Active control of the blade passage frequency noise level of an axial fan with aeroacoustic sound sources

Jan Schulz,
Technische Universität Berlin,
Sonderforschungsbereich 557,
Müller-Breslau-Str. 8,
10623 Berlin,
Germany

Neise Wolfgang,
Deutsches Zentrum für Luft- und Raumfahrt e.V.,
Institut für Antriebstechnik, Abteilung Turbulenzforschung Berlin,
Müller-Breslau-Str. 8,
10623 Berlin,
Germany

Möser Michael,
Technische Universität Berlin,
Institut für Technische Akustik,
Einsteinufer 25,
10587 Berlin,
Germany

This paper presents results of a research project on active control of the blade passage frequency tone of an axial fan. The secondary sound field is generated by aeroacoustic sources, which are produced by actively controlling the flow around the impeller blade tips. Both amplitude and phase can be controlled in such a way that a destructive superimposition with the primary sound field is possible. The flow distortions can be achieved using different actuators; results using steady and unsteady jets of compressed air and piezo-electric actuators are presented.

The tonal noise of axial turbomachines is due to the periodic forces that are exerted by the flow on the rotor blades, stator vanes, and the casing. As shown by Tyler and Sofrin [1], the interaction between the rotor and inlet flow distortions and the interaction of the wake flow off the impeller blades with the downstream stator vanes are the main causes for the blade tone spectrum of axial turbomachines.

Conventional active noise control experiments use loudspeakers to generate the secondary anti-phase sound field which is superimposed destructively on the sound waves radiated from the primary source, see papers by e.g. Burdisso et al.[2], Smith et al.[3], Enghardt et al. [4].

The possibility to reduce the fan noise by using flow control has been the focus of several investigations, i.e. Rao et al. [5] and Leitch et al. [6]. The aim of their work was to compensate the wakes of inlet stator vanes by trailing edge blowing and to reduce the unsteady interaction with the downstream rotor. Polacsek [7] showed that the blade passage frequency level can be reduced by generating an additional sound field by means of flow distortions of an upstream active grid and its interaction with the downstream impeller.

In this study, the required anti-phase sound field for active noise control is produced by additional aerodynamic sound sources. This can be achieved by disturbing the flow field around the rotor blade tips by either blowing air jets into the blade tip flow regime or by placing small flow obstructions like piezo-electric actuators or small rods upstream of the impeller blade tips. In this way, additional periodic forces are set up on the rotor blade tips which in turn form the secondary aerodynamic sound sources which are adjustable in both amplitude and phase. A principal sketch of this arrangement is depicted in Figure 1.

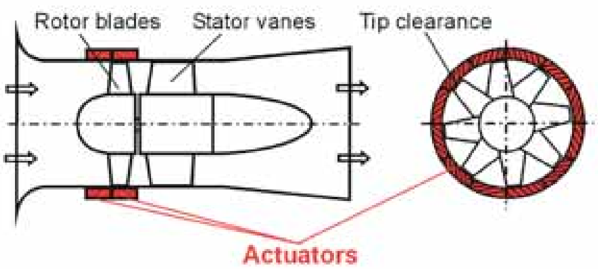

Fig. 1: Principle of the experimental set-up with actuators

Experimental facility

The experiments were performed with a low-speed high-pressure axial fan with outlet guide vanes in a ducted inlet/ducted outlet configuration. A schematic presentation of the experimental set-up along with its major dimensions is given in Figure 2. The principal properties of the impeller are: diameter D = 357.4 mm, hub-to-tip ratio $\varepsilon = 0.62$, NACA 5-63 blade profile, blade chord length at the tip c = 53.6 mm, maximum blade thickness 3 mm, blade stagger angle at the tip $\theta = 27°$. The tip clearance gap width is s = 0.3 mm which corresponds to a tip clearance ratio of $\zeta = s/c = 0.0056$. Two different impellers with Z = 16 and Z = 18 blades were used for the experiments. The stator row consists of V = 16 stator vanes. The axial distance between rotor and stator at the impeller blade tips is $\Delta x/c = 0.7$.

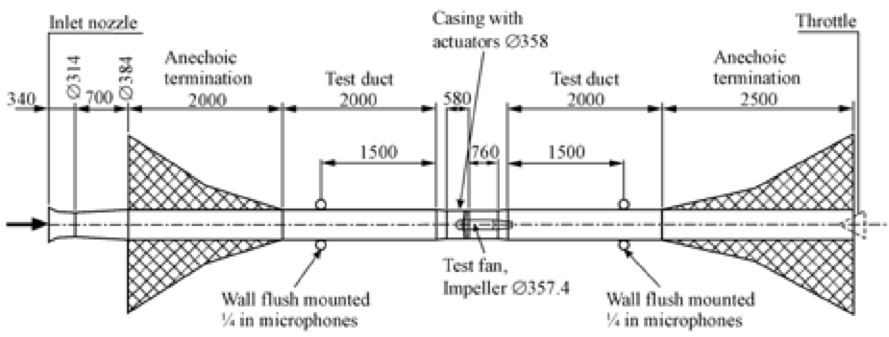

Fig. 2: Experimental set-up for the active noise control (dimensions in mm)

The volume flow rate of the fan was determined via the static pressure Δpstat in the bellmouth nozzle of the inlet duct. Pressure taps in the inlet and outlet ducts were used to measure the fan pressure rise. No flow straighteners were installed in the inlet duct. In principle the test rig is in accordance to the international standard ISO 5136 but the length of the test ducts does not fulfill all requirements due to space limitations of the laboratory. This is here not necessary either, as the main focus of the measurements are the differences in the radiated sound pressure of different configurations and not absolute sound power measurements. On both fan sides, 16 wall-flush mounted 1/4-inch microphones, equally spaced circumferentially, were used to monitor the sound fields in the anechoic fan ducts. The circumferential sound pressure distribution was then resolved into azimuthal duct modes.

To influence the flow conditions near the blade tips, actuators are installed in the fan casing wall. Small jets of compressed air are blown into the blade tip region through different types of nozzles. The principle of the wall flush mounted nozzles is illustrated in Figure 3a. Both the axial and the circumferential positions of the nozzles were varied. Compressed air is used to drive the jets flows.

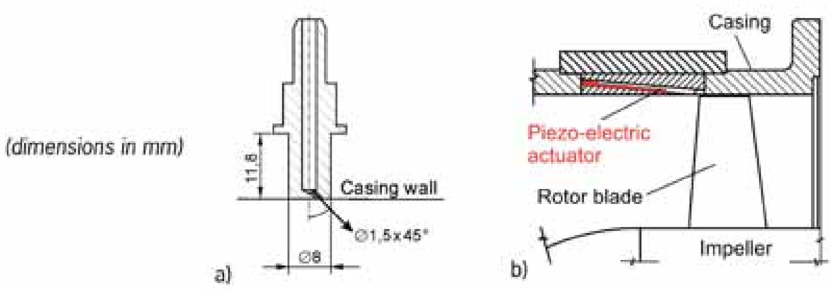

Fig. 3: a) Schematic of the nozzles used to generate the flow disturbances; b) Flow distortion with piezo-electric actuators upstream of the impeller, wall flush mounted with radial deflection

Furthermore piezo-electrical actuators were tested. The piezo-elements were placed upstream of the impeller. The piezo-electric actuators were installed flush with the inner casing wall, as illustrated in Figure 3b. When actuated, the maximum deflection of the tip of the piezo-elements is 1.2 mm into the flow so that the shape of the housing can be changed dynamically. This results in an incoming flow with a wall boundary layer of varying circumferential thickness. When actuated, the piezo-elements produce periodic flow distortions in the incoming flow of the fan, which interact with the blade tips of the rotor. As in the case of the nozzles, both the axial and the circumferential positions of the actuators were varied.

Short cylindrical rods and small airfoils extending from the casing wall into the fan duct up- or downstream of the impeller were also tested, but will not be discussed in this paper. Results using a different configuration of the piezo-electric actuators are presented in Schulz et al. [8]; for experiments with short cylindrical rods downstream of the impeller refer to Neuhaus et al. [9].

Experimental results for steady and unsteady air injection

Control of plane wave sound field at the blade passage frequency

In the first phase of the study, 16 rotor blades and 16 stator vanes were used, thus the sound field generated by rotor/stator interaction was dominated by the plane wave. The sound pressure level of other azimuthal modes was at least 25 dB below the plane wave. The maximum impeller speed was 4000 rpm at which the blade passage frequency (BPF) was 1066 Hz. The first tests were carried out with steady air jets at different axial and circumferential positions. Active noise control with steady blowing was tested successfully; for more detail on these investigations see Schulz et al. [8], [10].

Further experiments were performed with unsteady blowing. The pulsating flow of the air jets was synchronized with the BPF of the impeller by means of electronically driven oscillating valves. The maximum operating frequency of the valves was 200 Hz so far, which limited the speed of the 16-bladed rotor to 750 rpm. The phase of the pulsating jets of compressed air was adjusted relative to the circumferential position of the impeller blades.

Figure 4 shows the result of the experiments with the air jets blowing at the rotor blades trailing edges in the direction of the mean flow. The BPF level was reduced by 19.6 dB in the outlet duct and 10 dB in the inlet duct. Because of the reduced impeller speed, the broadband noise of the fan alone is fairly low and is increased considerably when the air injection is turned on. As a beneficial side effect of the unsteady blowing, the fan pressure was raised by up to 15%. This can be explained by an improvement of the flow conditions around the rotor blades at this operation point.

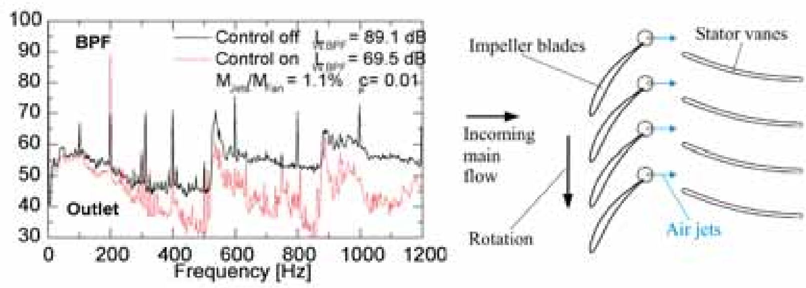

Fig. 4: Sound power spectra in the outlet duct with unsteady air jets synchronized with BPF; nozzles placed at the impeller blade trailing edges ($\Delta x/c = 0$) blowing in the direction of the mean flow; n = 750 rpm, Z = 16, V = 16, Znoz = 16, $\varphi = \varphi_{opt}$.

The overall noise reduction effect of the method is also limited by the increase of the higher harmonics of the BPF. This can be explained by an unwanted effect of the interaction of the air pulses with the impeller blades. The air jets lead to a periodic circumferential excitation. The jets impinge like sharp pulses on the impeller blade wakes, which excites all higher harmonics of the BPF over the entire spectrum, just as a Fourier-transform of the Dirac-δ-function results in an equal energy distribution.

Other experiments were performed with the air jets at an axial position 0.5 mm upstream of the leading edges of the impeller blades blowing in the direction of the chord of the impeller blades. The sound power level of the BPF in the outlet was reduced by 16.6 dB with lower mass flow through the nozzles, see Figure 5. In the inlet the noise level dropped by 10 dB.

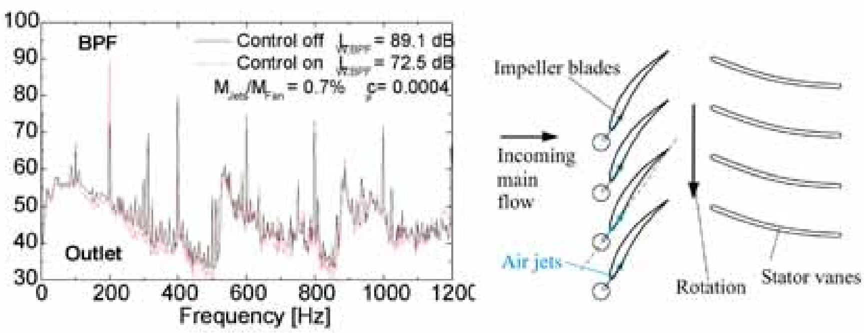

Fig. 5: Sound power spectra in the outlet duct with unsteady air jets synchronized with BPF; nozzles placed 0.5 mm upstream of the impeller blade leading edges ($\Delta x/c = -0.009$) blowing in the direction of the chord of the impeller blades. n = 750 rpm, Z = 16, V = 16, Znoz = 16, $\varphi = \varphi_{opt}$.

Compared to the case considered in Figure 4, the blowing direction of the air jets is changed and the axial position of the nozzles is moved 0.5 mm upstream of the rotor. As a result, the impeller blades now cut through small portions of the jets leading to a stronger blade/jet interaction. In turn, the necessary injected mass flow, and hence the momentum of the air jets, is significantly lower than in Figure 4, because the flow disturbances needed to generate the wanted secondary aeroacoustic sound sources are achieved more easily with this configuration of nozzles. The unwanted interaction of the air pulses with the impeller blades is stronger here, and hence the increase of the sound pressure level at higher harmonics of the BPF is larger. On the other hand due to the lower mass flow injected trough the nozzles no increase of the broadband noise was observed.

To reduce the negative effect of the unsteady blowing on the higher harmonics of the BPF, tests were performed with the nozzles placed further downstream of the impeller blade trailing edges at an axial position !x/c = 0.15 with the jets blowing in the direction at right angle to the impeller blade chord such that they cause a velocity component in the rotational direction of the impeller. In this case the BPF levels in the outlet and inlet duct were reduced by 18.1 dB and 3.6 dB, respectively. For more detail on these tests refer to Schulz et al. [8], [10].

To obtain a better understanding of the physical mechanisms involved in the interaction of the air jets and the rotor blades, flow visualisation experiments were carried out with a stationary two-dimensional blade cascade using PIV measurement technique. The investigation revealed that the air injection produces vortex generator jets causing additional unsteady longitudinal structures in the flow. The interaction of these additional structures with the impeller blades can be interpreted as the generating mechanism of the additional aeroacoustic sources for the ANC experiments. For more details on these results refer to Schulz et al. [10].

Control of higher-order mode sound field at the blade passage frequency

For the second phase of the study, an impeller with Z = 18 blades was installed while the number of stator vanes remained unchanged. This resulted in a dominant duct mode of azimuthal order m = 2 at the BPF which is propagational in the fan duct at frequencies above 860 Hz. This is beyond the useful frequency range of the unsteady valves, and therefore only experiments with steady blowing were possible up to now. As in the previous experiments 16 nozzles, which is equal to the number of stator vanes, were used to generate the same azimuthal mode as the primary rotor/stator interaction. The axial positions of the nozzles as well as the directions of the air jets relative to the main flow were varied. The experiments were performed at impeller speeds of 3000 rpm and 4000 rpm where the blade passage frequencies are 900 Hz and 1200 Hz, respectively.

A general finding of these tests is that the method proposed is also applicable to higher-order mode sound fields. Figure 6 (left) shows the circumferentially averaged sound power spectrum for the case of steady blowing at an axial position 12 mm ($\Delta x/c = 0.22$) downstream of the impeller in the direction of the impeller blade trailing edges.

The BPF level reductions in the outlet and inlet ducts amounted to 20.6 dB and 5 dB. Due to the larger distance between the impeller and the jets, the higher harmonics of the BPF were not increased as much as in the previous experiments.

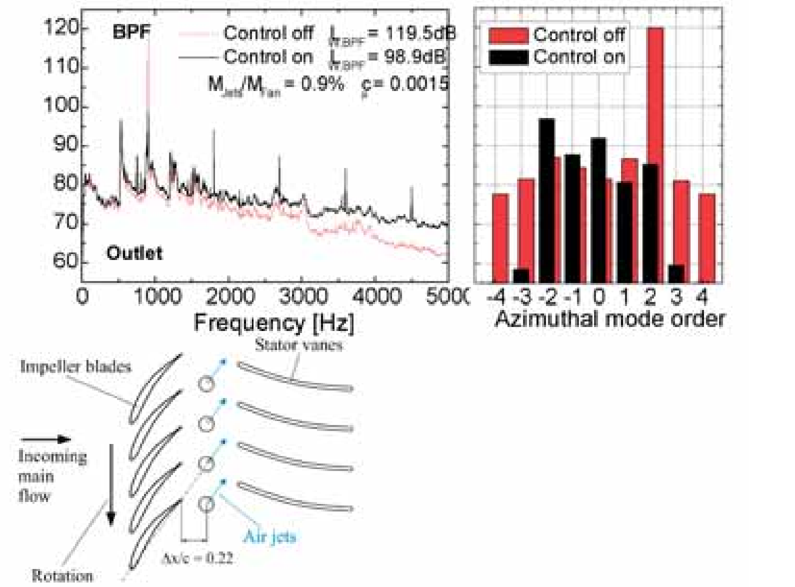

Fig. 6: Sound power spectra in the outlet duct with steady air jets (left) and azimuthal mode spectra (middle) at the blade passing frequency; nozzles placed $\Delta x/c = 0.22$ downstream of the impeller blade trailing edges blowing in direction of the chord of the impeller blades; n = 3000 rpm, Z = 18, V = 16, Znoz = 16, $\varphi = \varphi_{opt}$; (right) sketch of the principal arrangement for this measurement.

The broadband noise level was higher by a few decibels, which is due to the noise of the air injection itself. Figure 6 (middle) shows the azimuthal mode spectrum for the BPF components at 900 Hz with and without steady blowing. As expected, the dominant azimuthal mode without control is m = 2. When steady blowing is applied, this mode is reduced drastically and consequently the BPF level decreases.

To study the effect of a non-uniform inflow on the active noise reduction of the BPF with blowing air jets, experiments were made with single sided obstacles of different heights installed in the inlet duct at various axial positions. Figure 7 shows experimental results for the case where a flat plate protruded into the fan intake perpendicular to the main flow at an axial position of $\Delta x/c = 2.4$ upstream of the blade leading edges, see the sketch in Figure 7. The general set-up remained unchanged compared to the case presented in Figure 6. The smallest radial position of the plate edge is equal to that of the hub, i.e. several blade channels are blocked simultaneously. The disturbed intake flow results in a small reduction of the dominant m = 2 mode and – with it – the overall BPF level. The plane wave mode m = 0 and the azimuthal modes m = -2, -1 and 1 are amplified as well. Some of the level changes observed in the outlet duct are most likely caused by reflections of the modes at the plate.

The random noise components are somewhat higher in level in the case of the disturbed inflow.

The BPF level reductions achieved with steady blowing amounted to 10.5 dB in the outlet and 3.8 dB in the inlet duct (compare the red and black graphs in Figure 7). The again higher broadband noise level was due to the noise of the air injection itself.

As a general finding one can point out that the stronger the inflow distortion and the closer it is situated to the impeller the lower is the reduction of the BPF achievable. This effect is partly due to the fact that the tonal noise components diminish somewhat already in the case of the non-uniform inflow such that the potential for the reduction is lower. The controlled interaction of the blowing air jets with the impeller blades can reproduce a phase shifted secondary field for the rotor/stator interaction mode m = 2, but not for the additional modal components of the BPF due to the disturbed inflow. This appears to be the limiting factor of the active control of the BPF in this case so far. Further experiments to reduce this effect using different actuator concepts are planned.

Experimental results with unsteady driven piezo-electric actuators

Other experiments were carried out to test different actuator concepts like piezo-electric actuators. For first experiments 16 impeller blades and 16 outlet guide vanes were used again to investigate whether these actuators are suitable for active noise control. The impeller speed was 750 rpm, which was chosen to allow comparison with the results of the experiments using unsteady air jets blowing. The piezo-elements are of the bending type and were installed flush with the inner casing wall, compare Figure 3b. For experiments with a different actuator configuration refer

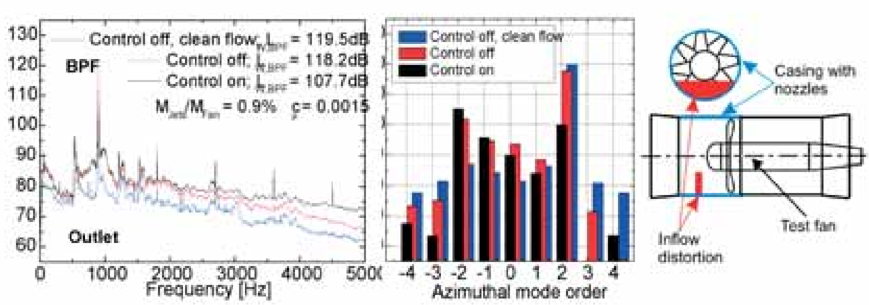

Fig. 7: Sound power spectra in the outlet duct with steady air jets (left) and azimuthal mode spectra (middle) at the blade passing frequency. Test conditions as shown in Figure 6, but here with strong distortion of the incoming flow, as depicted in the sketch (right).

to Schulz et al. [8]. Because of the deflection of the actuators (1.2mm) the wall boundary layer of the incoming flow has a dynamically varying circumferential thickness, which interacts with the blade tips of the rotor. The deflection of the piezo-elements was electronically synchronised with the impeller blade passing frequency to control the phase of the excited aeroacoustic sound sources.

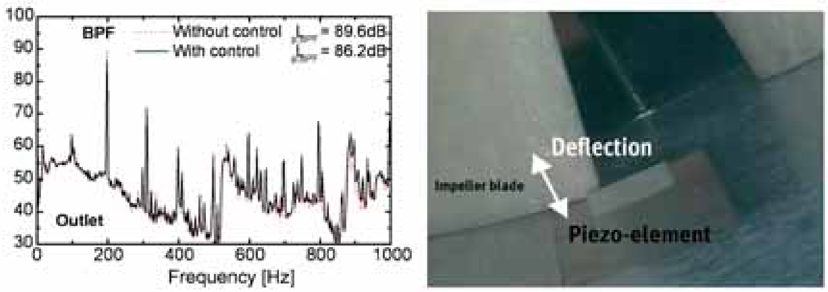

Fig. 8: Sound power spectra in the outlet duct with wall flush mounted piezo-elements (refer to Figure 3b) 0.5 mm upstream of the rotor blade leading edge, synchronized with the blade passing frequency, maximal deflection 1.2 mm; n = 750 rpm, Z = 16; V = 16; Zpiezo = 16, φ = φopt.

With the piezo-electric actuators placed 0.5 mm upstream of the impeller blades, the sound power level of the BPF in the outlet duct was reduced by 3.4dB, see the sound power spectra in Figure 8, and that in the inlet duct was increased by 1 dB. No negative side effects were observed. Because the flow distortions are relatively small and extend only in the region of the blade tips, the higher harmonics of the BPF are not increased. Further tests using this actuator set-up for sound fields with higher-order azimuthal modes are in preparation.

Conclusions

The tonal noise components of an axial turbomachine can be reduced using aeroacoustic sound sources for active noise control. The secondary sound field can be generated by actively controlling the flow around the impeller blade tips. Both amplitude and phase can be controlled in such a way

Appendix

A	cross sectional area (A_0 = 1 m^2)
A_{Fan}	cross sectional area of the annulus determined by the impeller and the center body of the fan
A_{Noz}	cross sectional area of the outlet of the nozzle
c	blade chord
c_μ	$=2\, A_{Noz}/A_{Fan}\, (v_{Jet}\, p_{dyn})^2$; momentum coefficient
d	duct diameter
D	impeller diameter
f	frequency
L_W	sound power level
m	azimuthal mode order
M_{Jets}	jet mass flow
M_{Fan}	fan mass flow
n	impeller speed
p_{dyn}	dynamic pressure
Δp_{stat}	static fan pressure
Δp_t	total fan pressure (Δp_{t0} = 1 Pa)
s	tip clearance
u_∞	mean flow velocity in the cross section area AFan
U	impeller tip speed
v_{jet}	jet exit flow velocity calculated at ambient pressure
V	number of stator vanes
Q	volume flow (Q_0 = 1 m^3/s)
Δ_x	axial distance
Z	number of impeller blades
Z_{noz}	number of nozzles
Z_{piezo}	number of piezo-elements
α	angle of the blowing direction of the nozzles relative to the mean flow
ε	hub-to-tip ratio
ζ	= s/c; non-dimensional tip clearance
θ	blade stagger angle
ρ_0	air density
φ	$= 4Q/(\varpi D^2 U)$; flow coefficient
φ_{opt}	flow coefficient at the design point
ψ	$= 2\Delta p_t/(\rho_0\, U^2)$; pressure coefficient

that a destructive superposition with the primary sound field is possible. The method proposed is applicable for sound fields with higher-order modes.

The flow distortions can be achieved using different actuators. In this paper, results using steady and unsteady jets of compressed air and piezo-electric actuators are shown. With steady air injection, the sound pressure level at the BPF was reduced by up to 20.5 dB. An azimuthal mode analysis showed that the dominant azimuthal mode of the order m = 2 was suppressed by more than 30 dB. The experiments with unsteady air injection were only performed in the plane wave frequency region because of the limited frequency range of operation of the unsteady valves available. In this case was reduced by up to 20 dB.

Experiments with non-uniform inflow due to single sided flow obstacles in the inlet duct showed, that the method developed is applicable in this case too. The possible reduction of the sound pressure level of the BPF depends on the nature of the disturbed inflow, in the present experiments on the radial extension and the axial distance of the obstacle from the impeller.

Future experiments will use oscillating valves to generate unsteady air jets and piezo-electric elements as actuators for the active control of higher-order mode sound field at the blade passage frequency.

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