PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Experimental investigation of the influence of different leading edge modifications on the sound emission of axial fans downstream of a heat exchanger

Felix CZWIELONG[1], Florian KRÖMER[2], Paruchuri CHAITANYA [3],Stefan BECKER[4]

[1]Institute of Process Machinery and Systems Engineering, University of Erlangen, Germany, cz@ipat.fau.de
[2]Institute of Process Machinery and Systems Engineering, University of Erlangen, Germany, kro@ipat.fau.de
[3]Institute of Sound and Vibration Research, University of Southampton, England, C.C.Paruchuri@soton.ac.uk
[4]Institute of Process Machinery and Systems Engineering, University of Erlangen, Germany, sb@ipat.fau.de

Abstract
Axial fans have a major impact on the sound emission of technical systems. One of the common applications of low-pressure axial fans is their usage in air conditioning and cooling circuits. In most cases the fan operates downstream of a heat exchanger in this scheme. The suction side heat exchanger changes the upstream flow field of the fan, often resulting in an increase in the sound pressure level of the axial fan compared to undisturbed inflow conditions. Investigations on sound radiation of aerorfoils showed that leading-edge modifications like serrations or slits reduce the turbulence-aerofoil interaction noise. In this study, the impact of two different leading-edge modifications (sinusoidal and slit) on the sound emissions of a forward skewed low-pressure axial fan was examined. The inflow conditions varied between a free inflow and a disturbed inflow, generated by a heat exchanger located on the suction side of the axial fan. The results show that the modification of the leading edge has a positive influence on the sound radiation of the axial fan for both inlet conditions discussed above.

Keywords: Axial Fan, Leading Edge, Air Conditioning

1 INTRODUCTION

Axial fans are used in a variety of technical applications such as cars, trains, computers, air conditioners and heat pumps. With this wide range of applications, axial fans are part of our daily lives. Fans are one of the main sources of noise in these technical systems. The resulting noise is often felt by people as disturbing and can also lead to psychological stress [1]. For this reason, many investigations have been carried out in recent years with regard to the acoustic optimisation of axial fans. These investigations included on the one hand the reduction of sound radiation on stationary airfoils and on the other hand on rotating fans. As the leading edge of the blade in interactions with the turbulent inflow to the blade is known to be a dominant sound source, several studies investigated modifications of the leading edge under different inflow conditions. This study aimed to follow on from the previous studies and analyse the influence of different leading edge modifications on the sound radiation of axial fans. In order to illustrate a technically relevant case, the experiments are performed not only under free inflow conditions but also under disturbed inflow generated by a heat exchanger.

1.1 Leading-edge modifications

In the present study two different leading edge modifications are considered. The first modification is slits in the leading edge of the fan blade. On fixed blades it was found that slits in the leading edge cause a reduction of the sound pressure level. The greatest reduction could be achieved with a ratio of distance between slits and length of slits of $l_{LE}/w_{LE} = 6$. In the low frequency range, the noise reduction with slitted leading edges was greater compared to serrated leading edges consisting of a sinusoidal waveform [2]. We can add optimum slit dimensions are considered in this study as identified by [3]. The second modification are sinusoidal serrations on the leading edge. Experiments were performed by Biedermann et al.[4] with axial fans, which have a sinusoidally serrated leading edge. This could determine a reduction of the sound pressure level up to 3.4 dB in specific frequency ranges due to the leading edge modification. The investigations by Krömer et al. [5, 6] also showed that the use of sinusoidal leading edges can reduce the sound radiation of flat-plate fans. As a variant with the lowest sound emission, the leading edges with the highest amplitudes α_{LE} and the smallest wavelength λ_{LE} could be found.

1.2 Inflow Conditions

The aerodynamic and acoustic behaviour of low-pressure axial fans under disturbed inflow conditions was investigated in most cases with the use of passive turbulence grids. For this purpose, the grids were placed upstream of the fans and the turbulence characteristics of the flow were modified. It was found that the sound emission of the fans increases with increasing turbulence intensity [6]. The homogeneity of the flow field also had an effect on the sound emission, which was shown, for example, in an increased blade passing frequency [6, 7]. Practical cases with heat exchangers on the suction side or empty heat exchanger housings were also investigated. This showed that heat exchangers generate inhomogeneity in the flow field and can influence the turbulence intensity. The increased sound emission of fans with suction-side heat exchangers was traced back to these flow phenomena and to a varied interaction between tip gap flow and blade tip [8, 9].

2 FAN DESIGN

The axial fans were designed according to the blade element theory and have the same design parameters [6, 10]. The fans use the same hub, which has a diameter of $d_{hub} = 247.5\,\text{mm}$. The fan blades (NACA 4510 profile [11]) are screwed to the hub and can be replaced. The entire fan with blades has a diameter of $d_{fan} = 495\,\text{mm}$, see figure 1.

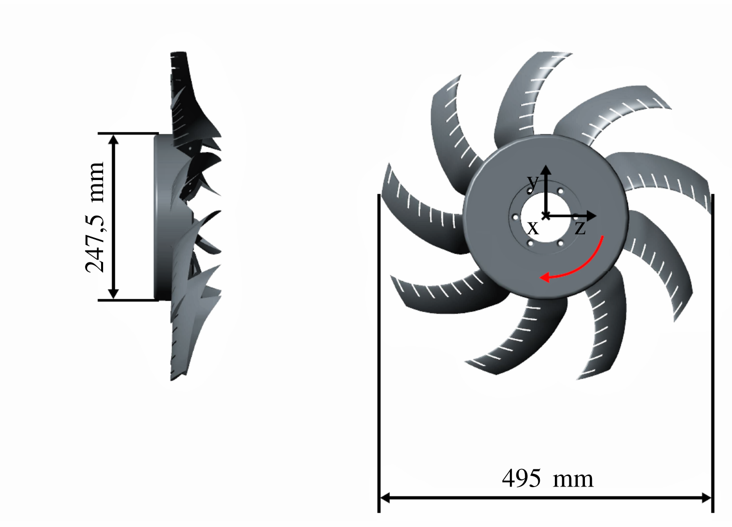
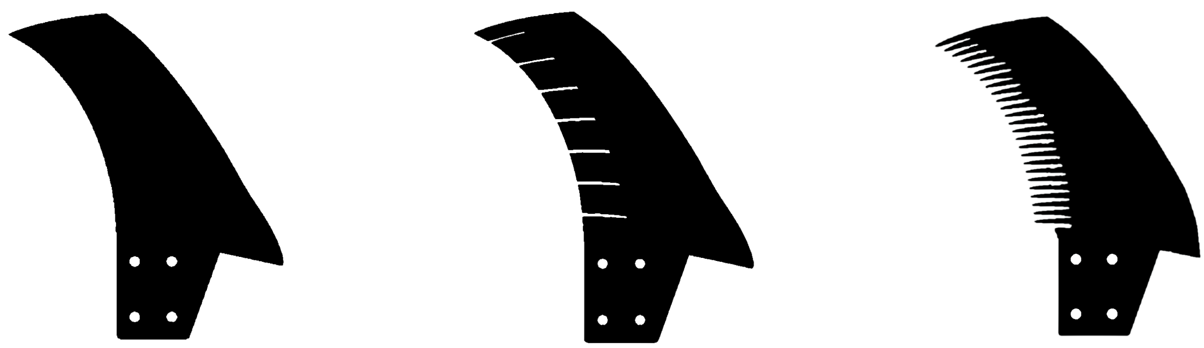


Figure 1. Illustration of the axial fan with slitted leading edges.

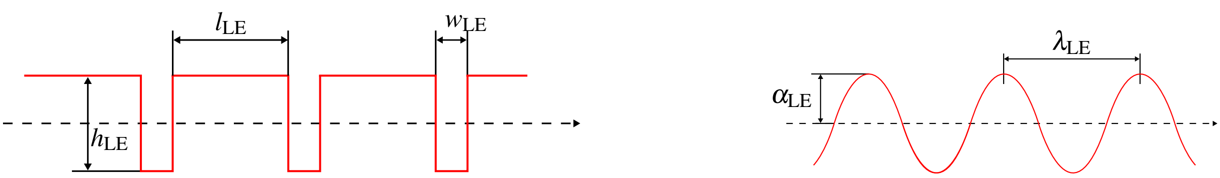
In this study three different fans are examined which differ in their leading edge modification. All fans have nine forward-skewed (FSK) fan blades. From previous studies it could be shown that forward-skewed blades reduces the sound emission of axial fans [12, 13, 6]. A fan with a straight leading edge (SLE) is selected as reference fan (FSK-SLE). The first leading edge modification has slits in the aerorfoil (FSK-SLIT). For this configuration a ratio of $l_{LE}/w_{LE} = 7.5$ was choosen. The second modification is a serrated leading edge (FSK-

SERR) where the aerofoil surface is kept constant, see figure 2. The individual design parameters are shown in figure 3 and listed in table 1 in relation to the mean chord length of the aerofoil. The mean chord length for the blades is $\overline{l_c} = 69{,}6\,\mathrm{mm}$. The axial fans operate in a duct with a diameter of $d_{\mathrm{duct}} = 500\,\mathrm{mm}$ and a speed of $n = 1000\,\mathrm{rpm}$. This speed is below the design speed, which is $n = 1486\,\mathrm{rpm}$. The tip gap of the fans has a dimension of $s_{\mathrm{tip}} = 2.5\,\mathrm{mm}$. The individual blades are made of PA3200GF material using the laser sintering process.



(a) FSK-SLE (b) FSK-SLIT (c) FSK-SERR

Figure 2. Fan Blades with different leading edges modnifcations, (a) reference fan blade FSK-SLE with straight leading edge, (b) fan blade FSK-SLIT with slitted leading edge and (c) fan blade FSK-SERR with sinusoidal serrated leading edge.



(a) parameters of slits (b) parameters of sinusoidal serrations

Figure 3. Schematic sketch for the parameters of the leading edge modification.

Table 1. Parameters for the leading edge modifications relativ to mean chord length.

parameters of slits		parameters of serrations	
l_{LE}	21,6%	λ_{LE}	6.7%
h_{LE}	32.3%	α_{LE}	16.7%
w_{LE}	2.9%		

3 EXPERIMENTAL SETUP

The fluid-mechanical and acoustic investigations were performed in the standardized axial fan test chamber of the University of Erlangen-Nuremberg [6]. The test bench is designed according to ISO 5801 [14], see figure 4.

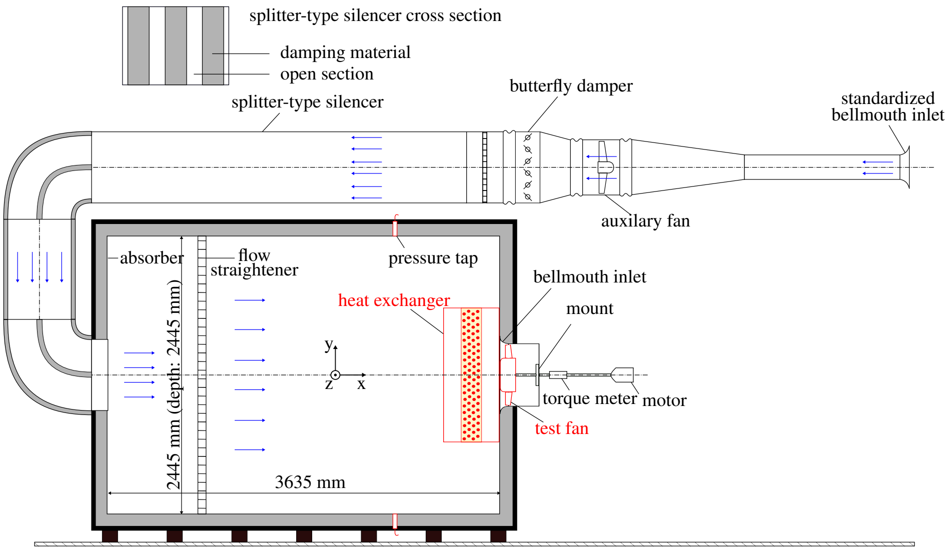


Figure 4. Standardized inlet test chamber according to ISO 5801 [14] with heat exchanger and axial test fan.

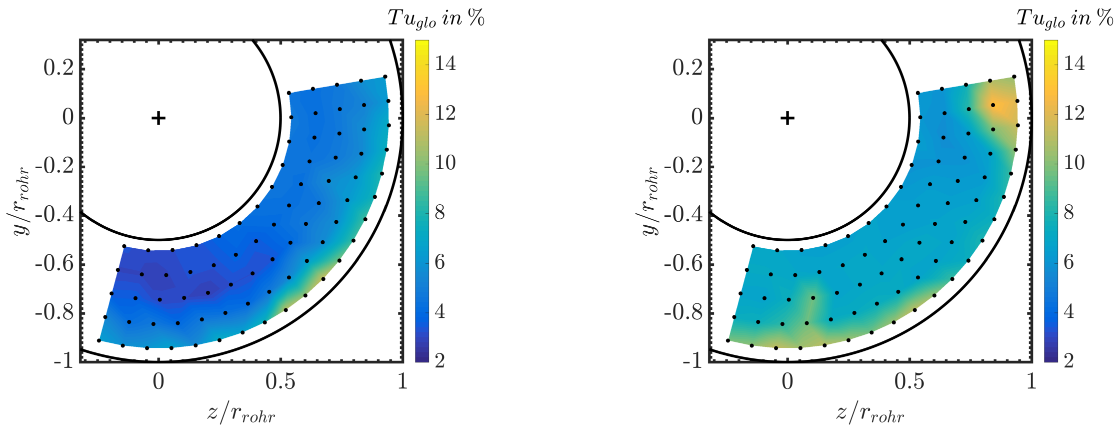
In order to examine the sound field on the suction side of the axial fans, the test rig has a anechoic chamber equipped with absorbers. This chamber has a volume of $V = 22\,\mathrm{m}^3$ and a quiescent sound pressure level of $L_\mathrm{p} = 28\,\mathrm{dB}$ in the frequency range of $f \in [0.1\,\mathrm{kHz}, 10\,\mathrm{kHz}]$. The volume flow rate $\dot{V}$ is measured with a standardized inlet bellmouth. For the adjustment of the operating point, an auxiliary fan and a butterfly damper are used. For a low-noise inflow there are splitter-type-silencers in the front of the measuring chamber. Inside the anechoic chamber, five half inch free-field microphones are set up for acoustic investigations. These are located at a distance of $R = 1000\,\mathrm{mm}$ from the inlet bellmouth of the fan, which is fixed to the wall of the test bench. Three microphoes are arranged in a horizontal quarter circle and two in a vertical quarter circle around the bellmouth. The microphones have a segmentation of $22.5°$. The fan is operated in a $d_\mathrm{duct} = 500\,\mathrm{mm}$ duct. A $3\,\mathrm{kW}$ asynchronous motor was used as the drive unit, which was operated at a constant speed of $n = 1000\,\mathrm{rpm}$. The speed is measured by a tachometer (one puls per revolution) located between the fan and the motor. The total-to-static pressure rise Δp_ts generated by the fan is determined by a differential pressure sensor between the environment and the suction side of the fan. For influencing the inflow to the fan a qudaratic heat exchanger with the hight $h_\mathrm{he} = 800\,\mathrm{mm}$ and width $w_\mathrm{he} = 800\,\mathrm{mm}$ was used. The coolant pipes have a diameter of $d_\mathrm{pipe} = 9{,}5\,\mathrm{mm}$ and the distance between the cooling slats is $s_\mathrm{slat} = 2.2\,\mathrm{mm}$. The inflow conditions were determined using 3D hot-wire anemometry. For these investigations the fan blades were removed and the flow field measured at the position where the leading edge of the fan blades is located. The hot-wire probe was automatically moved to 80 different measuring points by means of a traverse. The measuring points cover one third of the duct area. A waiting time of $t_w = 15\,\mathrm{s}$ was set before each measuring point [15]. A StreamLine Pro was used as the measuring bridge and processor. A measurement time of $t_s = 30\,\mathrm{s}$ and a sampling rate of $f_s = 48\,\mathrm{kHz}$ were selected per measuring point both for the measurements of the inflow conditions and for the measurements of the sound pressure. In both cases a PXIe-1075 front-end with 24-bit A/D converter NI PXie-4492 was used [8, 6].

4 RESULTS AND DISCUSSION

In this chapter, the turbulence characteristics of the suction-side flow field of the axial fan will be discussed first. Based on these results, the aerodynamic and acoustic behaviour of the axial fan will be analyzed in the following subchapter.

4.1 Inflow conditions

Figure 5 shows the contour plots of the turbulence intensity for the free inflow (5a) and for the flow downstream of the heat exchanger (5b). The plots represent the flow field at the leading edge of the fan at a volume flow of $\dot{V} = 0.8\,\mathrm{m^3/s}$.



(a) turbulence intensity for free inflow conditions (b) turbulence intensity for disturbed inflow conditions

Figure 5. Turbulence intensity for the free inflow (a) and the disturbed inflow condition (b) caused by a heat exchanger for a volume flow rate of $\dot{V} = 0.8\,\mathrm{m^3/s}$.

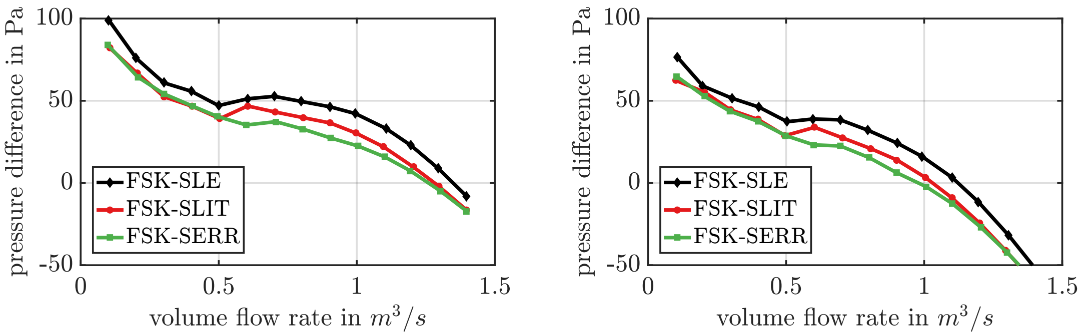
The flow field of the free inflow shows a homogeneous field with an average turbulence intensity of $\overline{Tu}_{\mathrm{glo}} = 4.88\,\%$. The flow field downstream of the heat exchanger, on the other hand, shows clear inhomogeneities which occur in the outer area of the duct. In addition, the mean turbulence intensity is increased to a value of $\overline{Tu}_{\mathrm{glo}} = 7.54\,\%$ compared to the free flow. The mean and maximum values of the integral length scale and the turbulence intensity are given in table 2. In addition to the increase in the turbulence intensity generated by the coolant pipes and cooling slats because they act like a turbulence grid, the integral length scale has been reduced due to these installations. The vortices are broken up by the cooling slats and smaller vortex structures are formed.

Table 2. Average and maximum inflow parameters.

inflow condition	free	heat exchanger
volume flow rate in $\mathrm{m^3/s}$	0.8	0.8
$Tu_{\mathrm{glo,max}}$ in %	11.49	13.06
$\overline{Tu}_{\mathrm{glo}}$ in %	4.88	7.54
Λ_{max} in mm	125.0	35.2
$\overline{\Lambda}$ in mm	93.3	12.7

4.2 Aerodynamic and acoustic characteristic of the axial fans

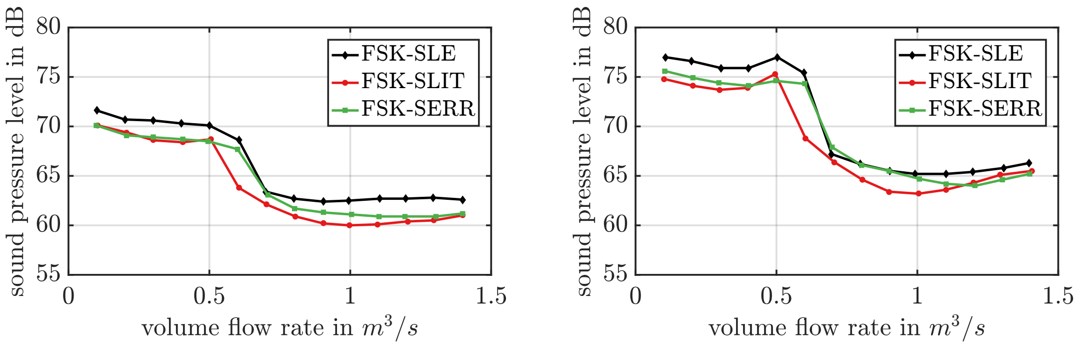
The characteristic curves of the fans show that the fan FSK-SLE generates the greatest pressure rise. The pressure build-up of the two leading edge modifications is below the reference fan, see figure 6. The modification with the slitted leading edge achieves a greater pressure build-up in the range of $\dot{V} = 0.5\,\mathrm{m^3/s}$ to $\dot{V} = 1.1\,\mathrm{m^3/s}$ than the fan with the serrated leading edge. This can be explained by a higher drag caused by the sinusoidal serrations [16]. The characteristic curves for the disturbed inflow are decreased to lower pressure differences. This is caused by the additional flow resistance of the heat exchanger.



(a) aerodynamic characteristic curves at free inflow conditions (b) aerodynamic characteristic curves at disturbed inflow conditions

Figure 6. Aerodynamic characteristic curves of the investigated fans: (a) free inflow condition, (b) disturbed inflow condition caused by heat exchanger.

The acoustic characteristics curves, see figure 7(a), show that a reduction of the sound pressure level due to leading edge modification can be achieved almost continuously for the free inflow. The mean reduction of the sound pressure level compared to the reference fan is 2.1 dB for the slitted leading edge and 1.4 dB for the sinusoidal serrated leading edge.

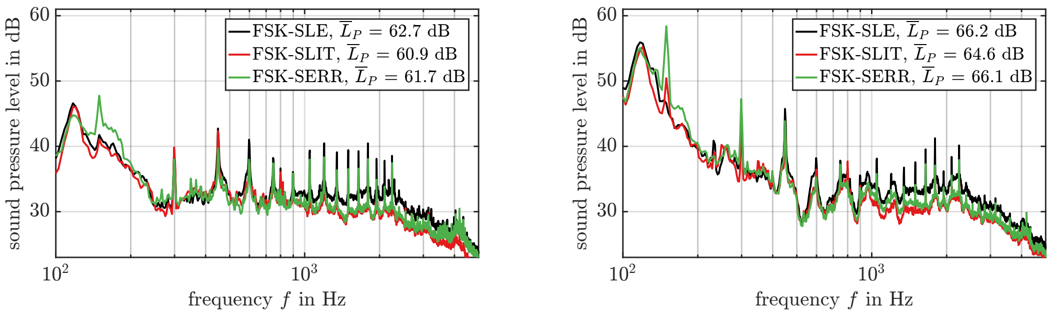


(a) acoustic characteristic curves at free inflow conditions (b) acoustic characteristic curves at disturbed inflow conditions

Figure 7. Sound pressure level over volume flow rate: (a) free inflow conditions, (b) distrubed inflow conditions due to heat exchanger.

In the transition from volume flow rate $\dot{V} = 0.6\,\mathrm{m^3/s}$ to $\dot{V} = 0.7\,\mathrm{m^3/s}$, a stronger reduction of the radiated sound pressure level is apparent for the reference case FSK-SLE as well as for the FSK-SERR fan. This can be explained by the fact that instabilities such as tip gap flow and rotating stall occur intensively for the operating points at low volume flow rates ($\dot{V} < 0.7\,\mathrm{m^3/s}$). This transition point is visible for the fan FSK-SLIT between the volume flows rates $\dot{V} = 0.5\,\mathrm{m^3/s}$ to $\dot{V} = 0.6\,\mathrm{m^3/s}$. This indicates that the slits provide a more stable aerodynamic characteristic and thus reduce the range in which the flow separates at the blades. In the case of a disturbed inflow due to the heat exchanger, see figure 7(b), the same tendencies exist between the fans as with the free inflow. A sound level reduction of 2.0 dB is achieved over the entire characteristic curve with the slitted leading edge and of 1.0 dB for the serrated leading edge. Therefore the positive effect of the sound reduction caused by the leading edge modification is reduced due to the suction side heat exchanger. The overall sound pressure level of the acoustic characteristic curve was increased by the heat exchanger by approximately 4 dB.

Figure 8 shows the sound pressure spectra of the fans for the operating point $\dot{V} = 0.8\,\mathrm{m^3/s}$. Compared to the FSK-SLE reference case, the modified leading edges reduce the broadband sound from a frequency of 1 kHz to 4 kHz. This frequency range can be assigned to the turbulent ingestion noise as well as to trailing edge noise of the aerofoils [6]. This means that on the one hand the sound sources at the leading edge are decorrelated by the leading edge modifications and on the other hand the changed flow over the aerofoil leads to a lower sound emission due to the trailing edge. This could be related to the fact that longitudinal vortices arise and increase the momentum transfer in the boundary layer. The harmonics of the blade passing frequency are also reduced due to the modifications. However, the FSK-SERR fan in particular shows an increase in the first blade passing frequency, which stands out clearly.



(a) sound pressure spectras for free inflow conditions

(b) sound pressure spectras for disturbed inflow conditions

Figure 8. Sound pressure spektras at a volume flow rate $\dot{V} = 0.8\,\mathrm{m^3/s}$: (a) free inflow conditions, (b) distrubed inflow conditions due to heat exchanger.

With regard to the disturbed inflow, it can be stated that the low-frequency range is influenced in particular. Since the frequency range lwoer then the blade passing frequency and between the blade passing frequency and its harmonics is affected, it can be concluded on the basis of the flow investigations that the inflow in the blade tip area is more turbulent due to the heat exchanger. This leads to an amplification of the sound generation mechanism due to the interaction between the vortex system in the tip region and the blade tips of the fan. The increased peaks of the blade passing frequency can be attributed to the inhomogeneities in the flow field. A further influence could be structural acoustic effects of the heat exchanger, which have not been investigated here.

5 CONCLUSION AND OUTLOOK

In this study the acoustic sound radiation of axial fans with different leading edge modifications (straight, slitted, serrated) was investigated. The inflow conditions were defined as free inflow and disturbed inflow due to heat exchangers. It could be shown that the heat exchanger increases the turbulence intensity and induces local spots with increased turbulence in the flow field. As a result, the heat exchanger increased the average sound emission of all fans by approximately 4 dB. The modifications of the leading edge reduced the emitted sound pressure level under both free and disturbed flow conditions. The greater reduction was achieved with the slitted leading edges, which were up to 2 dB in average over the entire characteristic curve. However, the modifications also lowered the aerodynamics of the aerofoils which led to a lower pressure rise of the fans. In the next step, the leading edge modifications at a higher turbulent inflow should be investigated.

REFERENCES

[1] Atmaca, E.; et al. Industrial noise and its effects on humans. Polish Journal of Environmental Studies, 14(6), 2005.

[2] Chaitanya, P.; et al. On the superior performance of leading edge slits over serrations for the reduction of aerofoil interaction noise. Proceedings of AIAA/CEAS Aeroacoustics Conference, Atlanta, Georgia, June 25-29, 2018, DOI:10.2514/6.2018-3121.

[3] Chaitanya, P.; Joseph, P. Slitted leading edge profiles for the reduction of turbulence-aerofoil interaction noise. The Journal of the Acoustical Society of America 143, Acoustical Society of America, 2018, DOI:10.1121/1.5040972.

[4] Biedermann, T.; et al. Optimised test rig for measurements of aerodynamic and aeroacoustic performance of leading edge serrations in low-speed fan application. Proceedings of ASME Turbo Expo 2018: Turbomachinery Technical Conference and Exposition, American Society of MEchanical Engineers, 2018, DOI:10.1115/GT2018-75369.

[5] Krömer, F.; Becker,S. Experimental investigation of the sound reduction by leading edge serrations on a flat-plate axial fan. Proceedings of AIAA/CEAS Aeroacoustics Conference, 2018, DOI:10.2514/6.2018-2955.

[6] Krömer, F. Sound emission of low-pressure axial fans under distorted inflow conditions, FAU University Press, 2018, DOI:10.25593/978-3-96147-089-1.

[7] Carolus, T; Stremel, M. Blade surface pressure fluctuations and acoustic radiation from axial fan rotor due to turbulent inflow. Acta Acustica united with Acustica, 88, 2002.

[8] Czwielong, F; et al. Experimentelle Untersuchung der Schallabstrahlung von Wärmeübertrager-Axialventilator-Modulen. Proceedings of Deutschen Arbeitsgemeinschaft für Akustik (DAGA), Rostock, Germany, March 18-21, 2019.

[9] Lucius, A; et al. Experimental and numerical investigation of axial fan aeroacoustics at disturbed inflow conditions. Proceedings of FAN, Darmstadt, Germany, April 18-20, 2018.

[10] Pfleiderer, C. Strömungsmaschinen. Springer-Verlag, 2013, DOI: 10.1007/b138287.

[11] Abbott, I.; Von Doenhoff, Theory of wing sections, including a summary of airfoil data, Courier Corporation, 1959.

[12] Zenger, F.; et al. Acoustic characterization of forward-and backward-skewed axial fans under increased inflow turbulence, AIAA Journal, 2017, DOI: 10.2514/1.J055383.

[13] Zenger, F.; et al. Experimental investigation of the noise emission of axial fans under distorted inflow conditions, Journal of Sound and Vibration, 2016, DOI: 10.1016/j.jsv.2016.07.035.

[14] DIN EN ISO 5801.Industrial fans-Performance testing using standardized airways, International Organization for Standardization, 2007 .

[15] Geyer, T.; Hobracht, M. Noise generated by a leading edge in anisotropic turbulence, INTER-NOISE and NOISE-CON Congress and Conference Proceedings, 2016.

[16] Zenger, F.; et al. Experimental investigation of the sound reduction by leading-edge serrations in axial fans, AiAA Journal, 2017, DOI:10.2514/6.2017-3387.