NUMERICAL STUDY OF WAKE EFFECTS ON THE BOUNDARY LAYER OF A HIGH LIFT TURBINE CASCADE AT SEVERAL STROUHAL NUMBERS AND FLOW COEFFICIENTS

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ABSTRACT
In this study, the flow through the MTU-T160 low pressure turbine cascade is computed in a set of steady and unsteady RANS simulations involving wake impingement. Two characteristic variables, the Strouhal number $Sr$ as well as the flow coefficient $\phi$ are modified while keeping the Reynolds number $Re_2$ and Mach number $Ma_2$ fixed. It is observed that increasing $Sr$ leads to lower total pressure loss of the cascade for $\phi \leq 1$ and higher total pressure loss for $\phi > 1$ while increasing $\phi$ generally leads to larger losses. While reducing the size of the separation bubble, increased values of $\phi$ also produce more turbulence friction losses upstream of the separation and downstream of the reattachment of the flow compared to lower flow coefficients. Steady state simulations with mixing plane interface show significantly different results compared to unsteady time-mean simulations in terms of qualitative and quantitative loss change with variation of $Sr$ and $\phi$.

KEYWORDS
TRANSITION, WAKE, LOW-PRESSURE TURBINE, STROUHAL NUMBER, FLOW COEFFICIENT
**NOMENCLATURE**

- bc  boundary condition
- $c$  chord [m]
- $c_f$  skin friction coefficient
- $\delta_2$  momentum thickness [m]
- $\eta$  isentropic stage efficiency
- $g$  pitch [m]
- $\gamma$  intermittency
- $k$  turbulence kinetic energy [$m^2/s^2$]
- $Ma_2$  exit Mach number
- $n_s$  number of stator blades
- $n_w$  number of wakes
- $\omega$  specific dissipation rate [1/s]
- $\phi$  flow coefficient
- $Re_2$  exit Reynolds number
- $Re_{\Theta}$  Reynolds number based on momentum thickness
- $Sr$  Strouhal number
- $\Theta_{0,i}$  initial wake momentum thickness [m]
- $t_w$  distance between wakes [m]
- $u_{fs}$  freestream velocity
- $u_x$  axial velocity [m/s]
- $u_y$  circumferential velocity [m/s]
- $w_h$  wake half width [m]
- $\hat{x}$  non-dimensional distance
- $x_{TE}$  coordinate of trailing edge
- $y^+$  non-dimensional wall distance
- $\zeta$  total pressure loss coefficient

**INTRODUCTION**

In the optimization process of turbomachinery blade geometries, quick turnaround times with acceptable CFD accuracy are crucial. Thus, the optimization frequently involves only steady state RANS simulations for the preliminary design approach. This requires a certain accuracy of the results obtained by steady state simulations. The study conducted in this paper focuses on the ability of steady state RANS simulations to capture the wake-induced transition effects on LPT blades as well as the actual changes in performance given by unsteady time-mean simulation. Mayle (1991) has found that wakes are able to trigger an earlier laminar-turbulent transition in boundary layers and are thus able to reduce the time-mean size of laminar separation bubbles generally reducing losses. As LPT blades can operate at fairly low Reynolds numbers, laminar separations are present in most of the operating conditions. Thus, they cannot be neglected when optimizing LPT blade geometries. Coull and Hodson (2011) conducted experiments on a flat plate with a streamwise pressure gradient similar to modern high-lift LPT blades with impinging wakes. They observed that the transition process is mainly driven by interaction between boundary layer instabilities and the disturbances of the free-stream caused by the wakes. Liang et al. (2015) experimentally investigated the effects of different wake passing frequencies on laminar-turbulent transition on a LPT cascade. At a fixed flow coefficient they concluded that the optimal wake passing frequency is the one that balances out the separation loss and turbulence friction loss. Modeling different wake profiles through rotating bars, Hammer et al. (2018) investigated the T106A linear LPT cascade using LES. They observed that the turbulence levels generated by non-rotating bars are several times higher than those present in actual LPT blade wakes. According to their findings, the weakest generated wakes at constant flow coefficient and wake passing frequency resulted in the largest separation bubble as well as the greatest reduction of the overall LPT loss. Also through LES, Zhang et al. (2012) simulated...
the T106D-EIZ LPT cascade in the presence of 4 different wake passing frequencies at a fixed flow coefficient of $\phi = 0.83$ with varying FSTI levels. They observed that an increase of the wake frequency leads to shorter separation bubbles. Further work was done by Michelassi et al. (2016), who also performed a set of 8 LES for the T106A LPT cascade. They also observed a drop in losses with an increase of the wake passing frequency for decreasing flow coefficients.

The aim of this work is to extend the investigations to new combinations of the wake passing frequency and the flow coefficient, together with smaller steps in order to create a detailed performance change matrix. The emphasis lies rather on the global cascade parameters than a detailed analysis of wake mechanisms during convection through the passage and interaction with the boundary layer. Also, it is investigated in what way steady state simulations with mixing plane interfaces can be used for the estimation of turbomachinery performance involving wake induced transition.

**NUMERICAL METHOD**

For all simulations conducted, the parallel CFD solver TRACE of DLR Köln has been applied, cf. Nürnberger (2004) and Kügeler (2005). In TRACE, the three-dimensional Reynolds-averaged Navier-Stokes equations are solved on multiblock structured meshes by using a finite volume method. The discretization of the convective fluxes is done by the TVD upwind scheme of Roe (1981), the diffusive fluxes are discretized by a central differencing scheme. An implicit predictor-corrector time integration algorithm has been applied. The turbulence model in use is the two equation $k-\omega$ model by Wilcox (1993) together with the stagnation point anomaly fix of Kato and Launder (1981). The laminar-turbulent transition of the boundary layer is modeled by the $\gamma-Re_\Theta$ model by Langtry and Menter (2009). Being widely used for the prediction of the boundary layer transition, it is a local formulation to evaluate the local flow features in terms of natural, bypass and separation induced transition. Only the wall distance formulation used is not local. For further information regarding the $\gamma-Re_\Theta$ transition model, please refer to the work of Langtry (2006). All boundary layers have been resolved with a dimensionless wall distance of $y^+ \leq 1$.

**DESIGN OF SIMULATIONS**

As the simulations carried out aim to represent rotor-stator interaction between two cascades in an LPT, it is necessary to capture the effect induced by the impinging wakes on the downstream stator blade. The Strouhal number $St$ as well as the flow coefficient $\phi$ are determined (see eqn. 1 and 2) and varied while $Re_2$ and $Ma_2$ are kept fixed. This is to make sure that only the characteristic of the wake convection through the stator cascade is responsible for the change in blade performance. As can be seen from eqn. 2, both modified variables are not independent of each other. For a given geometry, the axial chord length $c_{ax}$ is fixed as a change of $c_{ax}$ would also imply a change of the Reynolds number. Also, the absolute velocity with respect to the stator cascade reference frame is constant for all $\phi$ in order to fix $Re_2$ and $Ma_2$. In order to modify the two observed characteristic variables independently, it is crucial to alter the wake frequency of the upstream blade. Since the circumferential velocity of the upstream rotor cascade $u_y$ is also fixed for a given $\phi$, the circumferential distance $t_w$ between two impinging wakes is the only value that can be changed.

$$\phi = \frac{u_x}{u_y}$$

(1)
Figure 1: Illustration of the rotor (not modeled) and the stator (meshed, every fourth node shown). Proportions are skewed and do not represent the actual blade geometry.

\[
Sr = \frac{u_y \times c_{ax}}{u_x \times t_w} = \frac{c_{ax}}{t_w \times \phi}
\]  

(2)

However, when applied to a blade geometry used in turbomachinery, a change of \( t_w \) implies a modification of the number of rotor blades as well as the pitch \( g \), and finally, the loading of each blade. This, when computing a full LPT stage, would lead to significantly different characteristics of the produced rotor wake which would in turn add another parameter to the study. Thus, the task is to get a variable \( t_w \) without sacrificing the consistency of the impinging wakes. For the simulations performed, it was chosen to not model the actual rotor blade (see. fig. 1). This also makes for a major performance improvement as only the stator grid has to be modeled. For the wakes, a set of correlations was used to reproduce the time averaged wake dynamics induced by the upstream rotor blade. The correlational framework for modeling time averaged wakes of aerodynamic profiles has been created in a previous work by Führing et al. (2018). There was a minor recalibration needed for the LPT blade used in this paper. The overall agreement of the computed LPT blade wake at fixed conditions with the correlations used is satisfying as shown below. All simulations involving wakes were conducted using the ‘2D GUST’ inlet boundary condition (bc) implemented in TRACE. The GUST bc is an inhomogeneous boundary condition that is used to map the simulated wakes on the inlet boundary.

However, \( t_w \) cannot be chosen freely since the periodicity of the incoming wakes has to be preserved. This means, that the modification of \( t_w \) can only follow eqn. 3 with \( n_w \) being the number of wakes mapped on the inlet boundary.

\[
t_w = \frac{1}{n_w} \times g
\]  

(3)

In order to preserve a fixed \( \phi \) and achieve an approximately similar \( Sr \), the stator blade as well as the inlet block are duplicated. The inlet blocks are then merged and \( n_w \) wakes are mapped onto the boundary. This extends eqn. 3 to eqn. 4 with \( n_s \) as the number of stator blades.
As φ can be fixed easily through a choice of \( u_y \) for fixed \( Ma_2 \) and \( Re_2 \), the variable to be approximated is \( Sr \) which can be achieved through different combinations of \( n_s \) and \( n_w \). Table 1 shows the chosen combinations as well as the resulting characteristic variables. As already mentioned, the value of \( Sr \) is only approximated by the chosen pairings because of performance limitations as for some combinations, as many as 50 actual stator blades would have to be modeled in order to exactly fix \( Sr \) to 3 decimals. With the values shown in the table, the maximum relative deviation of \( Sr \) is 3.99% with the mean being 1.53%.

Table 1: Chosen pairings of \( n_s \) and \( n_w \) for the shown combinations of approximated \( Sr \) and \( \phi \).

<table>
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<tr>
<th>( \phi )</th>
<th>0.25</th>
<th>0.385</th>
<th>0.565</th>
<th>0.69</th>
<th>0.9</th>
<th>1.1</th>
<th>1.36</th>
<th>1.83</th>
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<tbody>
<tr>
<td>( n_s )</td>
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<td>( n_s )</td>
<td>( n_w )</td>
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<td>1</td>
<td>7</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>0.64</td>
<td>7</td>
<td>1</td>
<td>9</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>0.82</td>
<td>11</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>1</td>
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<td>1.00</td>
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The values of \( Sr \) and \( \phi \) chosen in this study aim to represent a suitable set of boundary conditions found in engine operation as well as cascade experiments conducted (see fig. 2). For the transitional behavior of the boundary layer of the stator blade, the two observed variables can be evaluated qualitatively. A higher \( Sr \) at a fixed \( \phi \) would mean there are more wakes present in the flow field at any given point as the distance \( t_w \) between the periodic wakes is shorter. This would lead to a higher density of time-mean convected wake turbulence through the cascade and ultimately, an earlier laminar-turbulent boundary layer transition (cf. Abu-Ghannam and Shaw (1980)). Regarding \( \phi \), a change of this parameter implies quite complex mechanics as an increase of \( \phi \) leads to a wake that is more parallel to the blade surface and is not able to roll up the vortex in the separated shear layer. At the same time, the parallel convection of the wake increases the time the suction side boundary layer is affected by the greatly increased turbulent intensity (cf. Zou et al. (2018)). In the simulations conducted in this study, the wake conditions are kept fixed in terms of relative velocity defect and turbulence parameters despite a change of the flow coefficient in a real stage simulation would also alter these variables. This is to isolate the wake convection characteristics in a better way.

For the LPT blade in this study, it was chosen to fix the Reynolds number at \( Re_2 = 90,000 \), the exit Mach number at \( Ma_2 = 0.6 \), and the inlet freestream turbulence level at \( Tu = 1\% \) as those conditions represent a characteristic LPT environment. During this study, 48 cases have been computed, each with three different setups: first, the flow field is initialized and converged in a steady state simulation with homogenous inlet conditions. Then, the 2D GUST inlet condition is used to map wakes onto the inlet boundary. The case is then converged in a steady state simulation. The third setup is an unsteady simulation of the flow field for 8 periods in order
to reach periodic unsteady behavior. Both cases involving wakes are then compared to the steady state case without wakes. Between the upstream block and the modeled stator grid, an interface is used that applies a mixing plane algorithm in both steady state simulations and is then switched to a zonal rotor-stator interface for the unsteady calculation. The mixing plane approach (cf. Du and Ning (2016)) is a way to transfer circumferentially averaged and mixed out flow variables between flow fields with different reference frames in the form of steady state boundary conditions. This, opposed to the frozen rotor approach, mixes out unsteady structures, but avoids the problem of upstream wakes being directed at the exact same position of the downstream blade (clocking). The zonal approach involves a direct mapping and interpolation of flow variables onto the opposing side of the interface and is therefore used for the unsteady computations. For the unsteady RANS computations, 384 physical timesteps with up to 20 sub-iterations each were used per blade passing period in order to resolve the unsteady effects. The time-mean results shown are the averaged results of one blade passing period each. The unsteady RANS simulations used a corresponding steady state solution as initial condition and were computed using 8 blade passing periods in order to ensure periodicity of the wake effects.

**Generation of the Wake Profiles**
A set of correlations is applied to estimate the upstream blade wake that is entering the flow domain through the rotor-stator interface. It was chosen to place the interface at a distance of $\Delta x = -0.25 \times c$ from the leading edge of the stator blade. The GUST bc was applied to an upstream block with 8 cells in axial direction. This block is necessary as the GUST bc is inhomogenous but not unsteady so in order to move the rotor wake in front of the stator blade, the upstream block is translated along the rotor-stator interface. The overall axial distance between the trailing edge of the rotor and the leading edge of the stator is assumed to be $\Delta x = 0.5 \times c_{ax}$. The GUST bc block upstream of the interface has a width of $1/29 \times c$. This means, a wake with the characteristics of $\Delta x \approx 0.217 \times c$ axial travel distance has to be mapped onto the inlet boundary. As an overview, the computed wake of the LPT blade is shown together with the results of the set of correlations for the velocity profile, the turbulent kinetic energy, and the turbulent dissipation rate (see fig. 3). Also, the decay of the maximum velocity defect (see eqn. 5) is shown for the non-dimensional travel distance $\tilde{x}$ given in eqn. 6. For the mapping of the inlet boundary, the profiles shown in fig. 3 were scaled in order to match inlet

![Figure 2: Approximate values of the Strouhal number and flow coefficients for LTP blades found in engine operating conditions as well as cascade experiment conditions.](image)
conditions.

\[ u_{d,max} = \frac{u_{fs} - \min(u)}{u_{fs}} \quad (5) \]

\[ \tilde{x} = \frac{x - x_{TE}}{\Theta_{0,i}} \quad (6) \]

For this parameter study, it was chosen to conduct only quasi-2D computations of the undisturbed midspan flow in order to isolate the response of the blade performance to the wake effects. While actual three-dimensional engine computations involve flow phenomena in radial direction as well as highly turbulent tip leakage phenomena that are responsible for a considerable portion of the overall losses, the effects of unsteady periodic wake-blade interaction are dominant in the midspan flow. Thus, the modeling of three-dimensional sidewall effects would exceed the scope of this study.

In the velocity profile of the wake (see fig. 3), there is a discontinuity noticeable at \( y/w_h = \pm 2.5 \) which is caused by the inhomogeneous freestream velocity profile at the considered plane. In the final inlet profile, this is accounted for by a linear transition from \( u(y/w_h = 2.5) \) to \( u(y/w_h = -2.5) \) between the synthesized wakes.

Validation of the Setup

For the study, a total of 5 different computational grids were created from the geometry using initially \( n = 6,200 \) cells as well as \( [2, 4, 8, 16] \times n \). They were extruded surface meshes with one cell in spanwise direction with a height of \( 1\% \times c \) making it a quasi-2D computation. A convergence study was conducted through comparison of three parameters: the overall total pressure loss coefficient, the velocity profile of the outlet boundary, and the wall shear stress profile on the suction side of the LPT blade. The results of the grid used in this study showed less than \( 2\% \) relative difference from the finest grid used in terms of the observed characteristic variables. The grid used in this work has a number of \( n_c = 4 \times n \) cells per stator modeled as well as a non-dimensional wall distance of \( y^+ \leq 1 \) for all cases. Figure 4 (r.) shows the progression of \( y^+ \) at the blade surface for the highest Reynolds number \( Re = 4 \times 10^5 \) chosen in the validation process. Prior to the numerical study, the simulation was validated using data obtained in a wind tunnel. The setup of the experiments were replicated with the mesh generated earlier. The change of the total pressure loss coefficient (see eqn. 7) with a modification of \( Re_2 \) was observed (see fig. 4). The conditions of \( Sr \) and \( \phi \) used in the experiments were matched. The experiments were conducted with and without wakes generated by a rotating bar mechanism and are compared to steady (with and without mapped wake) and unsteady simulations using the same inlet wake. It can be seen that the trend is captured by all setups for their respective boundary conditions. The steady state simulations without wake (---) are able to reproduce the quantitative behavior of the loss coefficient quite well when compared to the steady state results (\( \Delta \)) obtained from the experiment. For the steady state case with mapped wake inlet conditions (---), the quantitative deviations from the experiments (○) as well as the unsteady simulations (---) are considerably large while the setup correctly captures the trend. For all \( Re_2 \) the steady state wake cases are underestimating the total pressure losses of the cascade while the unsteady time-mean results show a much smaller quantitative deviation as well as a more accurate representation of the trend that at \( Re_2 \geq 200,000 \), the blade performance is
RESULTS

For the study, a total of 144 simulations of the MTU-T160 LPT blade were carried out at \( Re_2 = 90,000 \) and \( Mo_2 = 0.6 \) in order to evaluate blade performance change with an isolated modification of either \( Sr \) or \( \phi \) (see fig. 2). For the results, the total pressure loss coefficient of the cases involving wakes are compared to their respective steady state result without wakes \( \zeta_{ref} \) (see fig. 3). It should be noted that the definition of \( \zeta_{ref} \) in this part differs from the definition used in the comparison with the experimental data. While for the experiments, all \( \zeta \)

\[
\zeta = \frac{p_{t,1} - p_{t,2}}{p_{t,1} - p_2} \quad (7)
\]
Figure 4: (l.) Relative change of the total pressure loss coefficient $\zeta$ with increase of $Re_2$ with respect to the experimental value $\zeta_{ref}$ at $Re_2 = 120,000$. (r.) Wall values of $y^+$ for the worst case operating point of $Re_2 = 400,000$. $y_{max}^- = 0.95$, $y_{mean}^- = 0.47$.

were compared to an arbitrarily chosen reference value, the reference value $\zeta_{ref}$ here is the total pressure loss coefficient of the corresponding steady state simulation without any wake effects at $Re_2 = 90,000$. From the unsteady analysis, it seems that an increase of $Sr$ in the range $0.5 \leq \phi \leq 1$ leads to a decrease of $\zeta/\zeta_{ref}$ while an increase of $Sr$ in the range $\phi > 1$ has the opposite effect. An increase of $\phi$ leads to an increase of $\zeta/\zeta_{ref}$ for the considered range of the modified variables. This trend is only partially confirmed by the steady state computations using a mixing plane interface. Both simulations agree on the relatively high total pressure loss at very high $Sr$ and high $\phi$ while only correctly capturing the qualitative behavior in steady state. The steady state analysis shows a non-linear behavior of $\zeta$ for a fixed $\phi = 0.412$ with the range $0.5 \leq Sr \leq 1.4$ leading to lower losses than $Sr$-values below or above mentioned range. For fixed $\phi = 2.0$, the steady state simulations predict an almost linear increase of $\zeta$ with increasing $Sr$. Opposed to that, the unsteady set of computations predict an almost linear decrease of losses for increasing $Sr$ at a fixed $\phi = 0.412$ as well as a non-linear increase of losses for increasing $Sr$ at a fixed $\phi = 2.0$. The minimum total pressure loss coefficient is found to be at $Sr_{min}, \phi_{max}$ for the steady state computations as well as $Sr_{max}, \phi_{min}$ for the unsteady analysis which is quite contrasting. For a comparison of the influence of different flow coefficients, two different $\phi = [0.412; 1.51]$ are investigated at a fixed $Sr \approx 1.1$ as these are conditions that can appear in engine applications. Figure 6 illustrates the changes in wake kinematics with the two different flow coefficients at a fixed $Sr$. A comparison of these two exemplary cases with the results not involving wakes shows that the flow is reattached upstream of the trailing edge at both $\phi$ while it is not reattached in the case without wakes (see fig. 7). Also, the skin friction is generally higher for higher $\phi$ which in turn leads to higher turbulence friction losses. The simulations of the two compared flow coefficients shown in fig. 7 were taken out of the set of unsteady computations done for the parameter study and then recomputed on the finest grid from the computational grid generation step in order to ensure the most accurate representation of the involved phenomena. While the separation of the case without wakes occurs at around $0.79 \times c$, it is notable that the separation is delayed as well as reduced in size for higher $\phi$. To study the
accumulated loss, a comparison of the development of the momentum thickness $\delta_2$, normalized by the momentum thickness $\delta_{2,\text{ref}}$ for the case without wakes at the trailing edge is done.

In terms of the momentum thickness, the case involving a higher flow coefficient generates more losses due to the higher turbulence friction loss upstream of the flow separation. This results in an overall higher loss compared to the case with a lower $\phi$ even though the separation bubble is smaller. This confirms the findings of Hammer et al. (2018) that the total pressure loss is not proportional to the size of the flow separation. It seems that the increased friction loss upstream of the separation and downstream of the reattachment position is counteracting the loss reduction through the alteration of the separation. Generally, it can be said that in the range covered in this study, the LPT blade develops the least losses in a combination of high $Sr$ and low $\phi$ values. This would mean that many wakes are entering the flow field with a very steep convection angle. This would lead to a better wake mixing compared to a shallow incidence angle happening in the cascade as concluded from fig. 6.

Concerning the prediction accuracy of the steady state simulations involving impinging wakes, the qualitative as well as the quantitative results contrast strongly with the unsteady results as shown in fig. 5. The steady state results underestimate the maximum and minimum loss reduction by up to 6% and also show a different trend of the change of $\zeta/\zeta_{\text{ref}}$ with modification of either $Sr$ or $\phi$. For example, at $\phi \approx 0.5$, the steady state simulation predicts an almost

Figure 5: Relative change in total pressure loss coefficient $\zeta$ with respect to the loss of the corresponding steady state simulation with homogenous inlet conditions $\zeta_{\text{ref}}$ for the steady state (left) and unsteady time-mean (right) case with wakes.

Figure 6: Illustration of wake kinematics with $\phi = 0.412$ (l) and $\phi = 1.51$ (r) at a fixed $Sr \approx 1.1$. 
constant $\zeta/\zeta_{ref}$ for all $Sr$ while the unsteady time-mean results show a decrease in losses for increasing $Sr$. Obviously, steady state simulations are not able to accurately capture the wake effects. Hence, unsteady simulations or adequate modeling of wake effects is necessary. In order to provide an orientation on the impact of loss coefficient change on the stage efficiency, the corresponding bookkeeping is briefly presented. A change of $\Delta \zeta/\zeta_{ref} \approx 5.4\%$ leads to a change in isentropic stage efficiency of $\Delta \eta = 1\%$ at core flow region. Taking into account the end wall effects, which make up for roughly one half of the losses, the change in isentropic stage efficiency including secondary flow effects is estimated to be $\Delta \eta = 0.5\%$ at mentioned $\Delta \zeta/\zeta_{ref}$.

Figure 7: Comparison of $c_f$ for the case with no wakes and with low and high $\phi$ at $Sr \approx 1.1$ as well as the relative change in $\delta_2$, referenced to $\max(\delta_2)$ for the steady case at the trailing edge.

CONCLUSIONS
A set of 48 configurations with varying Strouhal numbers $Sr$ and flow coefficients $\phi$ has been performed using steady state and unsteady RANS simulations. An increase of $Sr$, i.e. the wake passing frequency led to a decrease of the total pressure loss coefficient $\zeta$ for $\phi \leq 1$ as well as an increase of the total pressure loss for $\phi > 1$. An increase of the flow coefficient $\phi$ generally led to an increase of the loss coefficient while further reducing the size of the suction side separation bubble. Higher flow coefficients also lead to higher friction losses upstream of the separation and downstream of the reattachment of the flow which seems to affect the overall losses negatively. Thus, in this case a large separation bubble leads to a smaller total pressure loss coefficient than an almost suppressed separation of the suction side boundary layer. The steady state simulations using the mixing plane are only able to reproduce the wake effects for the rather unusual combination of very high $Sr$ and very high $\phi$. Thus, further work will focus on modeling wake effects in steady state simulations for the covered $Sr - \phi$ range. The operating conditions of the stator cascade were chosen in order to show a strong response of the blade performance to the wake effects. At large Reynolds numbers, the wake effects are expected to be less prominent than with the set of boundary conditions used in this work.
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