Trailing Edge Blowing for Reduction of Rotor-Stator Interaction Noise:
Criteria, Design and Measurements

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Abstract
A major source of broadband 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 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 wake turbulence. Special attention is given to different wake filling strategies. Extensive numerical and experimental results show a clear effect of TEB on the wake. Wake filling is particularly successful at blade midspan, whereas in the hub and tip region secondary flow phenomena counteract efforts of wake management.

Nomenclature

\begin{align*}
D_A & \text{ rotor diameter [m]} \\
D_I & \text{ hub diameter [m]} \\
QP & \text{ quality parameter [-]} \\
Tu & \text{ turbulence intensity [-]} \\
V & \text{ volume flow rate [m}^3/\text{s]} \\
c & \text{ absolute flow velocity [m/s]} \\
h & \text{ blade height [m]} \\
h_{\text{slot}} & \text{ slot height [m]} \\
l & \text{ chord length [m]} \\
m & \text{ mass flow rate [kg/s]} \\
n & \text{ rotational speed [rpm]} \\
s & \text{ distance reference plane from rotor TE [m]} \\
u & \text{ velocity around isolated airfoil [m/s]} \\
w & \text{ relative velocity [m/s]} \\
x,y,z & \text{ cartesian coordinates} \\
z & \text{ number of blades [-]} \\
\Delta & \text{ width of the wake velocity deficit [m]} \\
\Theta & \text{ momentum thickness [m]} \\
\beta & \text{ flow angle [°]} \\
\delta & \text{ displacement thickness [m]} \\
\theta & \text{ circumferential angle [°]} \\
\rho & \text{ density of air (main flow and jet) [kg/m}^3\text{]} \\
\end{align*}

Subscripts

\begin{align*}
2 & \text{ stator leading edge plane} \\
in & \text{ position upstream of fan} \\
m & \text{ medirional (axial)} \\
out & \text{ position downstream of fan} \\
r & \text{ radial} \\
* & \text{ non-dimesional} \\
u & \text{ circumferential} \\
\end{align*}

Abbreviations

CV \quad \text{control volume isolated airfoil} \\
GGI \quad \text{general grid interface} \\
HDA \quad \text{hotwire anemometry} \\
MSE \quad \text{mean square error} \\
RANS \quad \text{Reynolds-averaged Navier-Stokes} \\
RSI \quad \text{rotor-stator interaction noise} \\
TE \quad \text{trailing edge} \\
TEB \quad \text{trailing edge blowing sampling} \\

Introduction
Since the start of commercial aviation, the development of jet-powered commercial aircraft has progressed steadily. Thus, 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. In recent years, several research projects have addressed this issue through the development of innovative concepts based on adaptive and passive flow control technologies. One of the noise reduction techniques to be examined is called trailing-edge blowing (TEB). It targets the noise produced by the interaction of a rotating fan with downstream positioned stator vanes (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** produced by the turbulence in the wake.

*Fig. 1: Flow field between the rotor and the stator in a circumferential cut.*

The aforementioned 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 [1, 2] 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 in the tip region. Using this TEB blowing distribution, an 85% reduction in the first three blade-passing frequency wake harmonic amplitudes, referenced to the unblown case, was achieved. The stator unsteady 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. [3] focused on the acoustic benefit of the TEB technique. Blowing was applied on a low-speed fan \((D_A =1.219 \text{ m}, \ n = 1700 – 1900 \text{ rpm, 16 blades and 14 stator vanes})\) by implementing 19 blowing slots per fan blade. The blowing mass flow entered the rotating system through the drive shaft and was delivered to the hollow blades. Inside of the blades, the flow was guided by 18 internal vanes. 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 of Sutliff et al. [4] 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 hub span was under-filled. This resulted in a non uniform wake filling and a smaller reduction in turbulence (25 - 50%) at lower relative blade heights. The overblown tip wake results in stronger turbulence production, but it is 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. These results could not be confirmed by far field acoustic measurements. The reduction was negligible.

The present paper is focused on the realization of a more uniform wake velocity profile to manipulate wake turbulence best. This will require a criterion for optimal wake filling which will be derived and proved by RANS simulations in the following sections. The TEB fan design, the experimental setup as well as 3D HDA measurements will show the potential of TEB as an active noise reduction mean.

**TEB Strategies and Quality Parameters**

To derive strategies and quality parameters for optimal 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 [5]). Assuming (i) a periodic inflow resp. outflow through the upper and lower boundary of the control volume \(CV\) and (ii) a comparably small transverse flow deflection and a temperature of the jet being equal to the one of the main flow one obtains

\[
F_0 - F_{\text{drag}} - F_{\text{wake}} + F_{\text{jet}} = 0 \tag{1.1}
\]

with the forces

\[
F_{\text{b/wake}} = \int_{-\gamma_{CV}}^{+\gamma_{CV}} \rho u_{b/wake}^2 \, dy, \tag{1.2}
\]

\[
F_{\text{jet}} = \int_{h_{\text{ax}}} \rho u_{\text{jet}}^2 \, dy. \tag{1.3}
\]

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

Combining Eq. 1.1 with the continuity equation...
\[
\begin{align*}
\int_{-y_{CV}}^{+y_{CV}} \rho u_{y} dy - \int_{-y_{CV}}^{+y_{CV}} \rho u_{wake, y} dy + \int_{\text{h}_{\text{slot}}}^{+y_{CV}} \rho u_{jet, y} dy &= 0 
\end{align*}
\]
and after some rearrangements, it follows that
\[
F_{\text{drag}} = \rho \int_{-y_{CV}}^{+y_{CV}} u_{wake}(u_{0} - u_{wake}) dy - \rho \int_{\text{h}_{\text{slot}}}^{+y_{CV}} u_{jet}(u_{0} - u_{jet}) dy
\]
\[
= \rho u_{0} \int_{-y_{CV}}^{+y_{CV}} u_{wake}^2 dy - \rho \Theta_{jet} u_{0}^2
\]  
(1.4)

with the momentum thicknesses
\[
\Theta_{wake} = \frac{1}{u_{0}^{2}} \int_{-y_{CV}}^{+y_{CV}} u_{wake}(u_{0} - u_{wake}) dy
\]  
(1.6a)
\[
\Theta_{jet} = \frac{1}{u_{0}^{2}} \int_{\text{h}_{\text{slot}}}^{+y_{CV}} u_{jet}(u_{0} - u_{jet}) dy
\]  
(1.6b)

The first term of the right-hand side of Eq. 1.5 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. 1.5). That integral can be split into two parts
\[
\rho \int_{\text{h}_{\text{slot}}}^{+y_{CV}} u_{jet}(u_{0} - u_{jet}) dy = \rho \int_{\text{h}_{\text{slot}}}^{+y_{CV}} u_{jet} dy - \rho \int_{\text{h}_{\text{slot}}}^{+y_{CV}} u_{jet}^2 dy
\]  
(1.7)

which can be identified as forces due to added mass and the jet momentum. Dividing Eq. 1.5 by the force per unit span due to the dynamic pressure \(0.5\rho u_{0}^2\) leads to the non-dimensional form
\[
c_{\text{drag}} \equiv \frac{2}{1} \Theta_{wake} + c_{\mu, jet} - c_{\mu, mass}
\]  
(1.8)

with the blowing momentum loss coefficient \(c_{\mu, mass}\) and the blowing momentum coefficient \(c_{\mu,jet}\).

\[
c_{\mu,jet} = \frac{\int_{\text{h}_{\text{slot}}}^{+y_{CV}} u_{jet}^2 dy}{\frac{1}{2} u_{0}^2 \text{h}_{\text{slot}}}. \tag{1.9}
\]

Now, assuming a constant velocity over the slot height, we obtain
\[
c_{\mu,jet} = \frac{\text{h}_{\text{slot}}}{2} \left[ \left( \frac{u_{jet}}{u_{0}} \right)^2 \right]. \tag{1.10}
\]

We now disregard the added mass effect, i.e. set \(c_{\mu, mass} = 0\). Then, to aim at zero change of momentum in the control volume, i.e. \(\Theta_{wake} = 0\), requires
\[
\frac{2}{1} \Theta_{wake} = c_{\text{drag}} - c_{\mu,jet} = 0. \tag{1.11}
\]

For non-existing TEB \(u_{jet}\) becomes 0 and \(\Theta_{wake}\) is named \(\Theta_{wake,0}\). We now assume that \(c_{\text{drag}}\) remains untouched by TEB, i.e. eq. 1.8 gives \(c_{\text{drag}} = 2\Theta_{wake,0}/1\). With eq. 1.11 we end up with
\[
c_{\mu,jet} = \frac{2\Theta_{wake,0}}{1}. \tag{1.12}
\]

and the blowing jet velocity for a momentumless wake
\[
u_{jet} = u_{\infty} \sqrt{\Theta_{wake,0}/\text{h}_{\text{slot}}}. \tag{1.13}
\]

(Winkler [5], Waitz et al. [7] and Sell [8]). \(\Theta_{wake,0}\) is evaluated as
\[
\Theta_{wake,0} = \frac{1}{u_{\infty}^{2}} \int_{-y_{CV}}^{+y_{CV}} u_{wake}(u_{\infty} - u_{wake}) dy \tag{1.14}
\]

with the mean velocity outside the wake
\[
u_{\infty} = \frac{1}{2y_{CV}} \int_{-y_{CV}}^{+y_{CV}} u_{\text{wake}} dy. \tag{1.15}
\]

\(\Theta_{wake}\) 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 [4]. Hence, it seems more desirable to aim not at a momentumless, but at a ‘flat’ wake profile. This can be achieved by minimizing the mean square error (MSE) of the wake velocity profile (Fig. 3)
\[
\Theta_{\text{MSE}} \equiv \frac{1}{u_{\infty}^{2}} \int_{-y_{CV}}^{+y_{CV}} (u_{\infty} - u_{\text{wake}})^{2} dy \rightarrow 0. \tag{1.16}
\]

Note that for non-existing TEB \(\Theta_{\text{MSE}}\) is named \(\Theta_{\text{MSE,0}}\).

Now, wake filling quality parameters are defined as
\[
Q_{\text{P1}} \equiv \frac{\Theta_{\text{wake,0}} - \Theta_{\text{wake}}}{\Theta_{\text{wake,0}}} = 1 - \frac{\Theta_{\text{wake}}}{\Theta_{\text{wake,0}}}. \tag{1.17}
\]

and
\[
Q_{\text{P2}} \equiv \frac{\Theta_{\text{MSE,0}} - \Theta_{\text{MSE}}}{\Theta_{\text{MSE,0}}} = 1 - \frac{\Theta_{\text{MSE}}}{\Theta_{\text{MSE,0}}}. \tag{1.18}
\]

No wake blowing corresponds to 0 of both quality parameters, optimal wake filling to 1, overblowing to values > 1.

**Fig. 3:** Schematic wake velocity profiles: 1 without TEB, 2 momentumless due to TEB, 3 flat due to TEB.
Guided by this analysis we want to apply two TEB strategies as summarized in Tab. 1 to a low pressure fan stage. In reality there is a severe constraint in TEB slot geometry. Since all airfoils are very thin in the TE region, the slot height is limited. We decide to select geometry as depicted in Fig. 4 and keep it constant throughout the study.

Tab. 1: TEB strategies applied to fan stage

<table>
<thead>
<tr>
<th>TEB</th>
<th>Objective</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>baseline</td>
<td>no TEB</td>
</tr>
<tr>
<td>1</td>
<td>momentumless wake</td>
<td>TEB with $u_{jet}$ acc. to eq. 1.13</td>
</tr>
<tr>
<td>2</td>
<td>flat wake profile</td>
<td>TEB with $u_{jet}$ for min. $\Theta_{MSE}$ (eq. 1.16)</td>
</tr>
</tbody>
</table>

Fig. 4: TEB blade section with a constant slot height $h_{slot} = 1$ mm, chord length l from hub to tip = 94.6 – 96.0 mm

RANS simulations of the flow around the rotor blades including the flow in the TEB internal blade passages and experiments were carried out to assess the combined effect of centrifugal forces in the passages due to rotation of the rotor and the mixing of the jets with the external flow field. While applying blowing strategy TEB 1, the effect of the chosen blowing velocities according to Eq. 1.13 on the wake profile is evaluated. For blowing strategy TEB 2 the RANS serves to optimize the TEB mass flow rates with respect to meet the aforementioned MSE quality parameter best.

**Fan Investigated and Test Rig**

A stage of a low-speed axial fan was designed. Some design parameters are given in Tab. 2 and Fig. 5.

Tab. 2: Design parameters of the fan stage

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume flow rate at the inlet $\dot{V}_{in}$</td>
<td>0.67 [m³/s]</td>
</tr>
<tr>
<td>(Mass flow rate at the inlet $m_{in}$)</td>
<td>0.79 [kg/s]</td>
</tr>
<tr>
<td>Rotor diameter $D_A$</td>
<td>0.2994 [m]</td>
</tr>
<tr>
<td>Hub diameter $D_l$</td>
<td>0.168 [m]</td>
</tr>
<tr>
<td>Rotor speed $n$</td>
<td>3000 [rpm]</td>
</tr>
<tr>
<td>Number of rotor blades $z$</td>
<td>6 [-]</td>
</tr>
<tr>
<td>Axial chord length rotor $l_{ax}$ at midspan</td>
<td>0.0605 [m]</td>
</tr>
</tbody>
</table>

For the rotor blade design, a NACA 6512-63 airfoil is used. The fan operates at its design flow rate coefficient

$$\phi_{in} = \frac{\dot{V}_{in}}{\pi D_A^2 n} = 0.201.$$  \hspace{1cm} (2.1)

The position of the reference plane corresponds to the stator leading edge located at a distance from the rotor trailing edge

$$s^* = \frac{s}{l_{ax}},$$  \hspace{1cm} (2.2)

where $l_{ax}$ is the axial component of the rotor blade chord length at $D_A$. The wake velocity profile is evaluated at a relative blade height

$$h^* = \frac{h}{(D_A - D_l) / 2}$$  \hspace{1cm} (2.3)

and along a relative circumferential angle

$$\theta^* = \frac{\theta}{2\pi / z}.$$  \hspace{1cm} (2.4)

Fig. 5: Schematic drawing of the TEB fan stage, left: meridional cut, right: coaxial section of cascade.

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

$$c_{m2} = \frac{\dot{V}_{out}}{\pi / 4(D_A^2 - D_l^2)}.$$  \hspace{1cm} (2.5)

Note that $\dot{V}_{out}$ is the volume flow rate through the fan and the blade trailing edges. As the circumferential velocity and hence the flow velocity around the blade increases from hub to tip, the wake deficit increases as well. This requires a spanwise distribution of the blowing parameters. For that each blade’s slot is divided into seven discrete orifices which are fed separately via internal passages. The blowing angle is determined by the orifice geometry and was aimed to equal the flow angle at the TE. Fig. 6 shows the internal passages, shaped carefully to avoid excessive pressure losses. The internal passages responsible for a specific blade height are connected in the hub. They are connected to seven small plenums in the hub. The complete rotor was manufactured with selective laser sintering technique. The air supply circuit is shown in Fig. 7. Based on mass flow meter (ABB Sensyflow FMT200-ECO2) readings the seven driving pressures are adjusted by proportional pressure valves accord-
ing 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 a large semi-anechoic room via an inlet nozzle. A duct with an anechoic termination was mounted on the duct of the fan stage. The operating point was controlled by a throttle downstream of the termination and measured by a hot film probe in the duct. 3D hotwire measurements in the reference plane (stator vanes leading edge) were carried out using a triple hot film sensor probe TSI 1299. The probe was operated in a constant-temperature mode, using the Streamline unit from Dantec Dynamics.

A temperature-correction was later applied to the measured signals. The probe was aligned to the absolute velocity $c_2$ and positioned in radial direction with a repeatability accuracy of 0.02 mm using a three-axes traverse system from ISEL. The sampling rate was chosen to be $f_s = 36$ kHz by a measured time signal of $T = 10$ s per radial position in the duct. The spatial radial resolution was $\Delta h^* = 1.5\%$ starting from $h^* = 7.5\%$ at the hub and ending at $h^* = 92.5\%$ near the shroud. The rotational speed of the TEB fan was triggered using a tachometer with an optosensor. Hereby the measured absolute velocity components $c_m$, $c_u$ and $c_r$ could be analyzed by the phase-locked averaging (PLA) technique [10]. The ensemble averaged velocities were transformed into typical turbo-machinery velocities and angles. As a result of this analysis, it was now possible to evaluate the relative velocity $w_2$, as well as the wake turbulence intensity $Tu$.

**Fig. 6:** Blade with internal passages (top); cut through fan rotor with seven blowing orifices and air supply through hub (bottom).

**Fig. 7:** Test rig (schematically).

**Numerical Setup**

The computational domain consists of one-sixth of the bladed annulus $1.0 \, D_A$ upstream and $1.5 \, D_A$ downstream of the rotor, Fig. 8. It also covers seven 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 were imposed in the circumferential direction. The inlet mass flow rate of the fan system was imposed on the upstream boundary according to the operation point of $\phi_{in} = 0.201$, while an opening pressure boundary condition was set at the downstream boundary.

At the entrance of each of the seven internal blade passages the mass flow was set corresponding to $\dot{m}_{jet}$ required for every blade strip. Of course no boundary conditions
have to be specified at the channels’ exit (i.e. the orifices) since the 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) was employed [9]. The block structured numerical grid consists of 5.5 million nodes. Special attention was paid to the wake region by using a very fine grid resolution of approx. 3 million nodes. Common grid quality criteria were considered in most of the fluid flow regions (grid angles > 20°). Due to geometrical restrictions, some grid angles in the TEB injection orifices were as small as 11°. In these regions, a finer grid was employed to ensure sufficient accuracy. For the simulation, the maximum value of $y^+$ for the first node adjacent to the blade surface was < 9, whereas the area averaged $y^+$ at the blade was < 1. The convergence criteria were set to $1 \cdot 10^{-5}$ RMS residuals.

![Fig. 8: Numerical domain of the TEB fan.](image)

**Results**

**Preliminary RANS Study**

It was anticipated that secondary flow structures in the bladed rotor at the hub and the blade tip can contaminate the wake in those regions. Hence to get a clear picture of the complete wake a trick was applied in a preliminary CFD study: the tip gap was set to zero, and moreover, the friction at the hub was “eliminated” by the use of a free slip boundary condition. Of course, no-slip boundary conditions were applied to shroud as well as to the blades throughout the study. Ideally, TEB 1 should yield a momentumless mean wake velocity profile along the complete blade height ($Q_{P_{TEB1}} = 100\%$). From TEB 2, upon iterative optimization, we expect a flat wake profile $Q_{P_{TEB2}} = 100\%$. Fig. 9 shows wake velocity profiles $w_2$ in the reference plane according to Fig. 5, normalized with the mean axial velocity (Eq. 2.5).

It is evident that both TEB strategies modify the wake. The depth of the mean wake velocity profile is smaller at $h^* = 30\%$ compared to the other relative blade heights and the blowing jet does not have a large effect. At 60% and 90%, the influence of the blowing jet is clearly visible. It does not hit the maximum wake deficit precisely. However, the wake deficit is compensated and the wake velocity profile seems to be flatter. At 90%, the wake velocity profile is slightly overblown in case of TEB 1. This is a typical wake form resulting from the momentumless wake criterion given by Eq. 1.13.

![Fig. 9: Wake velocity profiles from preliminary RANS simulation (i.e. without secondary flow effects); comparison of TEB strategies at various blade heights.](image)
tion of the relative flow by TEB. The diagrams in Fig. 10 depict the wake filling quality parameters along blade height. Although in our preliminary study tip gap was not present and friction at the hub was “eliminated” it is evident that wake filling is not equally successful for all blade heights.

Brookfield et al. [2] published their achievements in terms of $Q_{\text{TEB1}}$ and are shown for comparison in the upper diagram - their data show even larger shortcomings. There are several reasons for the deviations from the ideal results: (i) Mismatch of the slot geometry and the wake location, i.e. the jet does not meet the wake, (ii) Interference of the jets with the main flow field, (iii) Interference of the jets with each other.

The overall blowing rates applied are shown in Tab. 3.

**Full RANS simulation**

Now, a full RANS simulation including friction at the hub and the tip gap of 0.16 % of $D_A$ or 0.52% of tip chord length $l$ was performed. Fig. 11 visualizes secondary flow effects in the main flow as anticipated. The hub and the tip vortices disturb the blade wake velocity profiles clearly, Fig. 12. This effect is minimal in the midspan region.

**Tab. 3: TEB strategies**

<table>
<thead>
<tr>
<th>Strategy</th>
<th>$\phi_{\text{in}}$ [-]</th>
<th>$\bar{m}<em>{\text{TEB}}/\bar{m}</em>{\text{fan}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEB 0</td>
<td>0.2011</td>
<td>0.00</td>
</tr>
<tr>
<td>TEB 1</td>
<td>0.2065</td>
<td>2.68</td>
</tr>
<tr>
<td>TEB 2</td>
<td>0.2062</td>
<td>2.50</td>
</tr>
</tbody>
</table>

Fig. 11: Secondary flow effects from full RANS simulation; Hub vortex (left) and tip vortex (right).

Fig. 13 shows the development of the wake downstream of the rotor at approximately midspan. Close to the trailing edge at $s^* = 0.1$, the jet hits the wake velocity deficit exactly at its minimum but does not fill it perfectly. At $s^* = 0.4$ the momentum added is not sufficient to create a flat and smooth profile, but reduces the velocity deficit. Further downstream at $s^* = 1.0$ the wake velocity deficit is nearly mixed out anyway.

**Experimental Validation**

Fig. 14 shows wake velocity profiles from the 3D-hotfilm measurements. The wake velocity deficit is filled by both TEB strategies. Surprisingly the resulting profiles look rather similar. Moreover, it becomes obvious that the secondary flow effects have a severe impact on the wake velocity profiles. A direct comparison of RANS and experimental results is given in Fig. 15. Different from the RANS-simulation the profile outside of the wake shows a small velocity gradient in circumferential direction. This is attributed to the potential flow field. The agreement is good without trailing edge blowing (TEB 0), and satisfying with TEB 1 and 2.

Under the assumption that the measured velocities are cyclostationary it is possible to extract the velocity fluctuations of the absolute velocity $c_z$ using the Reynolds decomposition. The turbulence intensity in the wake can be calculated by
Fig. 12: Wake velocity profiles from full RANS simulation at various blade heights.

Fig. 16 shows the turbulent intensity as a contour plot in the reference plane with and without TEB. It is evident that the TEB strategies applied lead to a reduction of wake turbulent intensity over the whole blade height by roughly 2 - 3% points or 30% as compared to the unblown case.

Fig. 13: Wake velocity profiles from full RANS simulation as a function of downstream distance from the rotor; h* = 60% (approx. midspan).

Conclusions
Within the study we demonstrated the aerodynamic potential of TEB with respect to wake filling and turbulence wake management for reduction of rotor-stator interaction.
noise sources. Two strategies for TEB were derived, aiming at either a momentumless wake as in Waitz et al. [7] or a flat wake velocity profile. Expensive numerical and experimental results show a clear effect of TEB on the wake. The effect of both strategies is similar, with a tendency for better results from the flat wake strategy. Besides that secondary flow effects have a severe impact on the wake velocity profiles. Hence, the targeted wake filling quality parameters were not achieved in the blade hub and tip region. This could be an obstacle for tonal rotor-stator interaction noise reduction. However, hot wire measurements proved that turbulence intensity in the wake was reduced by TEB. This has the potential for broad band noise reduction. A quantitative assessment of TEB for noise reduction is part of future investigations.

![Figure 14](image1.png)

**Fig. 14:** Wake velocity profiles from 3D hotwire measurements.

![Figure 15](image2.png)

**Fig. 15:** Mean wake relative velocity profiles of CFD calculations and the 3D hotwire measurements; Comparison of TEB strategies in relation to the non blowing velocity profile at 60% h*.

![Figure 16](image3.png)

**Fig. 16:** Mean wake relative velocity profiles of CFD calculations and the 3D hotwire measurements; Comparison of TEB strategies in relation to the non blowing velocity profile at 60% h*. 

s* = 0.4

h* = 30%

s* = 0.4

h* = 60%

s* = 0.4

h* = 90%

s* = 0.4

h* = 30%

s* = 0.4

h* = 60%

s* = 0.4

h* = 90%

s* = 0.4

h* = 30%

s* = 0.4

h* = 60%

s* = 0.4

h* = 90%
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References