Steady and Unsteady RANS Modeling of Wake Effects and Grid Resolution Requirements in a Low-Pressure Turbine Cascade

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Abstract. Due to relative motion between rotors and stators in aircraft engines, periodic wakes are present in downstream blade rows, which exert significant influence at flow loss and engine efficiency. To quantify and reproduce this influence, a low-pressure turbine cascade is computed using steady and unsteady RANS methods in the flow solver TRACE by DLR and MTU Aero Engines. A thorough grid study is carried out and various aspects of grid resolution requirements are investigated for the setups and considered performance metrics respectively. A steady state transition model extension that has been developed and published by the authors is applied to the cascade flow at a number of operating points and validated with experimental data while being compared to the unsteady results as well as the steady state results without the wake effect extension. Further, a variation of wake-related parameters is carried out while discussing the effects modeled in the unsteady setup as well as the ability of the two steady state setups (with and without wake extension) to capture the trends identified by the unsteady results. A sufficiently accurate reproduction by the wake model extension enables steady simulations of the inherently unsteady effects in the aerodynamic design of the turbine, which results in an enormous saving of computational time and effort.

1. Introduction
As low-pressure turbines in aircraft engines often operate at very low Reynolds numbers, transition phenomena in general as well as wake-induced transition effects in particular, have to be considered when predicting the overall efficiency. In multistage turbomachinery flows, periodically unsteady wakes are present at all times which leads to an interaction of the impinging wakes with the boundary layer of downstream blade rows. Wakes have the ability to instantaneously increase the boundary layer intermittency (the fraction of time the flow is turbulent) which leads to an earlier transition onset as well as an overall quicker transition process [1]. Stieger et. al. [2] [3] found in an experimental study that wakes interact heavily with transitional separation bubbles on low-pressure turbine blades so that flow separation on the suction side of the blade can even be temporarily suppressed. In terms of the loss behavior of low-pressure turbine blades concerning transitional separation bubbles, Lu et. al. [4] concluded
that unsteady wakes reduce losses by interacting with separation bubbles while also increasing friction losses through the larger turbulent-wetted area caused by the impinging turbulent wakes. The impact of these counteracting effects also largely depends on the operating point of the blade. At start and landing of the aircraft, the Reynolds number is comparably high leading to small separation bubbles and a long attached boundary layer which is where impinging wakes are detrimental to the blade efficiency. At cruise conditions, however, the Reynolds number is small leading to large transitional separation bubbles on conventional blade geometries where the wakes are able to interact with the separation leading to an overall better efficiency. Thus, the performance of the blade is considered at a variety of Reynolds numbers with and without wakes in this study in order to give an estimation of the alteration of the loss behavior that arises from the inherently unsteady wakes.

2. Numerical Method

In this study, the numerical solver TRACE by DLR and MTU Aero Engines AG is applied, cf. [5, 6, 7, 8]. In order to model turbulent effects, the $k - \omega$ turbulence model by Wilcox (1988 version) [9] is used. The stagnation point anomaly fix by Kato and Launder [10] is utilized to prevent excessive turbulent production in stagnation regions. Transition modeling is done using the two-equation local correlation based $\gamma - Re_\Theta$ model by Langtry and Menter [11]. In order to meet the requirements of the transition model, all grids in this study have been resolved with a dimensionless wall distance of $y^+ \leq 1$ for all operating points.

This work contains results that have been obtained from a number of steady and unsteady RANS simulations using three different setup methods:

- steady state RANS computation using the $\gamma - Re_\Theta$ transition model in its original form as published by Langtry and Menter [11]
- unsteady RANS computation using the original model serving as numerical reference
- steady state RANS computation utilizing a transition model extension by the authors [12] called a "quasi-unsteady wake model" (QUWM)

The aim of the QUWM is that, through the extension of the $\gamma - Re_\Theta$ transition model by two additional transport equations, wake-related transition effects that are of an inherently unsteady nature, can be captured by steady state RANS simulations in a more effective way. This is done by evaluating the upstream interface of every blade row and computing a boundary condition for two transport variables that interact with the underlying transition model so that the unsteady averaged solution of the transition variables is reached. Consequently, the gap between the boundary layer solution of an averaged unsteady computation and the corresponding steady state computation is narrowed to a large extent. This allows for a more accurate prediction of boundary layer losses without sacrificing the performance margin of steady state computations. The formulation of the QUWM is given in [12].

3. Design of Simulations

The design of the numerical setup is based on the design of the corresponding experimental setup that has been established at the Von Karman Institute for Fluid Dynamics (VKI) using the T106C high-lift low-pressure turbine blade profile. Regarding the operating conditions, there are many publications about the wind tunnel experiment at the VKI, cf. [13, 14, 15] as well as additional measured data that was kindly supplied by Prof. Arts of the VKI [16]. The freestream inlet turbulent intensity is $Tu = 0.9\%$ for the setup involving homogeneous inflow without wake generators. As Bode et. al. [17] point out, the prescription of an adequate turbulent length scale $l_t$ is crucial for the correct modeling of the boundary layer. In this case, the length scale for the homogeneous inflow was chosen in order to model the correct turbulent decay and achieve highest possible similarity of the numerical and experimental results at the chosen operating point of
Figure 1: Illustration of the rotor (not modeled) and the stator cascade T106C, n/16 grid shown. Wakes mechanics are akin to a modeled upstream blade or bar wake.

$Re_2 = 100,000$ and $Ma_2 = 0.65$. In accordance with studies conducted by MTU Aero Engines AG [18], the inlet flow angle for the freestream boundary condition was altered to $\alpha = 35.7$ deg. Instead of the actually modeled moving upstream bars, an inviscid block is translated upstream of the rotor-stator interface as shown in Fig. 1. This type of setup has been used successfully by the authors in previous studies [19]. For the setup involving impinging wakes, the experimentally measured wake of the moving upstream bars [14] was mapped onto an inhomogeneous (GUST) inlet boundary condition. This provides an advantage over simulating upstream objects as all the wake characteristics from the experiment can be directly used and are not prone to modeling weaknesses of the RANS method. The numerical results incorporating wakes are compared to the publications of Arts [14] as well as Clinckemaillie et. al. [15]. The wake generating bars are run at different speeds for both studies which is reflected in the numerical boundary conditions used. While Arts is utilizing the maximum speed of 3,000 RPM, Clinckemaillie et. al. run the bars at 2,665 RPM which alters the wake response of the blade. These differences have been accounted for in the numerical setup so the results are compared to their experimental counterparts respectively. As the authors only aim to model the effects of the wakes in midspan flow, the study is carried out essentially on two-dimensional grids involving only 1 cell in spanwise direction. Thus, three-dimensional effects are not modeled by the numerical setup.

4. Grid Convergence Study

Before conducting the actual quantitative study with regards to wake alteration, a thorough grid convergence study is executed in order to ensure that the results are not influenced by the computational mesh used. Five grids are generated with the finest consisting of $n = 1 \times 10^5$ cells and the others resolved with $n/f$ cells with $f = \{1, 2, 4, 8, 16\}$ meaning a higher value of $f$ corresponds to a coarser grid resolution. All grids are generated from the original geometry with the meshing tool G3DHexa by DLR while keeping the $y^+$ value below 1. The operating point of $Re_2 = 100,000$ and $Ma_2 = 0.65$ is chosen for the grid convergence study as the low freestream turbulence levels lead to a relatively large transitional separation bubble and hence a strong response to the impinging wakes. In a first step, the flow around the cascade is computed on all grids using freestream boundary conditions. The isentropic Mach number distribution $Ma_{is}$ is compared for all grids as well as to the experimental data by Arts [16] (s. Fig. 2). The comparison of the various grids shows a consistent trend in result alteration with a change in the number of mesh cells. In the separation region that is shown in a zoomed in snippet, the difference between the grids is more pronounced. The finest resolution of $n = 1 \times 10^5$ cells comes...
closest to the experimental data. As this study puts focus on wakes and their interaction with the boundary layer, the grid resolution requirements are analyzed for the unsteady setup with inhomogeneous inflow in a second step. This is particularly interesting as in this case the grid is not only responsible for the boundary layer solution, but also for the transport of the wake information into the boundary layer in order to interact with the separation region. Fig. 3 shows the wakes convecting through the passage for the finest and the coarsest grid to illustrate the differences that arise from the grid resolution with respect to wake transport. Additionally, the presence of a highly unmixed wake introduces a new loss mechanism according to Denton [20] that has to be modeled by the numerical setup. Thus, the integral time-averaged loss is the sum of all loss mechanisms involved in the flow field and is therefore an important metric for the comparison of the grids. The total pressure loss coefficient $\zeta$ is computed according to eqn. (1) while variables $\bar{x}$ denote an area-weighted average.

$$\zeta = 1 - \frac{1 - \left(\frac{p_2}{p_{02}}\right)^{\frac{\kappa-1}{\kappa}}} {1 - \left(\frac{p_2}{p_{01}}\right)^{\frac{\kappa-1}{\kappa}}}$$

(1)

Fig. 4 (l.) shows the trend of the total pressure loss coefficient for the various grids. For the freestream boundary conditions, the coarsest grid predicts a severely lower $\zeta$ than the finest grid. This is mainly due to the differences in the predicted size of the separation bubble. In contrast to that, the differences in the estimation of the loss coefficient for the setup involving wakes are much smaller. As Fig. 4 (r.) depicts, there is a clear trend from the lowest to the highest grid resolution in the prediction of the separation region while the $n/2$ mesh completely overlays the $n$ mesh. The overall agreement of the numerical and the experimental data is not as good as for the homogeneous inflow in Fig. 2. However, all setups manage to capture the general mechanics of the wake-induced alteration of the suction side separation. As the solutions are almost identical in other regions of the blade, i.e. the leading edge region as well as the pressure side, there is only a zoomed snipped of the overall $Ma_{iso}$ plot shown. In order to pick a grid that can predict both types of boundary condition fairly accurate and hence removes the dependency of the solution on the number of cells while not sacrificing more performance than necessary, the mesh with $n/2$ cells is chosen as the one to be used for the numerical study.
5. Reynolds Lapse

With the identified grid to be used, the various operating points of the experiments are computed. While the exit Mach number is kept fixed at \( M_{ao2} = 0.65 \) for all simulations, the Reynolds number as well as the rotational speed of the wake generating bars is varied. As stated before, the two experimental studies are conducted at different wake generator speeds, hence the figures mention the results separately and refer to the publication of Arts \[14\] as "2013" that was run at \( \omega_{bar} = 3,000 \) RPM while the publication of Clinckemaillie et. al. \[15\] is referred to as "2015" with \( \omega_{bar} = 2,665 \) RPM. Fig. 5 shows the results of the steady and unsteady simulations compared to the respective experimental information. As can be seen, the unsteady setup does not make a noticeable difference between the two different wake generator speeds. The steady state simulations without bar wakes compare well to the studies by the VKI while the results in the range \( Re \leq 125,000 \) are closer to the findings of Clinckemaillie et. al. \[15\] whereas the results at higher Reynolds numbers are painting the same picture as Arts \[14\]. In terms of the unsteady results with bar wakes, the numerical data compares to the findings of Clinckemaillie et. al. fairly well. However, there are large differences between the findings of Arts and the corresponding numerically predicted loss coefficient. This can possibly be explained by the uncertainty of the
Figure 5: Comparison of the numerical steady (w/o bar) and unsteady (w/ bar) setups with the experiments of Arts [14] (2013) as well as Clinckemaillie et. al. [15] (2015).

experimental setup that is given as an absolute value of $\Delta \zeta = 0.034$ by Clinckemaillie et. al. [15] for the operating point $Re = 90,000$ which is considered quite large. It should be noted that the authors of the experimental study [15] claim that the results were very repeatable and that the uncertainty values are the result of a rigorous error propagation. Ultimately, the numerical setup is able to capture the overall trend of the experimental studies to a large degree.

Fig. 6 (l.) compares the results of the unsteady averaged numerical solution to both steady state setups, one with (QUWM) and one without (baseline) the transition model wake extension by the authors [12]. It is clearly noticeable that both steady simulations manage to capture the trend depicted by the unsteady averaged results. Also, the QUWM performs significantly better than the baseline setup and manages to close the gap in terms of the total pressure loss coefficient by up to 50% while maintaining the overall trend showing a very robust behavior of the model extension. While the QUWM is able to achieve a better overall prediction capability, there is about 12% more computational time needed compared to the baseline model which is still far lower than the unsteady computation which consumed at least 10 times the computational effort in order to reach a converged solution.

6. Change of Wake Parameters
In an additional exploratory study, the wake information at the inhomogeneous boundary condition is altered. For one of the setups, the inhomogeneous boundary condition only contains the turbulence data of the wake („only-turb“) while the other variables like the total pressure and total temperature are resembling homogeneous freestream flow. In another iteration, the boundary condition contains no wake turbulence information („no-turb“) but only the freestream turbulent intensity of $Tu = 0.9\%$ while the total pressure and total temperature values are describing the wake. The motivation for such a study is that the effects of the wake parameters can be evaluated largely separated from each other. However, it must be noted that the „no-turb“boundary condition, despite introducing no increased turbulence levels into the domain, will lead to increased turbulence through the wake velocity defect mixing process. Thus, the turbulent component cannot be entirely separated from the velocity defect and the associated strain field in this case. Fig. 6 (r.) shows the Reynolds lapse for both of the setups compared to the original unsteady computation that contains the full wake information. In this comparison, the evaluation of steady state mixing plane simulations does not seem useful as the wake velocity defect is fully mixed out in the interface before even entering the cascade passage. This way,
Figure 6: (l.) Normalized total pressure loss coefficient $\zeta/\zeta_{\text{norm}}$ for the homogeneous inflow boundary condition (bc), the normal experimental wake data bc „full wake“, the wake bc with only turbulent variables „only turb“, and the bc with wakes that have no increased turbulence levels „no turb“. (r.) Comparison of the unsteady averaged numerical results with the steady state setups with (QUWM) and without (baseline) the transition model extension.

there is not much theoretical potential for the steady state simulations to capture the results, especially for the „no-turb“ case. In terms of the total pressure loss coefficient $\zeta$, the numerical prediction varies greatly for the three considered boundary conditions. Surprisingly, the normal „full wake“boundary condition comes out in the middle of the other two setups. The wake boundary condition containing only the total pressure and temperature variables of the wake but no turbulent values such as $k$ or $\omega$ actually leads to noticeably higher losses than the wake boundary condition containing the full wake data. Lastly, the wake boundary condition with only the turbulent wake variables as well as a homogeneous total pressure and temperature level changes the overall pressure losses to a slightly lower level. While the „full wake“ as well as the „only turb“ manage to consistently lower the overall losses of the cascade flow, the wake without turbulent information is very close to the loss values of the homogeneous boundary condition. Due to space limitations, there is no in-depth analysis of the loss composition and the time and space progression of the wakes shown. Thus, the more detailed study will be part of future work.

7. Conclusion

A low-pressure turbine cascade was computed by means of steady and unsteady RANS simulations and validated with experimental data at low turbulent intensity values. A thorough grid study was carried out leading to an optimum value of $n = 50,000$ cells per spanwise cell layer in order to capture the steady and unsteady effects involved in the overall loss behavior of the cascade flow. Additionally, a steady state transition model extension developed by the authors was applied to the cascade flow closing the gap by up to 50% between the steady and unsteady results while increasing the computational effort by 12% as opposed to the unsteady averaged solution consuming at least ten times as many cpu hours. The validated setup was then used to derive two variants of boundary conditions, one containing no turbulent variables of the wake, the other one containing only the increased wake turbulence but no wake pressure and temperature profile. The evaluation of the area averaged total pressure loss coefficient showed that the boundary condition containing no wake turbulence led to the highest overall losses of all wake-related boundary conditions while the setup with only the turbulent wake information was able to reduce the total pressure loss coefficient the most.
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References

[1] Mayle R E 1993 Unsteady, multimode transition in gas turbine engines *Agard Conference Proceedings 527, Heat Transfer and Cooling in Gas Turbines* (Advisory Group for Aerospace Research & Development)

[2] Steiger R D, Hollis D and Hodson H P 2004 *Journal of Turbomachinery* **126** 544–550 ISSN 0889-504X (Preprint https://asmedigitalcollection.asme.org/turbomachinery/article-pdf/126/4/544/5695443/544_1.pdf) URL https://doi.org/10.1115/1.1773851

[3] Steiger R D and Hodson H P 2004 *Journal of Turbomachinery* **126** 536–543 ISSN 0889-504X (Preprint https://asmedigitalcollection.asme.org/turbomachinery/article-pdf/126/4/536/5694812/536_1.pdf) URL https://doi.org/10.1115/1.1773850

[4] Lu X, Zhang Y, Li W, Hu S and Zhu J 2017 *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* **231** 25–38 (Preprint https://doi.org/10.1177/0957650916671421) URL https://doi.org/10.1177/0957650916671421

[5] Becker K, Heitkamp K and Kügeler E 2010 Recent progress in a hybrid-grid cfd solver for turbomachinery flows *Proceedings Fifth European Conference on Computational Fluid Dynamics ECCOMAS CFD 2010*

[6] Kügeler E, Nürnberg D, Weber A and Engel K 2008 Influence of Blade Fillets on the Performance of a 15 Stage Gas Turbine Compressor *“Turbo Expo: Power for Land, Sea, and Air” (Turbo Expo: Power for Land, Sea, and Air)* vol 6: Turbomachinery, Parts A, B, and C (ASME) pp 415–424

[7] Franke M, Röber T, Kügeler E and Ashcroft G 2010 Turbulence treatment in steady and unsteady turbomachinery flows *Proceedings Fifth European Conference on Computational Fluid Dynamics ECCOMAS CFD 2010*

[8] Ashcroft G, Frey C, Heitkamp K and Weckmüller C 2013 *Journal of Turbomachinery* **136** ISSN 0889-504X

[9] Wilcox D C 1993 *Turbulence modelling for CFD* (DCW Industries, La Cañada)

[10] Kato M and Lauder B 1981 The modelling of turbulent flow around stationary and vibrating square cylinders *Proc. 9th Symp. on Turb. Shear Flow* vol 9 pp 10.4.1 – 10.4.6

[11] Langtry R B and Menter F R 2009 *AIAA Journal* **47** 2894 – 2906

[12] Führing A, Kožulović D and Franke M 2019 Quasi-unsteady wake effect modeling in steady state mixing plane simulations of turbines *Proceedings of DLRK 2019*

[13] Michálek J, Monaldi M and Arts T 2012 *Journal of Turbomachinery* **134** ISSN 0889-504X 061009 (Preprint https://asmedigitalcollection.asme.org/turbomachinery/article-pdf/134/6/061009/5845245/061009_1.pdf) URL https://doi.org/10.1115/1.4006291

[14] Arts T 2013 Aerodynamic performance of two very high lift low pressure turbine airfoils (t106c – t2) at low Reynolds and high Mach numbers *5TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)* (EUCASS)

[15] Clincemaiilie J, Fattorini L, Fontani T, Nuysts C, Wain G and Arts T 2015 *11th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics, ETC 2015*

[16] Arts T 2020 Private Communication

[17] Bode C, Außerheide T, Kožulović D and Friedrichs J 2014 The Effects of Turbulence Length Scale on Turbulence and Transition Prediction in Turbomachinery Flows (Turbo Expo: Power for Land and Air vol Volume 2B: Turbomachinery) (ASME)

[18] Fiala A 2020 Private Communication

[19] Führing A, Kožulović D and Franke M 2019 Modelling of wake effects in steady state mixing plane simulations of a high lift turbine cascade with different combinations of wake passing frequency and wake orientation *European Turbomachinery Conference, ETC13 Lausanne*

[20] Denton J D 1993 *Journal of Turbomachinery* **115** 621–656 ISSN 0889-504X (Preprint https://asmedigitalcollection.asme.org/turbomachinery/article-pdf/115/4/621/5551769/621_1.pdf) URL https://doi.org/10.1115/1.2929299