OPTIMIZATION AND VALIDATION OF TRAILING EDGE BLOWING FOR THE REDUCTION OF ROTOR-STATOR INTERACTION NOISE

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ABSTRACT

A major source of fan noise results from the interaction between the turbulent rotor blade wakes and the stator vanes. To control the aerodynamic structure of the wake and thus the rotor-stator interaction (RSI) noise sources, a secondary mass flow is ejected through the trailing edge of the rotor blades (trailing edge blowing, TEB). The objective of this study is to investigate the effect of this technique on the mean wake velocity and the acoustic farfield. Special attention is given to the quality of wake filling by numerical optimization of TEB mass flow rates through seven equally spaced slits in the trailing edge. The TEB fan was built and the optimized configuration was experimentally investigated. The estimated TEB rates were scaled down linearly since the wake deficit without TEB was smaller than expected and less TEB momentum was needed. The acoustic measurements showed only a small influence of TEB to the overall sound pressure level and the tonal noise on the first harmonic. However, the second harmonic decreased by TEB since most of the RSI noise affects this tone.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>( D_A )</td>
<td>rotor diameter [m]</td>
</tr>
<tr>
<td>( D_l )</td>
<td>hub diameter [m]</td>
</tr>
<tr>
<td>( L_{app} )</td>
<td>acoustic pressure PSD level [dB]</td>
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<tr>
<td>( QP )</td>
<td>quality parameter [-]</td>
</tr>
<tr>
<td>( V )</td>
<td>volume flow rate [m³/s]</td>
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<tr>
<td>( b_{slot} )</td>
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<td>( c )</td>
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<td>( f )</td>
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<td>( g )</td>
<td>tip gap height [m]</td>
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<td>( n )</td>
<td>rotational speed [1/s]</td>
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<tr>
<td>( s )</td>
<td>distance of reference plane from TE [m]</td>
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<tr>
<td>( u )</td>
<td>velocity around isolated airfoil [m/s]</td>
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<td>( w )</td>
<td>relative velocity [m/s]</td>
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<tr>
<td>( z_{\text{rotor/stator}} )</td>
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</tr>
<tr>
<td>( \Theta )</td>
<td>momentum thickness [m]</td>
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<td>( \beta )</td>
<td>flow angle [-]</td>
</tr>
<tr>
<td>( \theta )</td>
<td>circumferential angle [-]</td>
</tr>
</tbody>
</table>

Subscripts

- \( 2 \) stator leading edge plane
- \( \text{in} \) position upstream of fan
- \( m \) meridional (axial)
- \( \text{out} \) position downstream of fan
- \( r \) radial
- \( * \) non-dimensional
- \( u \) circumferential

Abbreviations

- CV control volume of isolated airfoil
- GGI general grid interface
- HWA hotwire anemometry
- MSE mean square error
- PSD power spectral density
- RANS Reynolds-averaged Navier-Stokes
- RSI rotor-stator interaction
- TE trailing edge
- TEB trailing edge blowing

INTRODUCTION

Since the start of commercial aviation, the development of jet-powered aircraft has progressed steadily. The development of aero engines evolved from single-spool turbofans to modern turbofan...
engines with high-bypass ratios. This technological progress shifted the primary sources of sound generation from high jet velocities to noise resulting from the rotating fan at the intake of the engine. Recently, several research projects addressed this issue by the development of innovative concepts based on adaptive flow control technologies. One of the noise reduction techniques to be examined is called trailing-edge blowing (TEB). It targets at the noise produced by the interaction of a fan with stator vanes positioned downstream (rotor-stator interaction noise, RSI noise). Due to losses in the boundary layer, a spatially and temporarily non-uniform flow field is generated by the rotor blades. This flow field impinges on the leading edge of the stator vanes and thereby leads to pressure and force fluctuations at the surface of the stator (Fig. 1). The emitted noise can be divided into two parts:
- The tonal RSI noise resulting from the periodic interaction of the mean wake velocity profile.
- The broadband RSI noise generated by the turbulence in the wake.

![Fig. 1: Flow field between the rotor and the stator in a circumferential cut.](image)

The TEB technique can be used to manipulate the wake in a way that eliminates the velocity deficit downstream of the blades and thereby the tonal noise source. Brookfield and Waitz (1998, 2000) investigated a compressor stage with two different spanwise blowing distributions along each rotor blade. Basically, the target was a momentumless wake. With the tip weighted blowing distribution, a momentumless wake was only achieved at approx. 80% relative blade height. The tip wake was overblown. Using this TEB blowing distribution, an 85% reduction in the first three blade-passing frequency harmonic amplitudes, referenced to the unblown case, was achieved. The unsteady stator loading, i.e. the fluctuating pressure on the guide vanes was reduced by 10 dB through TEB. Note that these authors did not present detailed acoustic measurements. Sutliff et al. (2002) focused on the acoustic benefit of the TEB technique. Blowing was applied on a low-speed fan (16 blades and 14 stator vanes) by implementing 19 blowing slots per fan blade. With an optimum blowing mass flow of 1.8% of the overall fan mass flow rate, a substantial tone reduction of around 10 dB was achieved. Further investigations by Sutliff et al. (2005) focused on the reduction of broadband noise by the use of TEB. It was assumed that minimizing the wake velocity deficit by TEB reduces velocity gradients in the wake, and hence the turbulence generated in the wake and eventually broadband noise due to wake interaction with a downstream stator as well. The blowing distribution at optimum blowing rate was not perfect. At the tip region, the mean wake profile was overfilled while the wake in the hub region was underfilled. This resulted in a non-uniform wake and a smaller reduction in turbulence. The overblown tip wake results in stronger turbulence production. It was pointed out that a uniform wake modification might lead to a more effective reduction. Surface pressure measurements at the stator leading edge showed an averaged reduction of broadband pressure fluctuations of 2 - 3 dB due to the turbulence decrease. However, these results could not be confirmed by far field acoustic measurements.

The present paper is focused on the realization of a more uniform wake velocity profile to manipulate RSI noise sources best. This will require a criterion for wake filling as a target for CFD-based optimization. A prototype was constructed in order to validate the CFD prediction of the
downstream velocity profile by hot-wire-anemometry (HWA). On top of that, the effectiveness of TEB as an active noise reduction measure is confirmed by acoustic far field measurements.

**Methodology**

**TEB optimization criterion**

To derive an optimization criterion for wake filling, the effect of blowing momentum addition is examined in more detail via a momentum analysis in x-direction around an isolated airfoil with TEB (Fig. 2, see also (Winkler, 2011)). Assuming (i) an incompressible fluid and uniform inflow, (ii) periodic inflow and outflow through the upper and lower boundary of the control volume CV and (iii) a comparably small transverse flow deflection and a temperature of the jet being equal to the one of the main flow one obtains

\[ F_0 - F_{\text{drag}} - F_{\text{wake}} + F_{\text{jet}} = 0 \]  

with the forces

\[ F_{\text{0/wake}} = \int_{-y_{\text{CV}}}^{+y_{\text{CV}}} \rho u_{\text{0/wake}}^2 \, dy, \]

\[ F_{\text{jet}} = \int_{h_{\text{slot}}}^{+h_{\text{slot}}} \rho u_{\text{jet}}^2 \, dy. \]

**Fig. 2:** Momentum analysis for an isolated airfoil with TEB

Combining Eq. 1 with Eq. 2 and 3 and using the continuity equation

\[ \int_{-y_{\text{CV}}}^{+y_{\text{CV}}} \rho u_0 \, dy - \int_{-y_{\text{CV}}}^{+y_{\text{CV}}} \rho u_{\text{wake}} \, dy + \int_{h_{\text{slot}}}^{+h_{\text{slot}}} \rho u_{\text{jet}} \, dy = 0. \]

yields

\[ F_{\text{drag}} = \rho \int_{-y_{\text{CV}}}^{+y_{\text{CV}}} u_{\text{wake}} (u_0 - u_{\text{wake}}) \, dy - \rho \int_{h_{\text{slot}}}^{+h_{\text{slot}}} u_{\text{jet}} (u_0 - u_{\text{jet}}) \, dy \]

\[ = \rho \Theta_{\text{wake}} u_0^2 - \rho \Theta_{\text{jet}} u_0^2 \]

with the momentum thicknesses

\[ \Theta_{\text{wake}} = \frac{1}{u_0^2} \int_{-y_{\text{CV}}}^{+y_{\text{CV}}} u_{\text{wake}} (u_0 - u_{\text{wake}}) \, dy \]  

\[ \Theta_{\text{jet}} = \frac{1}{u_0^2} \int_{h_{\text{slot}}}^{+h_{\text{slot}}} u_{\text{jet}} (u_0 - u_{\text{jet}}) \, dy. \]

The first term of the right-hand side of Eq. 5 is the drag of the blade section without TEB. This drag is reduced by injecting air through the slot at the trailing edge (second integral of the right-hand side of Eq. 5). That integral can be split into two parts

\[ \rho \int_{h_{\text{slot}}}^{+h_{\text{slot}}} u_{\text{jet}} (u_0 - u_{\text{jet}}) \, dy = \rho \int_{h_{\text{slot}}}^{+h_{\text{slot}}} u_{\text{jet}} u_{\text{jet}} \, dy - \rho \int_{h_{\text{slot}}}^{+h_{\text{slot}}} u_{\text{jet}}^2 \, dy \]

which can be identified as forces due to added mass and the jet momentum. Dividing Eq. 5 by the force per unit span due to the dynamic pressure \(0.5 \rho u_0^2 l\), leads to the non-dimensional form
\[
\frac{c_{\text{drag}}}{l} = \frac{2}{l} \Theta_{\text{wake}} + c_{\mu,\text{jet}} - c_{\mu,\text{mass}}
\]  \hspace{1cm} (8)

with the blowing momentum loss coefficient \(c_{\mu,\text{mass}}\) and the blowing momentum coefficient (Joslin and Jones, 2006)

\[
c_{\mu,\text{jet}} = \frac{\int u_{\mu,jet} \, dy}{0.5u_0^2/l_{\text{slot}}}.
\]  \hspace{1cm} (9)

Now, assuming a constant velocity over the slot height, we obtain

\[
c_{\mu,\text{jet}} = \frac{\dot{m}_{\text{jet}} u_{\text{jet}}}{0.5\rho u_0^2 l_{\text{slot}}} = \frac{2h_{\text{slot}}}{l} \left( \frac{u_{\text{jet}}}{u_0} \right)^2.
\]  \hspace{1cm} (10)

We now disregard the added mass effect, i.e. assume \(c_{\mu,\text{mass}} = 0\). Then, aiming at zero change of momentum in the control volume, i.e. \(\Theta_{\text{wake}} = 0\), requires

\[
\frac{2}{l} \Theta_{\text{wake}} = c_{\text{drag}} - c_{\mu,\text{jet}} = 0.
\]  \hspace{1cm} (11)

For non-existing TEB \(u_{\text{jet}}\) becomes 0 and \(\Theta_{\text{wake}}\) is named \(\Theta_{\text{wake},0}\). We now assume that \(c_{\text{drag}}\) remains untouched by TEB since the blade loading is not affected by the blowing, i.e. eq. 11 becomes \(c_{\text{drag}} = \frac{2}{l} \Theta_{\text{wake},0}/l\). We end up with

\[
c_{\mu,\text{jet}} = \frac{2}{l} \Theta_{\text{wake},0} / l, \text{ where}
\]  \hspace{1cm} (12)

\[
\Theta_{\text{wake},0} = \frac{1}{u_2^{+y_{CV}}} \int_{-y_{CV}}^{+y_{CV}} u_{\text{wake}}(u_{\infty} - u_{\text{wake}}) \, dy
\]  \hspace{1cm} (13)

with the mean velocity outside the wake

\[
u_{\infty} \equiv \frac{1}{2y_{CV}} \int_{-y_{CV}}^{+y_{CV}} u_{\text{wake}} \, dy.
\]  \hspace{1cm} (14)

\(\Theta_{\text{wake}}\) is an integral quantity. Thus, a momentumless wake does not necessarily imply a wake profile free of large transverse velocity gradients. Velocity gradients and the accompanying shear layers, however, generate turbulence and may cause RSI noise at a downstream stator (Sutliff, 2005). Hence, it seems more desirable to aim at a momentumless and ‘flat’ wake profile. This can be achieved by minimizing the mean square difference between the wake and the free stream velocity (Fig. 3).

\[
\Theta_{\text{MSE}} \equiv \frac{1}{u_{\infty}^{2}} \int_{-y_{CV}}^{+y_{CV}} (u_{\infty} - u_{\text{wake}})^2 \, dy \to 0
\]  \hspace{1cm} (15)

Fig. 3: Schematic wake velocity profiles: 1 without TEB, 2 momentumless and 3 flat due to TEB.

Note that for non-existing TEB \(\Theta_{\text{MSE}}\) is named \(\Theta_{\text{MSE},0}\). Now, the wake filling quality parameter is defined as

\[
QP = \frac{\Theta_{\text{MSE},0} - \Theta_{\text{MSE}}}{\Theta_{\text{MSE},0}} = 1 - \frac{\Theta_{\text{MSE}}}{\Theta_{\text{MSE},0}}.
\]  \hspace{1cm} (16)

No wake blowing corresponds to 0 of the quality parameter, optimal wake filling to 1, overblowing to values < 0.
Fan Investigated

A low-speed axial fan was designed. To prevent an influence of secondary flow effects, i.e. flow separation in the hub region and tip vortices, the operating point was set to

$$
\psi_t = \frac{\Delta \rho}{\pi^2/2 \rho D^2 \lambda^2} = 0 \quad \text{and the corresponding } \varphi_{in} = \frac{\dot{V}_{in}}{\pi^2 D_A^2} = 0.201.
$$

(17)

Using this configuration the pure interaction of the wake velocity deficit and the stator can be analyzed. To create the same loss of momentum at both sides of the blade and hence a uniform wake velocity profile, a symmetric NACA 0012 airfoil shape was used for rotor blade design. Fig. 4 shows a schematic drawing of the TEB fan stage.

![Schematic drawing of the TEB fan stage](image)

**Fig. 4:** Schematic drawing of the TEB fan stage: meridional cut (left), coaxial section (right).

The position of the reference plane corresponds to the stator leading edge located at

$$
s^* = \frac{s}{l_{ax}},
$$

(18)

where $l_{ax}$ is the axial component of the rotor blade chord length at midspan. The wake velocity profile is evaluated at a relative blade height $h^*$ and along a relative circumferential angle $\theta^*$

$$
h^* = \frac{h}{0.5(D_A - D_t)}
$$

(19)

$$
\theta^* = \frac{\theta}{2\pi / z}.
$$

(20)

All velocities are non-dimensionalized by the mean axial velocity at the stator outlet

$$
\frac{\dot{V}_{out}}{c_{m2}} = \frac{\dot{V}_{out}}{\pi / 4(D_A^2 - D_t^2)}.
$$

(21)

As the circumferential velocity and hence the relative velocity around the blade increases from hub to tip, the wake deficit increases as well. This requires a variation of TEB flow rates in spanwise direction. Thus, each blade’s slot is divided into seven discrete orifices (A-G) which are fed separately via internal passages. Due to the symmetric blade shape there is the same number of orifices at each side of the blade. This requires a split up of the main passage in two passages towards the orifices. The blowing angle is determined by the orifice geometry and was aimed to equal the TE flow angle. Fig. 5 shows the TEB fan with the internal passages, shaped carefully to avoid excessive pressure losses. The passages for a specific blade height are connected to small pressure plena in the hub.

![TEB fan with air supply through hub (left); Blade with internal passages (right)](image)

**Fig. 5:** TEB fan with air supply through hub (left); Blade with internal passages (right).

### Tab. 1: Characteristic quantities

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tr>
<td>$\psi_t$</td>
<td>0</td>
</tr>
<tr>
<td>$\varphi_{in}$</td>
<td>0.201</td>
</tr>
<tr>
<td>$z_{rotor/stator}$</td>
<td>6</td>
</tr>
<tr>
<td>$s^*$</td>
<td>0.4</td>
</tr>
<tr>
<td>$l_{ax}$</td>
<td>0.035</td>
</tr>
<tr>
<td>$D_A$</td>
<td>0.3</td>
</tr>
<tr>
<td>$D_t$</td>
<td>0.168</td>
</tr>
<tr>
<td>$g$</td>
<td>0.0003</td>
</tr>
<tr>
<td>$n$</td>
<td>2000</td>
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[1/min]
Optimization Strategy and Numerical Setup

The optimization strategy for wake filling is based on evolutionary algorithms summarized by Thévenin and Janiga (2008). Herein, every blowing configuration is considered as an individual with seven varying TEB mass flow rates as its genes. Each generation consists of 50 individuals. The first generation is obtained by random assignment of arbitrary blowing rates (within a reasonable range) to the individuals. The performance of each configuration with respect to the target function (maximization of QP) is evaluated by RANS simulations. Based on QP, the individuals are ranked where a better ranking increases the probability of an individual to participate as a parent in the reproduction procedure for the next generation. The probability of reproduction by means of averaging the genes of two parent individuals is 20% while 80% of the next generation is obtained from crossover, i.e. mixing the genes from two parent individuals. This reproduction procedure is enhanced by random mutations of selected genes. Eventually, the new generation is simulated and ranked offering the basis for the production of a further generation. This loop of repeated reproduction, evaluation and ranking is repeated several times resulting in generations with increasing QP. The computational domain of the simulations consists of one-sixth of the bladed annulus and extends $1.0 D_a$ upstream and $1.5 D_a$ downstream of the rotor. It also covers the internal blade passages from their inlet in the hub to their orifices where the jet flow mixes with the main flow. General grid interface (GGI) boundary conditions are imposed in the circumferential direction using the periodicity of blades. The inlet mass flow rate of the fan system is imposed on the upstream boundary according to the operation point of $\phi_n = 0.201$, while an opening pressure boundary condition is set at the outlet. At the entrance of each of the seven internal blades passages the mass flow is set corresponding to the generated genes. No boundary conditions have to be specified at the TEB orifices where the injected mass flow mixes with the main flow. To solve the RANS equations, ANSYS CFX with the standard SST-turbulence model and a 2nd order approximation (blend factor = 1) is employed. The block structured numerical grid consists of approx. 2 million nodes of which around one tenth is required for the TEB passages. Common grid quality criteria are considered in most of the fluid flow regions (e.g. grid angles > 20°). Due to geometrical restrictions, some grid angles in the TEB injection orifices can not be larger than 10°. In these regions, a finer grid is employed to ensure sufficient accuracy. For all simulations the maximum and averaged wall distance for the first node adjacent to the blade surface is $y^+_{\text{max}} < 13$ and $y^+_{\text{ave}} = 4$, respectively. Hence, a wall function is used. The expansion ratio of in the boundary and mixing layer is set to 1.3. The convergence criteria are set to $1 \cdot 10^{-5}$ RMS residuals with respect to conservation of mass and momentum.

![Fig. 6: Computational domain (left) and close view of the mesh near the blade (right).]
Experimental Setup

The complete rotor is manufactured with a selective laser sintering technique. The TEB test facility and the air supply circuit are shown in Fig. 7. Based on mass flow meter readings the seven driving pressures are adjusted by proportional pressure valves according to the desired flow rates. The hoses to the rotary air transducer in the rotor hub are hidden in the hollow stator vanes. The fan stage takes air from an aero-acoustic wind tunnel (Winkler and Carolus, 2009), which provides the auxiliary fan to realize the operation point. The wind tunnel is equipped with a muffler and several screens and honeycombs to produce a homogeneous velocity profile with low turbulence at the inlet of the fan stage. The flow passes the fan stage and exits in a semi-anechoic chamber allowing acoustic far field measurements. 3D hotwire measurements at the stator leading edge are carried out with a triple hotwire probe TSI 1299. The probe is operated in a constant-temperature mode, using the Streamline unit from Dantec Dynamics. A temperature-correction is later applied to the measured signals. The probe is aligned to the absolute velocity vector \( \mathbf{v}_0 \) and positioned in radial direction with an accuracy of 0.02 mm using a three-axes traverse system by ISEL. The sampling rate is chosen to be \( f_s = 24 \) kHz with a measured time signal of \( T = 6 \) s per radial position in the duct. The spatial radial resolution is \( \Delta h^* = 1.5\% \) starting from \( h^* = 7.5\% \) and ending at \( h^* = 92.5\% \). For a single hotwire probe, the relative combined standard uncertainty, including the effect of calibration curve-fitting, A/D conversion, probe positioning, temperature variation, ambient pressure and humidity variations, is estimated to be \( \varepsilon_r = 1.5\% \) of the measured velocities (Jorgensen, 2005). The rotational speed is triggered using a tachometer with an optosensor. Hereby, the measured absolute velocity components \( c_{n2}, c_{u2} \) and \( c_{r2} \) could be analyzed by the phase-lock averaging (PLA) technique (Bruun, 2002). The ensemble averaged velocities are transformed into turbomachinery velocities and angles. Now, it is possible to evaluate the relative velocity \( w_2 \), as well as the quality parameter \( QP \).

The sound pressure in the semi-anechoic chamber is measured by three microphones (Brüel & Kjaer type 4190) at a distance of 1.5 m and an angular spacing of -60°, -30° and 30° from the axis of rotation. All time signals of the sound pressure are captured with a sampling frequency \( f_s = 25.6 \) kHz. The signal analysis is based on the power spectral density which was obtained by the function pwelch in MATLAB with \( \text{window} = \text{hann(nfft)}, \text{noverlap} = 0, \text{nfft} = f_s \). The spectra from the windows are averaged with a final frequency resolution of \( \Delta f = 1 \) Hz.

![Fig. 7: Schematic drawing of the TEB test facility (top) and fan stage with pneumatic circuit (bottom): A centrifugal fan, B Vibration Isolator, C Muffler, D Screens/Honeycomb, E Contraction, F TEB fan stage, G Microphones, H Grid for Flow Recirculation; 1 pressure source, 2 compressed air reservoir, 3 5/2 directional control valve, 4 mass flow meter, 5 proportional pressure valves, 6 manometer, 7 DC motor, 8 rotary air transducer, 9 stator vanes and 10 TEB fan.](image-url)
Results

Numerical Optimization of TEB
For the numerical optimization of the wake filling quality parameter $QP$ (Eq. 16) 10 generations are computed and evaluated. The resulting $QP$s over the corresponding accumulated TEB rates, which are used as a second optimization criterion for energy efficient wake filling, are shown in Fig. 8. The points generate a clearly visible pareto front, which is the boundary between possible, but not optimal, and infeasible solutions. The maximum $QP$ is about 47.5 % at an accumulated TEB mass flow of 3.8 % in reference to the mass flow of the specified operation point. TEB mass flow rates below or above the optimum lead to underfilled or overblown wakes, respectively. A higher $QP$ cannot be realized since the blowing jets can only affect 63% of the wake due to the discretization and radial extent of the passages. The mass flow distribution along the blade height of the optimized TEB configuration (TEB 1) is shown in Tab. 2. Fig. 9 depicts wake velocity profiles $w_2$ in the reference plane normalized with the mean axial velocity. The remaining velocity gradients result from the potential flow field of the rotor blade and a small tip vortex at $h^* > 90 \%$. Hence, an entirely flat velocity profile over the circumference cannot be achieved. However, the wake deficit is attenuated.

Tab. 2: TEB mass flow distribution passage A - G for different wake filling strategies

<table>
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<tr>
<th>EEB</th>
<th>Strategy</th>
<th>$\dot{m}_{TEB,A}$</th>
<th>$\dot{m}_{TEB,B}$</th>
<th>$\dot{m}_{TEB,C}$</th>
<th>$\dot{m}_{TEB,D}$</th>
<th>$\dot{m}_{TEB,E}$</th>
<th>$\dot{m}_{TEB,F}$</th>
<th>$\dot{m}_{TEB,G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no TEB</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>1</td>
<td>Optimized TEB mass flow rates</td>
<td>0.45 %</td>
<td>0.41 %</td>
<td>0.53 %</td>
<td>0.53 %</td>
<td>0.55 %</td>
<td>0.60 %</td>
<td>0.73 %</td>
</tr>
<tr>
<td>2</td>
<td>near downscale of TEB 1</td>
<td>0.34 %</td>
<td>0.3 %</td>
<td>0.42 %</td>
<td>0.42 %</td>
<td>0.44 %</td>
<td>0.50 %</td>
<td>0.62 %</td>
</tr>
</tbody>
</table>

Fig. 8: Optimized wake filling $QP$ over relative accumulated TEB rate for 1$^{st}$ to 10$^{th}$ generation.

Experimental Validation
Fig. 9 shows wake velocity profiles from the 3D-hotwire measurements as well as a comparison between measurement and CFD simulations. It gets obvious that the simulated wake velocity deficit at the configuration without TEB is deeper and wider as compared to the measurements. Two major impacts occur: i) the potential of acoustic reduction is decreased since the RSI is smaller than expected, ii) it leads to an overestimation of needed blowing mass flow for wake filling by the CFD optimization. The measurement result for TEB 1 is an overblown wake and negative $QP$ at specific blade heights, Fig. 10. It is believed that the differences have two reasons. First, the boundary layer development is overpredicted by the wall model of the RANS simulations. Second, strong variations of the wake position and amplitude can be found in the measurement, which have an influence on the
ensemble averaging. However, the expected velocity profiles with TEB are nearly restored by linear downscaling of the blowing mass flow rates (Tab.2, TEB 2) referring to the missing momentum deficit of the unblown wake. With this TEB configuration the wake velocity deficit is significantly reduced, Fig. 9. Now, Fig. 10 shows a satisfactory agreement of measured and simulated $QP$. Please note, that the mixing of the blowing jets and the freestream is successful since no particular blowing effect is visible with TEB 2 configuration.

![Fig. 9: Relative wake velocity $w_2$ profiles from hotwire measurements without and with TEB compared to CFD results without TEB.](image1)

![Fig. 10: Comparison of wake filling quality parameter.](image2)
Acoustic Results

The averaged power spectral density of sound pressures in the farfield measured by the three microphones is presented in Fig. 11. The reduction of the overall sound pressure level $\Delta L_p$ is 0.3 – 0.4 dB although there is an increase in broadband noise above 2 kHz due to TEB which originates from the jet noise at the TEB orifices. The tonal noise is analyzed by an integration of the sound energy $S_{pp}$ over a small bandwidth of $i \cdot BPF \pm 7\,\text{Hz}$ with the blade passing frequency $BPF = n \cdot z$. Surprisingly, the tonal noise reduction at the 1\textsuperscript{st} BPF is small. TEB 1 and TEB 2 lead to a reduction of 0.3 and 0.4 dB, respectively. Since the interaction of the rotor wake with the stator leading edge is reduced, it is suggested that the interaction of the potential flow field becomes the significant RSI noise source. A hint for this assumption is shown by the evaluation of the pressure distribution in the wake from the RANS simulation of the non blowing case, Fig 12. The change of static pressure over the circumference is 4 times higher than the change of dynamic pressure caused by the wake velocity deficit. However, the second harmonic tone is reduced by TEB by 2.8 dB and 1.9 dB, respectively. This is coincident with an observation by Sharland (1964) that most of the noise generated by the impingement of wake deficits on the stator blade contributes to the fist harmonic. by an interaction of wake velocity deficit and potential flow field most of the noise generated by the impinging wakes on the stator leads to an increase of the second harmonic.

![Fig. 11: Spectra of the acoustic pressure PSD level without and with TEB.](image1)

![Fig. 12: Static pressure distribution in the wake of the rotor blades from RANS simulations: coaxial cut at $h^* = 0.5$ (left) and at the stator leading edge at $s^* = 0.4$.](image2)
CONCLUSIONS
For the purpose of controlling the aerodynamic structure of the wake and thus the rotor-stator interaction (RSI) noise sources, the technique of trailing edge blowing (TEB) was investigated. Ideally, the blowing jet compensates the velocity deficit, eliminates the upwash velocity and reduces the turbulence generated in the wake. Hence, the quality of wake filling has a significant impact on the acoustic sources. A quality parameter was derived by a wake momentum analysis and used as a target function for a CFD-based optimization of TEB flow rates. The test object was a fan equipped with internal TEB passages operating at a point of zero pressure rise for generation of an ideal wake velocity profile and minimum secondary flow effects. The optimized TEB configuration was experimentally investigated. A linear downscale of the estimated TEB rate was applied since the wake deficit without TEB was smaller than expected and less TEB momentum was needed. Acoustic measurements in the farfield downstream of the TEB fan stage showed only a small impact of TEB on the first harmonic. It is assumed that this is due to an influence of the potential flow field. However, larger reductions of the second harmonic are achieved. This corresponds to observations of Sharland (1964) who pointed out that most of the noise generated by the impingement of the viscous wakes lead to an increase of the second harmonic. Experiments with an increased distance between the rotor and stator are part of future investigations.

REFERENCES