SOUND REDUCTION BY LEADING EDGE SERRATIONS IN LOW-PRESSURE AXIAL FANS

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SUMMARY

In axial fan design, sound reduction has become an area of great interest. One approach to decrease the sound radiation of axial fans is the modification of the fan blade leading edges, particularly if the fan is operating under inflow conditions with a high inflow turbulence intensity. In this study, a generic flat-plate fan with different sinusoidal leading edge geometries was investigated to identify the impact of the leading edge design on the aerodynamic and acoustic properties. The results showed that the sound emission can be substantially decreased by the change in the leading edge geometry, along with an improvement of the pressure rise and the efficiency. These findings can be further used for the aeroacoustic optimization of axial fans.

INTRODUCTION

Low–pressure axial fans are used in a large variety of applications. Complex installation situations of axial fans often result in a distorted flow–field upstream of the fan with a noticeable increase in the turbulence intensity. Such distorted inflow conditions lead to a substantial increase in the sound radiation of the fan [1, 2, 3, 4, 5, 6, 7, 8]. For a selective reduction of the sound generation mechanisms under distorted inflow conditions, particularly turbulence ingestion noise, leading edge serrations have been used successfully on flat plates and airfoils. These sound reduction effects can, in theory, also be transferred to axial fans.

Sound reduction by leading edge serrations in flat plates and airfoils

In many cases, leading edge modification approaches include the use of sinusoidal leading edges or a variation of those. Important design parameters for sinusoidal leading edges are the serration wavelength λ_{LE} and the serration amplitude a_{LE} (Figure 1). They are often expressed in percentage of the chord length l_{c}.

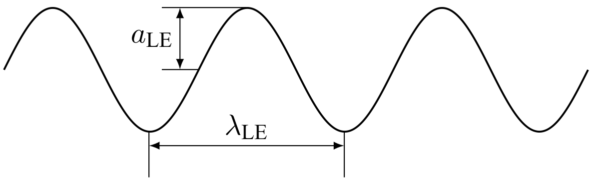

Figure 1: Serration wavelength λ_{LE} *and amplitude* a_{LE} *for a sinusoidal leading edge.*

The sound reduction for flat plates and airfoils is mainly achieved by a decrease in turbulence ingestion noise [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20].

On comparing the pressure fluctuation levels on straight and sinusoidal leading edges, it was found that the levels are substantially higher on straight leading edges than on sinusoidal leading edges. This occurs due to decreased pressure fluctuations at the top and midslope of the serrations. A decrease in acoustic pressure fluctuations in the leading edge region, i.e. turbulence ingestion noise, is thereby attributed to a reduction in hydrodynamic pressure fluctuations. [11, 15, 14, 13, 17, 18, 19, 20]

A reduction of hydrodynamic pressure fluctuations in the leading edge region is also associated with a reduction of unsteady blade forces [13, 15], which is a potential tonal sound source in axial fans [21, 22].

Besides this, leading edge serrations also induce a sound source decorrelation effect in the leading edge region [11, 13, 14, 15, 17, 18, 19]. For this, there are different suggestions on the optimal serration wavelength λ_{LE}. Clair et al. [11] state that the serration wavelength should be lower or close to the integral length scale of the inflow. In contrast, Chaitanya et al. [20] suggest a leading edge wavelength of four times the size of the integral length scale Λ for an optimal sound reduction.

For flat plates and airfoils, the sound reduction has been found to be greater influenced by the serration amplitude a_{LE} than by the serration wavelength λ_{LE} (for sinusoidal leading edge serrations). [9, 11, 13, 14, 16, 17, 19]

As a further development of sinusoidal leading edge, Chaitanya et al. [23] propose double-wavelength sinusoidal serrations (i.e. a superposition of two sinusoidal serrations). This approach showed a higher sound reduction, compared with single sinusoidal leading edge serrations, due to the occurrence of interferences between adjacent serration roots.

Sound reduction by leading edge serrations in axial fans

There are only a few studies on the application of leading edge serrations in axial fans, or rotating systems in general.

A numerical study of the aerodynamic impact of sinusoidal leading edges in a low-pressure axial fan was made by Corsini et al. [24]. The leading edge modifications were not applied along the whole fan blade span, but only to the outer 20 % of the fan blade. The sinusoidal serrations had an amplitude $a_{\mathrm{LE}} = 0.03\, l_{\mathrm{c,tip}}$ and a wavelength $\lambda_{\mathrm{LE}} = 31\, l_{\mathrm{c,tip}}$, with the chord length at the fan blade tip $l_{\mathrm{c,tip}}$. For the fan with the sinusoidal leading edges, a reduction in the sound power level of 2.3 dB was observed, compared with the reference fan with straight leading edges. Corsini et al. found that this reduction was induced by a change in the tip-leakage vortex behavior

The study by Corsini et al. [24] proved, that leading edge serrations can be successfully applied to axial fan blades for a decrease in the sound emission. Nevertheless, to date, there is still limited knowledge on the optimal leading edge parameters available. Hence the goal of this study was to deliver a compact parametric study of the impact of different leading edge geometries on the sound emission of a generic flat–plate fan.

EXPERIMENTAL SETUP

For the parametric study, a reference fan with straight leading edges, four fans with single-sine serrations (sinusoidal), and four fans with double-sine serrations (two sine waves superposed) were investigated with focus on their aerodynamic and acoustic properties.

Axial fan design and leading edge parameters

The generic flat–plate fan (Figure 2) had a hub diameter $d_{\text{hub}} = 250\,\text{mm}$, an outer diameter $d_{\text{fan}} = 497\,\text{mm}$ and a tip gap size $s_{\text{tip}} = 1.5\,\text{mm}$. Flat aluminum plates with a thickness $t = 6\,\text{mm}$ were used as fan blades. The blades were designed so that the leading edge coincides with the radial direction, thus eliminating the impact of any type of fan blade skew on the sound emission. As the flat plates were not twisted, the stagger angle was $\gamma = 20°$ along the whole fan blade span (Figure 2).

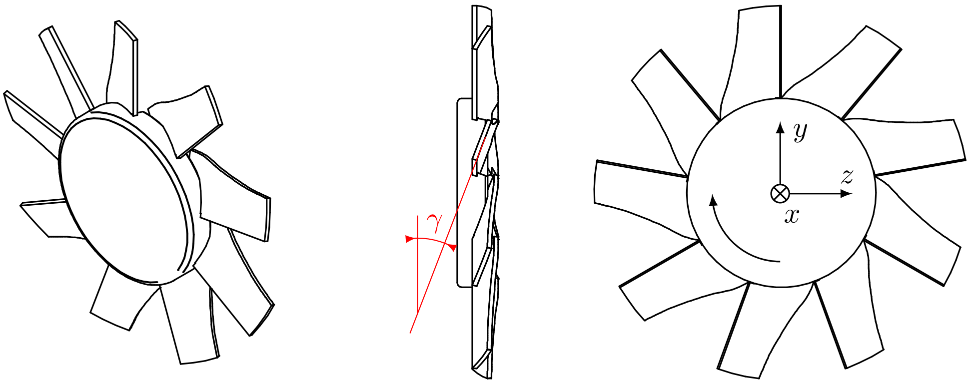

Figure 2: Simplified axial fan with straight leading edges.

The fan blades of the generic flat–plate fan were interchangeable, hence only one fan hub was used. As reference case (REF), a fan blade set with straight leading edges was used (Figure 2). The mean chord length l_c of the fan blades with leading edge serrations was identical to the chord length of the fan blade with straight leading edges (REF), with $l_c = 72\,\text{mm}$. The leading edge parameters for the single-sine serrations and the double-sine serrations are listed in Tables 1 and 2. For the double-sine serrations, Φ corresponds to the phase difference of the two sine waves.

Table 1: Single-sine serration parameters.

name	a_{LE} in % l_c	λ_{LE} in % l_c
A133λ67	13.3	6.7
A133λ100	13.3	10
A167λ67	16.7	6.7
A167λ100	16.7	10

The chosen values of the serration parameters correspond to typical values for leading edge serrations of flat plates and airfoils as described in the previous Section. A fan blade of each blade set is shown in Figure 3.

Table 2: Double-sine serration parameters.

name	a_{LE} in % l_{c}	$\lambda_{1,\mathrm{LE}}$ in % l_{c}	$\lambda_{2,\mathrm{LE}}$ in % l_{c}	Φ
A67λ67_133_0	6.7	6.6	13.3	0
A67λ67_133_2	6.7	6.6	13.3	$\pi/2$
A67λ100_200_0	6.7	10	20	0
A67λ100_200_2	6.7	10	20	$\pi/2$

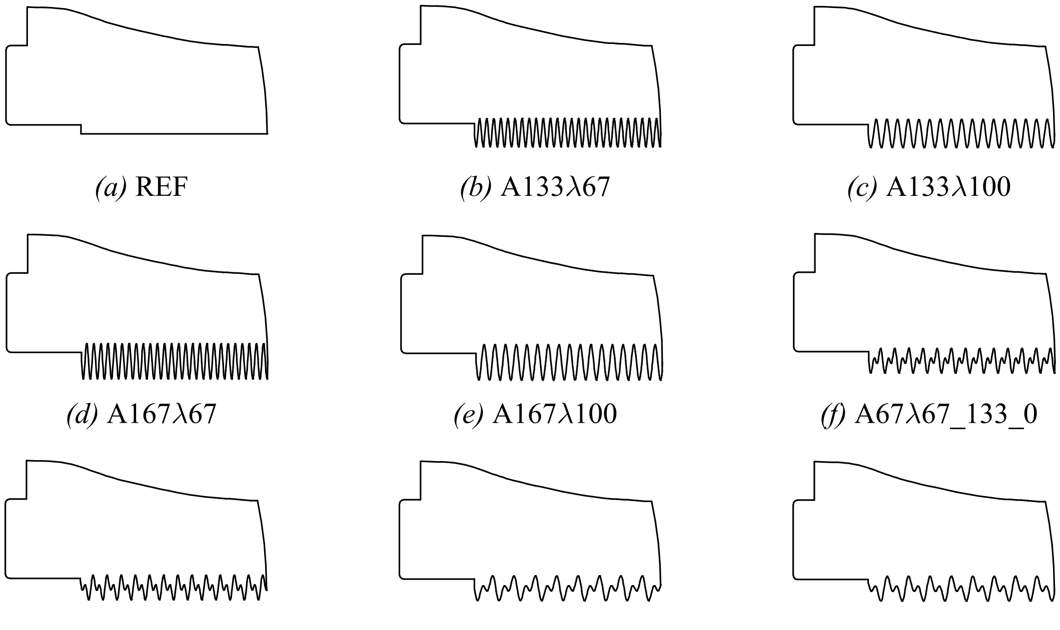
(a) REF *(b)* A133λ67 *(c)* A133λ100
(d) A167λ67 *(e)* A167λ100 *(f)* A67λ67_133_0
(g) A67λ67_133_2 *(h)* A67λ100_200_0 *(i)* A67λ100_200_2

Figure 3: Fan blade geometries with straight leading edge (a), single-sine leading edges (b) to (e) and double-sine leading edges (f) to (i).

Fan installation

All investigations were made in a standardized inlet test chamber, based on ISO 5801 [25], with absorbing walls, ceiling and floor (Figure 4). Thereby, the fans were installed in a short duct segment with a diffusor downstream of the fan and an inlet bellmouth upstream of the fan (Figure 4). To increase the inflow turbulence intensity, a grid, built up of rectangular cells with a mesh size $t_{\mathrm{mesh}} = 24$ mm, was used (Figure 4). The grid had a solidity of $\alpha = 0.31$. A study on the grid-induced inflow parameters can be found in [26].

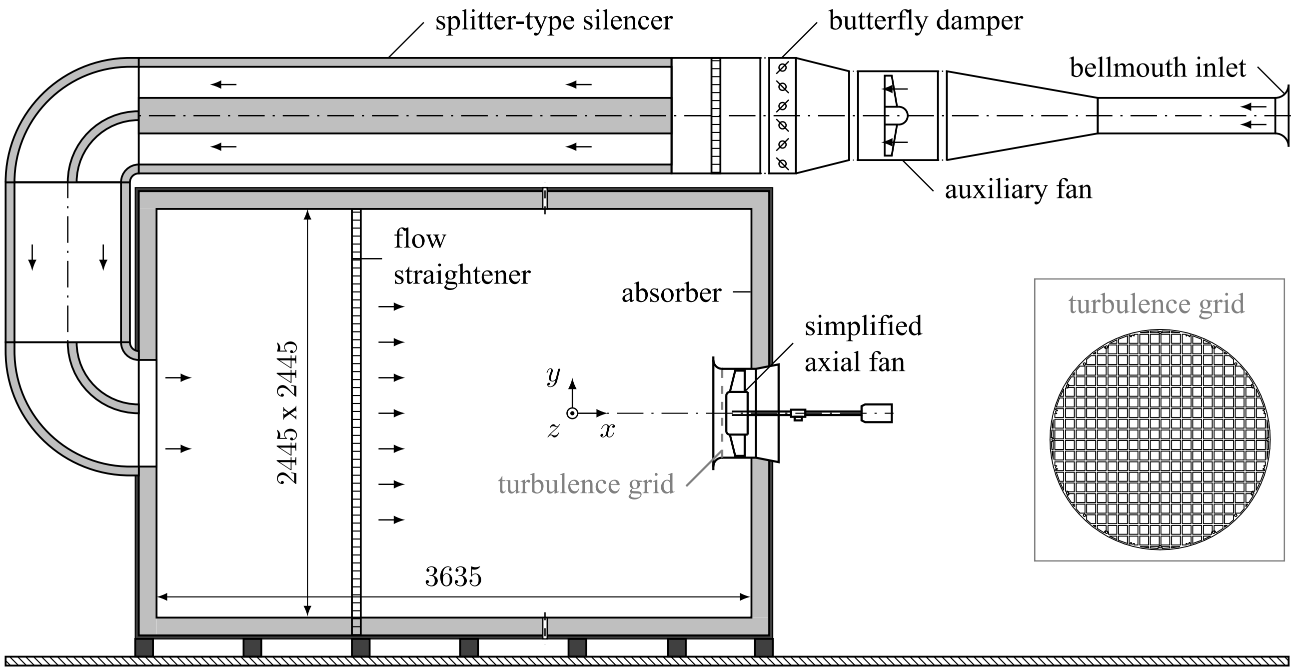

Figure 4: Inlet test chamber and fan installation. Dimensions in mm.

Sound field

The radiated sound field of the fans was captured with seven 1/2" free–field microphones that were arranged in a semicircle in a horizontal plane around the inlet bellmouth (Figure 5). Overall sound pressure levels and sound pressure spectra were averaged over the seven microphone positions.

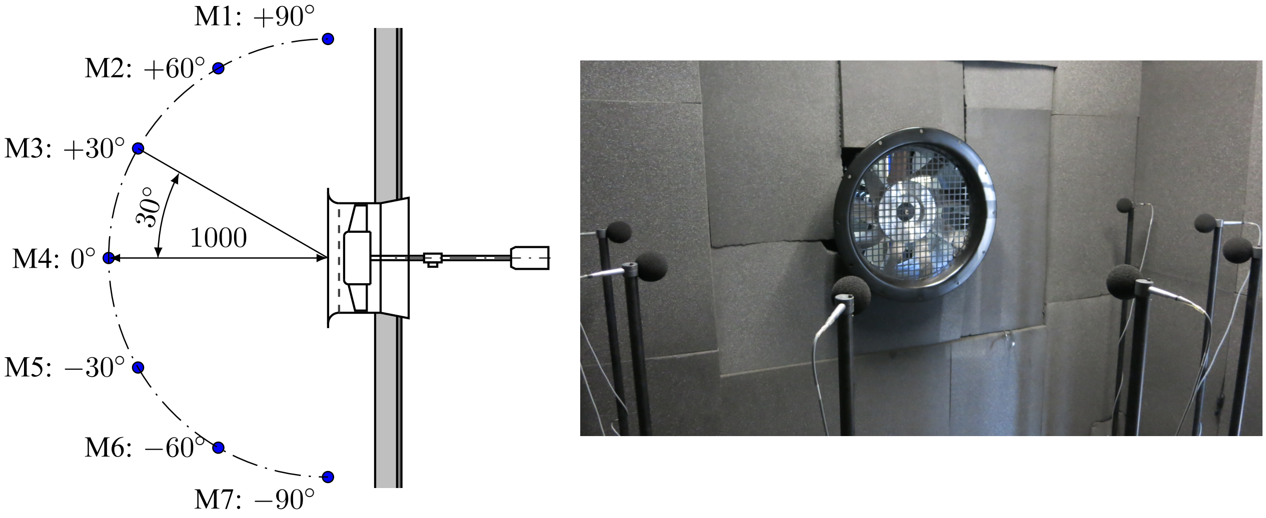

Figure 5: Microphone positions, schematic (left) and photograph (right). Dimensions in mm.

RESULTS

First, the impact of different leading edge geometries on the aerodynamic and acoustic characteristic curves is discussed. After that, the acoustic properties are examined on the basis of averaged sound pressure spectra at two different operating points.

Aerodynamic and acoustic characteristic curves

Aerodynamic and acoustic characteristic curves of the different fans are shown in Figure 6 (single-sine serrations) and Figure 7 (double-sine serrations).

Both single- and double-sine serrations lead to higher total-to-static pressure difference values Δp_{ts} in the range $\dot{V} \in (0.8, 1.2)$, compared with the reference fan with straight leading edges. Based on previous studies on flat plates and airfoils [27, 11, 28, 29, 30, 16], a shift of stall onset to higher angles of attack (i.e. lower volume flow rates for axial fans) is mainly expected for post-stall operating conditions. This corresponds to operating points at which stall occurs on the fan blades. In axial fans, stall usually occurs at volume flow rates that are smaller than the volume flow rate with the highest efficiency. Hence the operating points with increased total-to-static pressure difference values Δp_{ts} for the fans with leading edge serrations do not necessarily correspond to the post-stall region. However, owing to the constant stagger angle γ, the angle of attack α_{a} varies along the span. Consequently, it cannot be guaranteed that all blade sections (from hub to tip) are operating in the pre-stall range at the volume flow rate with the highest efficiency, particularly those near the fan hub. In general, all types of leading edge serrations provide similar improvements in the range $\dot{V} \in (0.9, 1.2)$. At lower volume flow rates, the double-sine serrations lead to a higher total-to-static pressure difference than the single-sine serrations.

Although there is no major impact on the total-to-static pressure difference, the total-to-static efficiency η_{ts} is substantially increased by all types of leading edge serrations. The efficiency for the fans with serrated leading edges is expected to be improved, due to streamwise vortices that develop on the serrations and interact with the radial directed flow [11, 29, 30, 28, 17, 17]. This also affects the tip vortex formation [31, 32, 33, 34] and hence reduces losses in the tip region, as observed by Corsini et al. [35, 36].

In addition to the efficiency improvements, the leading edge serrations lead to a greatly decreased sound emission. The averaged overall sound pressure levels $\overline{L}_p$ of the reference fan with straight leading edges are higher than those of the fans with modified leading edges. Thereby, differences of up to $\Delta\overline{L}_p = 6.6\,\mathrm{dB}$ occur (for the fan with the fan blades A167λ67 at a volume flow rate $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$). In general, the sound reduction is more prominent for the fans with single-sine serrations than for the fans with double-sine serrations. For the single-sine serrations, the fan blades with the smallest wavelength λ_{LE} and the largest amplitude a_{LE} shows the greatest sound reduction at nearly all considered volume flow rates. The acoustic characteristic curves for the fans with double-sine serrations are very similar with hardly any observable differences between the four investigated leading edge geometries. For the double-sine serrations, differences of up to $\Delta\overline{L}_p = 4.9\,\mathrm{dB}$ occur (for the fan with the fan blades A67λ67_133_2 at a volume flow rate $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$).

A detailed discussion of the impact of the leading edge serrations on the sound generation mechanisms in axial fans will be given on examining averaged sound pressure spectra at two different volume flow rates with $\dot{V} = 0.7\,\mathrm{m}^3/\mathrm{s}$ and $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$.

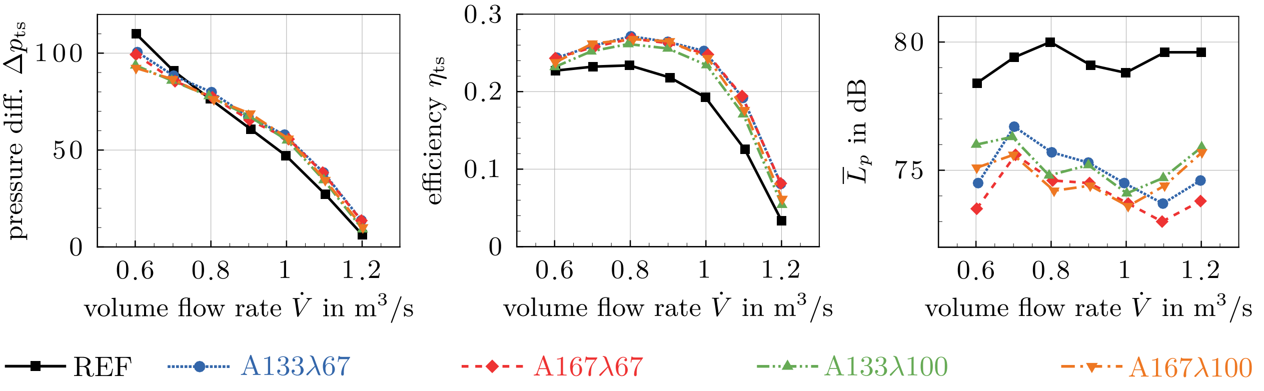

Figure 6: Aerodynamic and acoustic characteristic curves for the fans with single-sine serrations.

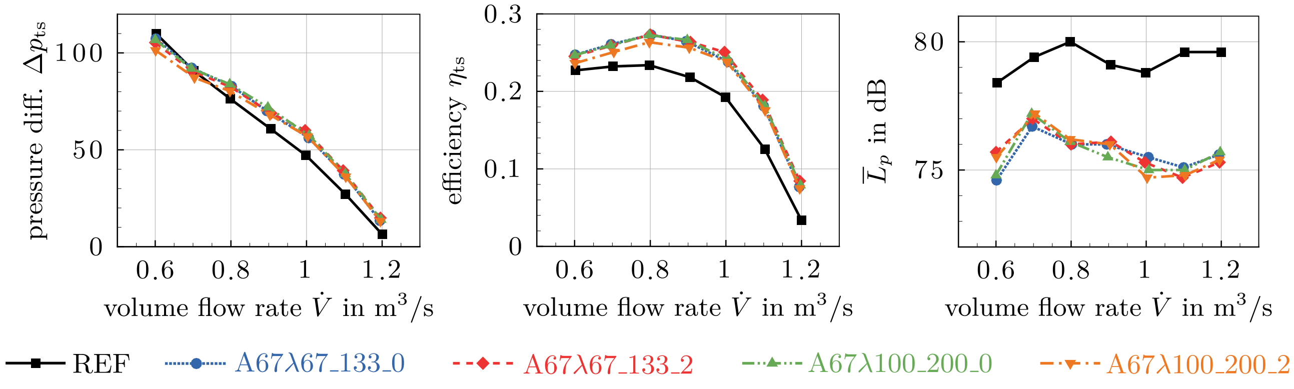

Figure 7: Aerodynamic and acoustic characteristic curves for the fans with double-sine serrations.

Averaged sound pressure spectra

Averaged sound pressure spectra are shown in Figures 8 and 9 for $\dot{V} = 0.7\,\mathrm{m}^3/\mathrm{s}$ and in Figures 10 and 11 for $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$.

For the spectra at $\dot{V} = 0.7\,\mathrm{m}^3/\mathrm{s}$, an impact of the leading edge serrations can be seen in the frequency range $f \in (0.4\,\mathrm{kHz}, 2\,\mathrm{kHz})$. Hence for this volume flow rate, mainly broadband sound is reduced. As already observed for the acoustic characteristic curves, this impact is more prominent for the fans with single-sine serrations than for those with double-sine serrations.

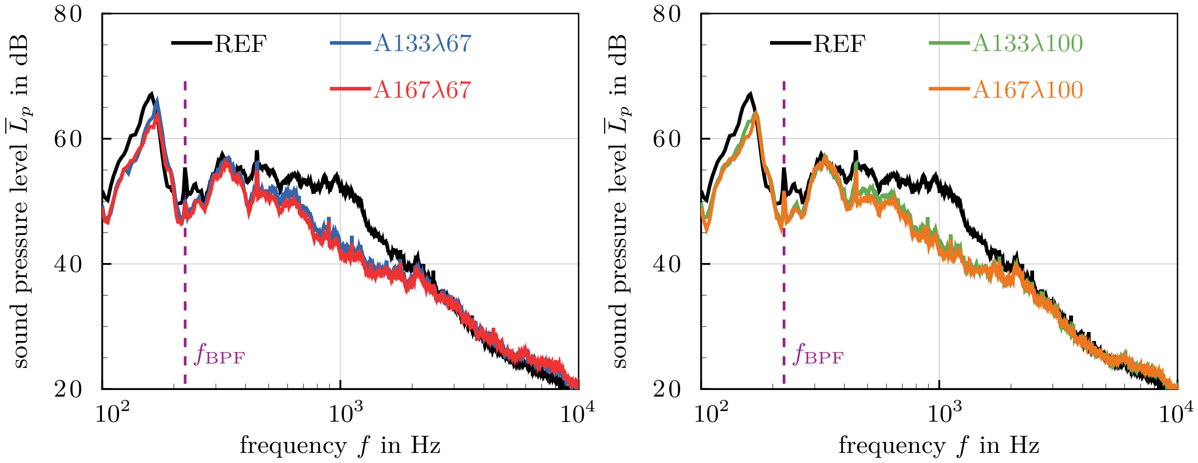

Figure 8: Averaged sound pressure spectra for the fans with single-sine serrations at a volume flow rate $\dot{V} = 0.7\,\mathrm{m}^3/\mathrm{s}$.

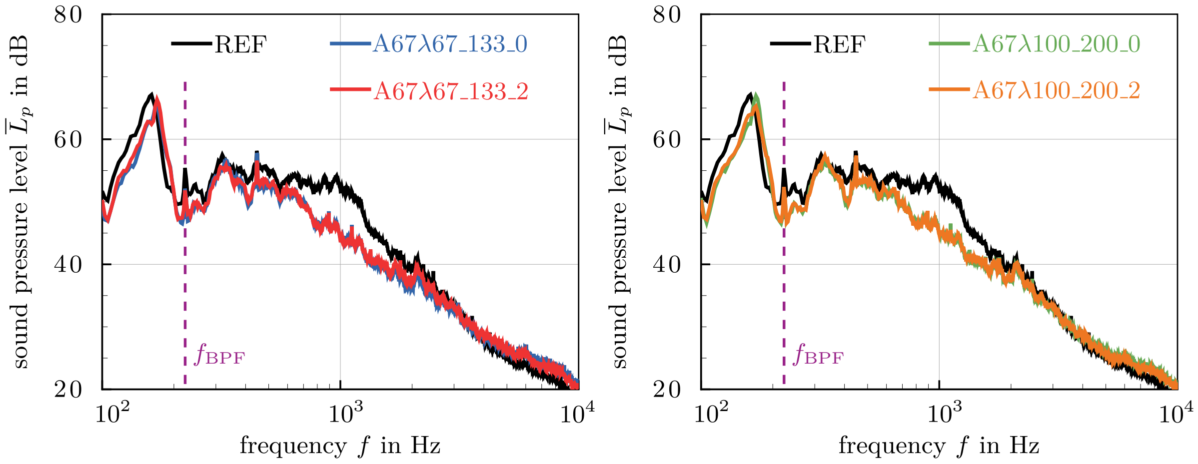

Figure 9: Averaged sound pressure spectra for the fans with double-sine serrations at a volume flow rate $\dot{V} = 0.7\,\mathrm{m}^3/\mathrm{s}$.

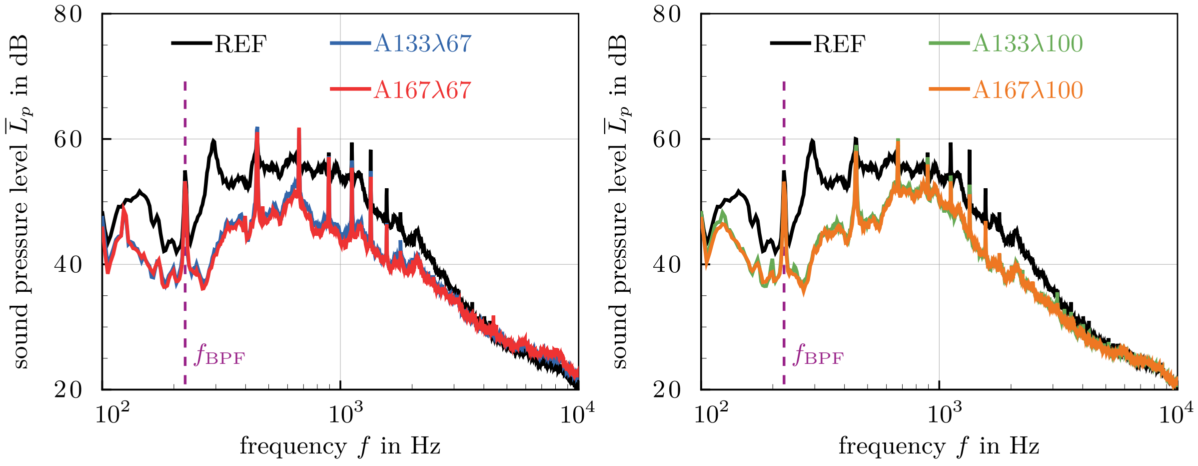

Figure 10: Averaged sound pressure spectra for the fans with single-sine serrations at a volume flow rate $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$.

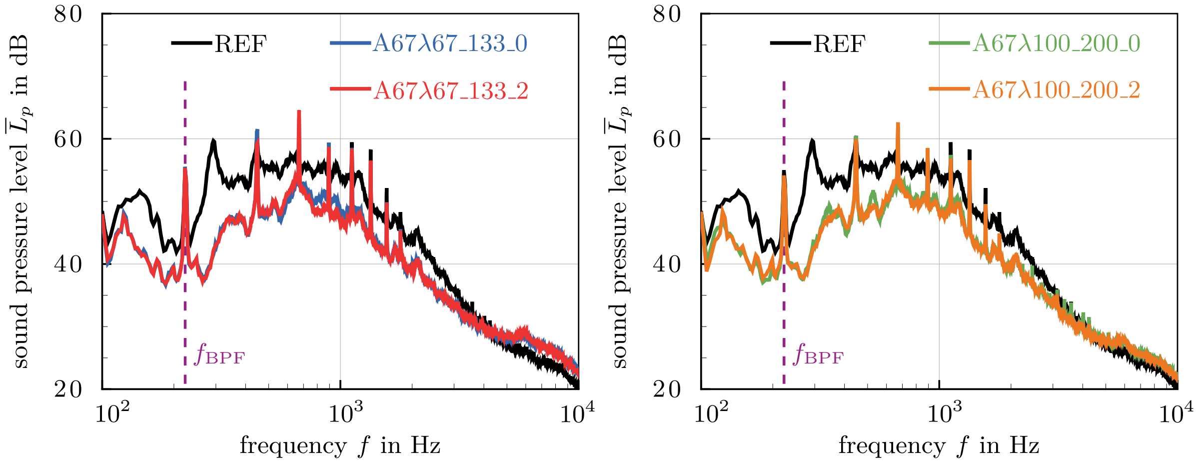

Figure 11: Averaged sound pressure spectra for the fans with double-sine serrations at a volume flow rate $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$.

In contrast to the spectra at a volume flow rate $\dot{V} = 0.7\,\mathrm{m}^3/\mathrm{s}$, a substantial impact of the leading edge serrations is observed at $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$ – not only for broadband components, but also for subharmonic narrowband (around $f = 290\,\mathrm{Hz}$) and tonal components at the blade passing frequency ($f = 223\,\mathrm{Hz}$) and harmonics.

A decrease in broadband sound components is clearly visible for the fans with leading edge serrations up to frequencies $f = 2 - 3\,\mathrm{kHz}$. Thereby, the single-sine serrations lead to a greater reduction than the double-sine serrations. One can argue that this is due to lower serration amplitude a_{LE} in the case of the double-sine serrations; however, owing to the superposition of two sine waves, the maximum (combined) amplitude of the double-sine serrations is similar to the amplitude of the single-sine serrations. Hence at similar amplitude values, the single-sine serrations provide a greater sound reduction than the double-sine serrations. For the single-sine serrations, the fan blades with a smaller serration wavelength λ_{LE} (A133λ67 and A167λ67) show a higher sound reduction for $f \in (0.4\,\mathrm{kHz}, 2\,\mathrm{kHz})$ and a volume flow rate $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$. At the volume flow rate $\dot{V} = 0.7\,\mathrm{m}^3/\mathrm{s}$, no dependency on the serration parameters is visible. The decrease in broadband components of the double-sine serrations is generally very similar among the four invested geometries, albeit a slightly higher decrease was observed for the fan blades with a smaller serration wavelength λ_{LE} (A67λ67_133_0 and A67λ67_133_2).

For flat plates and airfoils, in general no sound reduction of tonal components is observed with leading edge serrations. However, a reduction of unsteady blade forces has been reported [13, 15]. In axial fans, such unsteady blade forces are a very effective tonal sound source [21, 22]. These components occur at the blade passing frequency $f_{\mathrm{BPF}} = 223\,\mathrm{Hz}$ and harmonics. Particularly for the fans with single-sine leading edge serrations, the tonal peak at f_{BPF} is reduced. A further reduction is also observed for higher harmonics. In contrast, hardly any change in tonal components is observed for the double-sine serration fans. Hence at least for the single-sine serrations, a change in the leading edge geometry leads to an decrease in tonal sound components which can be related to a reduction of unsteady blade forces.

At a volume flow rate $\dot{V} = 1.1\,\mathrm{m}^3/\mathrm{s}$, there is a particularly high reduction of subharmonic narrowband sound components, that occur around $f = 290\,\mathrm{Hz}$. These components are induced by flow phenomena in the tip region. For the configurations with leading edge serrations, these contributions are greatly decreased. The reduction is slightly more pronounced for the fans with single-sine serrations than for the fans with double-sine serrations. In general, no dependency on the serration wavelength or amplitude is observed. The reduction of subharmonic narrowband components is a clear indicator of a substantially altered flow-field in the tip region, as the the tip vortex formation and the tip leakage flow are the driving parameters for this sound generation mechanism. It can be expected, that similarly to the observations by Corsini et al. [35, 36], counter rotating vortices that are induced by leading edge serrations interact with and weaken the tip vortex. Additionally, the vortices are expected to interact with the radial directed flow near the fan blade surface, which further suppresses the tip vortex formation [31, 32, 33, 34].

CONCLUSION

In this study, the effectiveness of leading edge serrations for reducing the sound emission of a generic flat-plate fan was investigated experimentally. In total, nine fans with different leading edge geometries were studied, among them four fans with single-sine leading edge serrations and four fans with double-sine leading edge serrations. The results showed that there is a high potential for reducing axial fan noise with a modification of the leading edge geometry. Thereby, analogies to the sound reduction mechanisms by leading edge serrations, applied to flat plates or airfoils, were found. Additionally, effects that occur only for rotating systems were uncovered. In general, single-sine serrations showed a higher sound reduction than double-sine serrations. Among the single-sine serrations, those with the smallest serration wavelength and the highest serration amplitude lead to the greatest decrease in the sound emission. This study suggests that there is a high potential for decreasing the sound emission of axial fans through the application of leading edge serrations.

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