S/D = 0.001) \) to minimize its impact. Moreover, the number of blades is constant \( (z = 9) \) to ensure equal blade passing frequencies at which the tonal components of the sound can be compared.
Table 1. Definition and ranges of optimization parameters.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol/Definition</th>
<th>Range</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub-to-tip ratio</td>
<td>( \nu = \frac{D_h}{D} )</td>
<td>0.3 – 0.6</td>
<td></td>
</tr>
<tr>
<td>Chord length ratio</td>
<td>( \frac{c}{D} )</td>
<td>0.133 – 0.333</td>
<td></td>
</tr>
<tr>
<td>Rel. camber</td>
<td>( \frac{f}{c} )</td>
<td>0 – 0.1</td>
<td>NACA airfoil section</td>
</tr>
<tr>
<td>Rel. position of max. camber</td>
<td>( \frac{x_f}{c} )</td>
<td>0.1 – 0.8</td>
<td>NACA airfoil section</td>
</tr>
<tr>
<td>Rel. max. thickness</td>
<td>( \frac{d}{c} )</td>
<td>0.05 – 0.15</td>
<td>NACA airfoil section</td>
</tr>
<tr>
<td>Rel. position of max. thickness</td>
<td>( \frac{x_d}{c} )</td>
<td>0.1 – 0.7</td>
<td>NACA airfoil section</td>
</tr>
<tr>
<td>Angle of attack</td>
<td>( \alpha )</td>
<td>-5° – +15°</td>
<td>Against relative inflow vector</td>
</tr>
<tr>
<td>Sweep angle</td>
<td>( \lambda )</td>
<td>-60° – +60°</td>
<td>Against relative inflow vector</td>
</tr>
<tr>
<td>Design flow rate</td>
<td>( \phi_d )</td>
<td>0.2 – 0.4</td>
<td>Required for ( \alpha ) and ( \lambda )</td>
</tr>
</tbody>
</table>

\(^1\) Defined at three equally spaced radial positions with polynomial interpolation in between.
\(^2\) Defined at five equally spaced radial positions with polynomial interpolation in between.

The optimization method is an evolutionary algorithm with a generation size \( N = 200 \). As mentioned before, the algorithm is an in-house implementation inspired by the work of Thévenin and Janiga\(^5\) as well as Nelles\(^6\). The algorithm is stopped manually when only minor improvements are observed from generation to generation. A typical number of generations required for each of the three optimization loops is around ten. The reproduction process of a new generation is merely based on crossover, i.e. mixing the parameters of two parent individuals (fan configurations). The probability of a fan configuration to participate in the reproduction process depends on its performance regarding the respective optimization target. Moderate mutations (random changes of parameters) are applied, too. The main reason for using evolutionary algorithms in this work is the capability of finding global optima. While the target function changes for every optimization, the design point \( \psi_0 \) is always incorporated as a constraint. For OTS and OTT, a single function evaluation at design point is sufficient whereas OOR considers the flow rates \( \phi_1 = 0.15, \phi_2 = 0.2, \) and \( \phi_3 = 0.25 \) to maximize the average of the three corresponding total-to-static efficiencies.

The target functions are always evaluated by RANS simulations. The rotating computational domain is discretized with the commercial grid generator ANSYS TurboGrid\(^8\) 14.0. The grid is block-structured and contains approx. 500,000 hexahedral elements. The domain extends one fan diameter upstream and two fan diameters downstream of the fan blade. A general grid interface (GGI) is placed in the tip clearance. To save computational time, only one blade passage with periodic boundary conditions at the sides is simulated. Further boundary conditions are rotational speed, given mass flow rate at the inlet, ambient pressure at the outlet, and no slip at the walls (hub, shroud, and blade). The solver is ANSYS CFX\(^9\) 14.0 and the shear stress transport (SST) turbulence model is selected. The pressure is evaluated at planes a little upstream of the leading edge and a little downstream of the trailing edge, respectively. All simulations are run until the convergence criteria are fulfilled, i.e. the maximum residuals with respect to conservation of mass and momentum must be smaller than \( 10^{-4} \).

B. Measuring set-up

The characteristic curves of the fans are measured at the test rig of the University of Siegen according to DIN 24163\(^13\). The results are required to validate the CFD results. The fan’s suction side is connected to the chamber and exhausts into the free atmosphere. The static pressure is measured in the chamber assuming \( p_t = p \) due to the very low flow velocity and atmospheric pressure is assumed downstream of the fan due to the free blowing conditions. This means that it is not possible to determine the total-to-total pressure rise because the swirl energy downstream of the fan cannot be measured. An auxiliary fan is installed upstream of the chamber to facilitate higher flow rates. Air density, volume flow, torque and rotational speed are captured as well and the important dimensionless values \( \phi, \psi \) and \( \eta \) are computed according to Eqs. 1, 2, 6, and 7.

Sound is measured in a semi-anechoic chamber with three microphones by Brüel&Kjaer. The microphones are placed in the height of the rotation axis, at a distance of 1.3 m from the leading edge, and at the angles of -35, 0 and +35° from the rotation axis. A further microphone is placed in the duct downstream of the fan. This configuration allows determining the sound power level \( L_{W4} \) in the semi-anechoic chamber as well as the sound power level \( L_{W5} \) in the duct (according to DIN ISO 5136\(^14\)). All time signals of the sound pressure are captured with a sampling frequency \( f_s = 25.6 \) kHz for a duration of \( T = 10 \) s. The power spectral density is obtained by the Matlab\(^8\) function \( \text{pwelch} \) (window, noverlap, nfft, fs) where the input is selected as follows:

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- \( p \): signal to be analyzed
  - here: acoustic pressure from measurements
- \( \text{window} \): window size
  - here: Hann window with window size = \( f_s \)
- \( \text{nooverlap} \): overlapping of windows
  - here: no overlapping (\( \text{nooverlap} = 0 \))
- \( \text{nfft} \): number of FFT points
  - here: equal to window length
- \( f_s \): sampling rate
  - here: \( f_s = 25600 \)

Pictures of both test rigs are shown in Fig. 1.

C. Separation of acoustic effects

In the optimization loops, the blade sweep angle is one of several parameters that is optimized for the specific aerodynamic target. However, it also has a direct impact on sound emission which originates from oblique impingement of turbulent structures at the blade leading edges and phase-shift canceling of noise generated at different spanwise positions. Fundamental work on this was done by Kerschen\(^{15}\) and Ffowcs Williams and Hall\(^{16}\) who investigated the acoustic effect of sweep at isolated airfoils or planes, respectively. Assessment of the impact of the design strategy on sound emission must take effects due to sweep into account in order to avoid misinterpretations. Assuming the simple law that \( p_{ac} \sim w_n^2 \), where \( w_n \) is the component of the relative flow velocity \( w \) that is normal to the blade stacking line, the impact of sweep at each radial position can be estimated by

\[
\Delta L_{\text{wp}}(r) = L_{W,\text{unswept}} - L_{W,\text{swept}} = 40 \cdot \lg \left( \cos \left( \frac{\lambda(r)}{\cos(\lambda)} \right) \right) \text{ dB}
\]  

(8)

Note that the increased edge length of one blade segment \( \frac{\Delta r_{\text{swept}}}{\Delta r_{\text{unswept}}} = \frac{\cos(\lambda)}{\cos(\lambda - \epsilon)} \) decreases the exponent by one, i.e. \( p_{ac} \sim \cos^3(\lambda) \).

III. Results

A. Optimization results and validation

A top view of the four fans is depicted in Fig. 2. Three observations are obvious at first sight:

1. The \( \eta_t \)-optimization leads to a very small hub-to-tip ratio. Although this is not surprising due to the dependency between exit losses and throughflow area, it is interesting how the other parameters are adjusted to enable such a small hub. Normally, small hub-to-tip ratios lead to aerodynamic problems as suggested by the validity criteria by de Haller\(^{17}\) or Strscheletzky\(^{18}\). In contrast, the \( \eta_r \)-optimized fan has the largest hub which leads to favorable flow conditions with low secondary flow effects.
2. In all three cases, the optimization algorithm uses the sweep angle parameters to create a straight leading edge which is almost a radial beam. Normally, the leading edge is oblique or even curved due to the spanwise variations in chord length.

3. The range optimized fan has an extremely short chord length at midspan. It is assumed that this separates flow features at the two endplates and consequently delays stall.

A more detailed aerodynamic explanation of the flow phenomena behind the optimization results is currently investigated but kept short for the present paper.

Fig. 3 compares the numerically predicted characteristic curves of the final designs. Note the common point $\psi_{ts}(\phi = 0.2) = 0.18$ which was the constraint in the optimization. The optimization with respect to different target functions is considered successful as the targets are reflected in the graphs. OTS and OTT have the highest total-to-static or total-to-total efficiencies, respectively. OOR is somewhere in between at the design point and has the greatest range between stall and zero-crossing. All numerically predicted curves are validated against measurements which is shown in Fig. 4. Since $\Delta p_{nl}$ cannot be measured on the test rig described previously, only the total-to-static curves are plotted. All curves show good agreement. This proves that the optimizer really improves performance rather than just exploiting numerical weaknesses which wrongly promise high efficiencies.

The maximum impact of leading edge sweep according to Eq. 8 is expected for the $\eta_{ts}$-optimized fan with an overall sound reduction by only 1.1 dB. Consequently, remarkable differences in sound emission cannot be ascribed to the direct acoustic effect of blade sweep, but must originate from other effects.

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Blade element momentum method (BEM)  
$\eta_{ts}$-optimized (OTS)  
$\eta_{tt}$-optimized (OTT)  
Optimized for operating range (OOR)

**Fig. 2:** Top view of the fans investigated. All fans are manufactured by selective laser sintering.
**B. Acoustic comparison at design point**

The sound power level is determined at several fan speeds between \( n_{\text{min}} = 1400 \, \text{min}^{-1} \) and \( n_{\text{max}} = 2400 \, \text{min}^{-1} \) leading to the Mach numbers \( M_{\text{amin}} = 0.064 \) and \( M_{\text{amax}} = 0.11 \). The results are depicted in Fig. 5. It is distinguished between \( L_{W,\text{o},\text{spec}} \) in the anechoic chamber and \( L_{W,\text{o}} \) in the duct downstream of the fan. Given the measuring points, the two unknowns in Eq. 4 (\( L_{W,\text{o},\text{spec}} \) and \( \alpha \)) can be determined by fitting the equation to the measuring data with the least squares method. Table 2 summarizes the results. A direct comparison of \( L_{W,\text{o},\text{spec}} \) would be misleading because the
exponents $\alpha$ are quite different. Instead, $L_{W, o}$ is compared for distinct Mach numbers as shown in Figure 6. It can be observed that OTT and OTS are quietest at low and high Mach numbers, respectively. The critical Mach numbers where OTT and OTS have the same sound power level is $Ma = 0.12$ (for $L_{W4,o}$) or $Ma = 0.1$ (for $L_{W5,o}$). Since low pressure axial fans are usually operated at rather low Mach numbers, the superiority of OTT in that area will be more significant. It is remarkable that OOR is the loudest fan at almost all Mach numbers that are considered and even exceeds the sound power level of the analytical design.

Table 2. Specific sound power and acoustic exponent of all fans at design point.

<table>
<thead>
<tr>
<th>Type</th>
<th>$L_{W4,spec}$ [dB]</th>
<th>$\alpha_4$</th>
<th>$L_{W5,spec}$ [dB]</th>
<th>$\alpha_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEM</td>
<td>-83.4</td>
<td>2.9</td>
<td>-75.9</td>
<td>3.6</td>
</tr>
<tr>
<td>OTS</td>
<td>-89.5</td>
<td>2.5</td>
<td>-101.0</td>
<td>1.4</td>
</tr>
<tr>
<td>OTT</td>
<td>-81.0</td>
<td>3.4</td>
<td>-67.1</td>
<td>4.7</td>
</tr>
<tr>
<td>OOR</td>
<td>-62.0</td>
<td>4.7</td>
<td>-68.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Fig. 5: $L_{W4,o}$ and $L_{W5,o}$ at design point over Mach number. Markers: measuring points. Solid lines: fitting curves according to Eq. 4 obtained by the least squares method.

Fig. 6: $L_{W4,o}$ and $L_{W5,o}$ at design point over Mach number according to Eq. 4 and Table 2. Measuring data exists until $Ma_{max} = 0.11$. The sound at higher Mach numbers is extrapolated.
C. Acoustic comparison at various flow rates

So far all comparisons were drawn at the design point, i.e. $\phi = 0.2$. Fig. 7 plots $L_{W,\text{spec}}$ according to Eq. 4 over flow rate. Although the acoustic exponent of each fan was determined at the design point, we here apply it to all flow rates. Again, a direct comparison of $L_{W,\text{spec}}$ would be misleading due to the different exponents $\alpha$. Hence, a comparison is conducted at a realistic Mach number, more specifically at $Ma = 0.11$ which corresponds to the maximal fan speed that was measured. Fig. 8 illustrates that at this Mach number the optimized fans OTS and OTT are not only quieter at the design point, but over the complete operating range. OOR is loudest at all design points. However, adequate comparisons must take the different characteristic fan curves into account (see Fig. 3). While the sound power level of OOR approaches the levels of the other designs at very high or low flow rates, it has the best aerodynamic characteristics in terms of pressure coefficient and efficiency under those operating conditions. Hence, optimization with respect to operating range can also have acoustic advantages.

Fig. 7: Specific sound power over flow coefficient for all fans.

Fig. 8: Sound power over flow coefficient for all fans at $n = 2400 \text{ min}^{-1}$ ($Ma = 0.11$).
D. Comparison of acoustic spectra at design point

Fig. 9 shows the acoustic spectra of all fans at design point and maximum speed, i.e. $\phi = 0.2$ and $n = 2400 \text{ min}^{-1}$. The frequency is normalized with the blade passing frequency $\text{BPF} = n_z = 360 \text{ Hz}$. The most important observation is that there is no apparent correlation between the tones (and their harmonics) and the design strategy. In contrast, Fig. 10 clearly shows that the acoustic benefits obtained by the optimization work originate from broadband effects. The difference between the four designs regarding broadband sound is considerably higher than indicated by the plots in Figs. 6 and 8 which also take the tone and its harmonics into account. This observation is not surprising as the main acoustic effects addressed by the optimization, i.e. reduction of secondary flows (OTT) and reduction of blade load (OTS), mainly contribute to reduced broadband sound. The tones possibly originate from the interaction of the blade with large-scale inflow distortions. (Recently, it was shown by Sturm and Carolus\cite{19} that the room-specific inflow conditions have a major impact on the tone even if the test rig is built according to the present ISO standards.) Assuming that these distortions are similar for all designs, the tone of each configuration is determined by the leading edge shape which was not controlled in the optimization loops. It is planned to repeat the acoustic investigations with a turbulence screen to eliminate any impact of inflow distortions.

![Fig. 9: Acoustic spectra of all fans at design point, $n = 2400 \text{ min}^{-1}$ ($Ma = 0.2$). The tone at the BPF and its first three harmonics are additionally highlighted by dots.](image1)

![Fig. 10: Acoustic spectra of all fans at design point, $n = 2400 \text{ min}^{-1}$ ($Ma = 0.11$). The tone at the BPF and its first three harmonics are additionally highlighted by dots.](image2)
IV. Conclusions

A case study was conducted comparing the acoustic impact of four distinct aerodynamic fan design strategies on sound emission. The design methods utilized were (i) the straightforward analytical blade element momentum method, (ii) optimization with respect to total-to-static efficiency, (iii) optimization with respect to total-to-total efficiency, and (iv) optimization with respect to operating range. The design point was defined by total-to-static pressure rise at a specific flow rate. Optimization was done by CFD simulations embedded in an evolutionary algorithm. It was shown that steady-state simulations with a relatively coarse computational grid are suitable as the CFD results were successfully validated against experimental measurements. However, it is uncertain if the full potential was exploited or if the results would have been even better using unsteady simulations with a finer grid.

Acoustic investigations showed that the optimization with respect to total-to-total efficiency is most efficient to reduce sound at low Mach numbers whereas optimization with respect to total-to-static efficiency is most efficient to reduce sound at high Mach numbers. However, the Mach numbers at which the total-to-static optimization becomes superior are higher than usually applied for low pressure axial fans. Nevertheless, optimization with respect to total-to-total efficiency cannot be recommended universally because of the increased power consumption as compared to the total-to-static optimization and due to the long development time as compared to the analytical design. Practical design work will always be a trade-off between sound emission, power consumption, and development cost. A more obvious conclusion is that optimization with respect to operating range can only be recommended if it is actually known that various operating conditions exist because this design is loudest at design point. However, it was also shown that this observation vanishes when moving away from the design point where the other designs show weaker aerodynamic performance which also compromises the acoustic properties.

Spectral analysis revealed that the most significant differences occur regarding broadband sound whereas there is no apparent correlation between aerodynamic design strategy and tones. This originates from the fact that the most important acoustic effects of the optimization work, i.e. reduction of secondary flows and reduction of blade load, mainly address broadband sound.

In future work, similar investigations at other design points should be conducted to check for generalization of the results. Such investigations are of particular interest at untypical design points at which the blade element momentum method is less precise. It is assumed that the acoustic advantage due to aerodynamic optimization will be greater at such points. A more significant difference is also expected when a turbulence screen upstream of the fan minimizes the impact of inflow distortions on sound. Such a configuration would allow for a cleaner acoustic analysis which does not suffer from the impact of room-specific inflow conditions. These investigations are currently prepared. Moreover, transient simulations of the four fans are planned to gain more insight into the flow phenomena behind the acoustic results described in this work.

References


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