MEASUREMENT AND SIMULATION OF A TURBULENT BOUNDARY LAYER EXPOSED TO ACCELERATION ALONG A FLAT PLATE

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ABSTRACT
Flow in turbomachines is generally highly turbulent. The boundary layers, however, often exhibit laminar-to-turbulent transition. But also relaminarization of the turbulent flow may occur.
It is therefore important for the designer to understand the process of boundary layer transition in both directions and to determine the position of transition onset and the length of the transitional region. In the last decades several transition models have been developed to enable modern CFD codes to predict the transition and relaminarization processes. This has the advantage that the boundary layer behavior can be analyzed in advance, which enables the design of blades which trigger a ”suitable” boundary layer. But in order to use CFD for designing tasks, the code must predict accurately and reliably the transition and relaminarization processes within the boundary layer.
Therefore in this work, the $\gamma$-$Re_\theta$ transition model is tested regarding relaminarization prediction. An in-house flat plate test case is analyzed where extensive measurement results are available. Since the test case shows flow pulsations caused by a separation bubble, different cases are investigated where either the full range of the measured velocity fluctuations or only the fluctuations above the integral subscale are prescribed as boundary conditions. Both boundary conditions are combined with either a steady or unsteady simulation where the latter allows to consider the velocity fluctuations additionally. Aim of this variation is to understand the influence of inlet turbulence boundary condition of the predictions of the transition model regarding relaminarization.

KEYWORDS
Relaminarization, transition modeling, CFD, turbulence, RANS, URANS

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$c_f$</td>
<td>Local skin friction coefficient</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>ISW</td>
<td>Institute of Fluid Mechanics and Heat Transfer</td>
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<tr>
<td>ITTM</td>
<td>Institute for Thermal Turbomachinery and Machine Dynamics</td>
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<tr>
<td>$K$</td>
<td>(Launder) acceleration parameter</td>
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<tr>
<td>$k$, $k_{tot}$</td>
<td>Turbulent kinetic energy</td>
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<tr>
<td>$k_T$</td>
<td>Model-related turbulent kinetic energy</td>
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<tr>
<td>$k_V$</td>
<td>Turbulent kinetic energy resulting from velocity fluctuations</td>
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<tr>
<td>LDA</td>
<td>Laser-Doppler anemometry</td>
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<tr>
<td>LIV</td>
<td>Laser interferometric vibrometry</td>
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INTRODUCTION

The boundary layer represents the narrow zone between a solid body wall and the free stream. In this small area viscous effects dominate the flow. The state of this boundary layer, whether it is laminar or turbulent, is on one hand influenced by free stream parameters, like the velocity, acceleration or turbulence level of the free stream and on the other hand influences the free stream itself as well as wall parameters, like skin friction or heat transfer (see e.g. Bader and Sanz [2015]).

These parameters are important in the real machine, since they strongly influence for instance the efficiency of a blade and also the thermal stresses which the blade has to withstand. Therefore, an understanding of the state of the boundary layer, moreover the position, length etc. of the transitional zone is very important for the designer of turbomachines.

At the first contact of a flowing fluid with a stationary structure, under appropriate flow conditions the boundary layer develops from laminar via a transitional zone to turbulent. The boundary layer passes through several stages within this transitional zone before becoming fully turbulent. Schlichting and Gersten [2006] extensively discussed these different stages.

It is vitally important to understand the influences from the various parameters on the onset position and length of the transitional zone in order to predict and potentially control the state of the boundary layer. In turbomachinery, the efficiency of blades and stages can be improved considering transition. This allows the overall machine performance to be improved. Mayle [1991] published a comprehensive review of the importance of transition in gas turbines. He analyzed experiments performed by several research groups in order to find the influence of different flow parameters on the transition process.

In the last years, additional experiments were performed by many research groups in order to better understand the processes in the boundary layer. Many different measurement techniques were used to find out more details of the boundary layer flow, e.g. Yip et al. [1993], Oyewola et al. [2003], Bader and Sanz [2016], Shin and Song [2015].

So far, only the transition from laminar to turbulent flow was described. Under certain flow conditions (like strong acceleration), however, a reverse transition or relaminarization from turbulent to laminar can occur. Up to now, only few measurements on relaminarization were reported (e.g. Narasimha and Sreenivasan [1979], Ichimiya et al. [1998], Escudier et al. [1998], Mukund et al. [2006]). Therefore, at the Institute for Thermal Turbomachinery and Machine
Dynamics (ITTM) of Graz University of Technology a project was launched in order to understand the process of relaminarization and its phases even further and evaluate common threshold values for relaminarization. First measurement performed at the institute showed the process of relaminarization (see Bader et al. [2016]).

Transition and relaminarization occurs in various cases in a turbomachinery (see e.g. [Mayle, 1991, Hampel et al., 2002, Händel et al., 2014]), however the focus in the last decades on this small share of the flow has been reduced, although it has an influence on the main flow as well as wall parameters like skin friction or heat transfer. The possibility to predict the state of the boundary layer in advance enables a design of a turbomachinery blade which benefits of the different advantages of the boundary layer stages. In order to enable such a design process, CFD codes can be used to analyze different variations of a blade. Therefore transition models have been developed, e.g. the $\gamma$-$Re_\theta$ [Langtry and Menter, 2009]. This model uses free-stream parameters like the turbulence intensity to trigger transition and relaminarization. As Bader et al. [2017] showed the model is capable of predicting relaminarization, but the length of the laminar-like zone before retransition is predicted too short. The authors found that this is caused by a too early decrease of $Re_\theta$ in the free stream.

In this paper the role of turbulence intensity in causing this early retransition should be analyzed. The idea for this investigation is, that the turbulence which is measured by CTA or LDA does not always agree to $Tu$ used within the simulation. The difference here lies in the definition of the turbulent kinetic energy $k$. While the simulation differs between unsteady velocity fluctuations and $k$ representing turbulence within the model, the measurement accumulates fluctuations of all frequencies to one root-mean-square (RMS) value of the velocity fluctuations and thus to $k_{tot}$. In the present case these differences are quite high, since an unsteady pulsation of a separation bubble triggers velocity fluctuations of rather low frequency, which is not captured as turbulence ($k$) by the turbulence model. The discrepancies between these two types of fluctuations (velocity and turbulent fluctuations) influences the set inlet turbulence and thus also the distribution of turbulence along the plate. The latter influences the transition model, thus the prediction of transition and relaminarization.

In this work also the question should be answered, if a stationary simulation is sufficient to predict a relaminarization process since it neglects unsteady velocity fluctuations entirely.

The following section presents the numerical setup and the test case used for the study. Thereafter we present and discuss the simulation results compared to the measurements. The paper ends with a short summary and the conclusions.
INVESTIGATED CASE AND NUMERICAL SETUP

The investigated case in this paper represents a flat plate test case, where the flow is accelerated due to a decrease of the cross-section of the flow area. A picture of the test bench can be seen in Fig. 1a. At the corner of the upper wall, at the end of the decrease of cross-section, a separation bubble is present. This separation bubble is small and does not extend to the boundary layer at the flat plate, but it pulsates and thus triggers fluctuation in the free stream. It has been found, that these fluctuations are not accounted by the turbulence model, but are measured by the LDA. The difference of the turbulent kinetic energy \( k \) between measurement and simulation is illustrated in Fig. 2b and is discussed later in this section.

The plate normal extension has been validated numerically and experimentally, and it has been found, that the separation bubble is small enough and does not influence the boundary layer directly, which means that streamlines inside the boundary layer remain undisturbed.

For the numerical simulation the commercial code ANSYS\textsuperscript{®} CFX\textsuperscript{®} v15.0 was used. The code uses a pressure correction scheme. The high resolution scheme has been selected for the advection as well as the turbulent numerics. The Navier-Stokes equation system is discretized with first order accuracy in areas where the gradients change sharply to prevent overshoots and undershoots and maintain robustness, and with second order in flow regions with low variable gradients to enhance accuracy [Ansys Inc., 2013].

As turbulence model the well-known SST \( k-\omega \) turbulence model by Menter [1994] has been used together with the \( \gamma-Re_{\theta} \) transition model by Langtry and Menter [2009].

The mesh used for the simulation is a 2D mesh consisting of approximately 660,000 nodes and \( y^+ \) was kept between 0.1 and 1 which is recommend by Langtry et al. [2004] for the \( \gamma-Re_{\theta} \) transition model. The mesh is shown in Fig. 1b. At the numerical inlet the boundary conditions have been taken from 2D hot-wire anemometry measurements and along the plate the experimental data has been acquired by 2D Laser-Doppler anemometry (LDA). The measurements have already been presented by Bader et al. [2016] and for more information the interested reader is referred to this publication.

As already described above, both measurement techniques measure fluctuations of all frequencies (between their minimum and maximum resolved frequencies) and return a time signal including all these fluctuations. The turbulent kinetic energy \( k \) can then be derived with

\[
k = \frac{1}{2} \cdot \left( (u')^2 + (v')^2 + (w')^2 \right)
\]

where \( u', v' \) and \( w' \) represent the fluctuations in the three spatial dimensions, respectively.

Figure 2a shows a typical distribution of \( k \) over the frequency. The range right of the maximum describes the dissipation of larger to smaller eddies (inertial subrange) and the final dissipation to heat (dissipation scale). These fluctuations are normally the turbulence which can be calculated by a turbulence model, in this work the SST \( k-\omega \) model

Below the inertial subrange fluctuations of lower frequencies are present in the so-called integral scale. These fluctuations can be found by an unsteady CFD calculation as unsteady velocity fluctuations.

Fig. 2b shows the distribution of \( k \) along the plate from the measurement results, the model-related TKE \( k_T \) which represents \( k \) taken directly from the turbulence model, a velocity-fluctuation-related TKE \( k_V \) found from an unsteady simulation and derived according to Eq. (1) and a total TKE which is described in the next section (see Eq. (9)). It can be seen, that the model-related \( k_T \) does not predict a rise in TKE as measured, since this rise is triggered by unsteady velocity fluctuations.
fluctuations. $k_V$ predicts this rise, but too early. Although the curves do not agree perfectly with the measurement, it shows that the model-related $k_T$ is not able to predict the measured distribution of $k$.

The question arising from these considerations is, how to set CFD boundary conditions correctly to enable the transition model – which is triggered beside others by the free stream turbulence – to predict transition and relaminarization correctly? In this work, this question should be answered together with the question, if the rise described above can only be predicted by an unsteady simulation and if a steady-state simulation for the present case with a pulsating separation bubble is acceptable? To answer these questions, four different simulations are performed within this work:

a) A steady state simulation, taking the measured $k$ directly as boundary condition (Label: SFF (Steady - Full Frequency))

b) A steady state simulation, taking a reduced $k$ from the measurement, representing only the fluctuations above the inertial subrange as boundary condition (Label: SHF (Steady - High Frequency))

c) An unsteady simulation, taking the measured $k$ directly as boundary condition (Label: UFF (Unsteady - Full Frequency))

d) An unsteady simulation, taking a reduced $k$ from the measurement, representing only the fluctuations above the inertial subrange as boundary condition (Label: UHF (Unsteady - High Frequency))

As described above, the result of the measurement returns a total turbulent kinetic energy, containing all ranges described above. In order to calculate a comparable TKE from the un-
steady CFD result, the computed total fluctuations are found as

\[ u'_i = u'_{Ti} + u'_{Vi} \]  

accumulating the subranges shown in Fig. 2a. Combining this equation with the general definition of \( k \)

\[ k_i = \frac{u'_i \cdot u'_i}{2} \]  

leads to

\[ k = \frac{(u'_{Ti} + u'_{Vi})^2 + (v'_{Ti} + v'_{Vi})^2 + (w'_{Ti} + w'_{Vi})^2}{2} \]  

Dissolving this equation leads to

\[ k = \frac{(u'_{Ti})^2 + (v'_{Ti})^2 + (w'_{Ti})^2}{2} + \frac{(u'_{Vi})^2 + (v'_{Vi})^2 + (w'_{Vi})^2}{2} + \frac{2(u'_{Ti}u'_{Vi}) + 2(v'_{Ti}v'_{Vi}) + 2(w'_{Ti}w'_{Vi})}{2} \]  

and substituting

\[ k_T = \frac{(u'_{Ti})^2 + (v'_{Ti})^2 + (w'_{Ti})^2}{2} \]  
\[ k_V = \frac{(u'_{Vi})^2 + (v'_{Vi})^2 + (w'_{Vi})^2}{2} \]  

leads to

\[ k = k_{tot} = k_T + k_V + (u'_{Ti}u'_{Vi}) + (v'_{Ti}v'_{Vi}) + (w'_{Ti}w'_{Vi}) \]  

where \( k_T \) represents – as discussed above – the model-related TKE and \( k_V \) the velocity-fluctuation-related kinetic energy. Both can be acquired directly from the unsteady CFD results. When both fluctuation parts \((x'_{Ti} \text{ and } x'_{Vi})\) are not correlated, the latter part of Equation (8) is equal to zero. In the present case these mean values of the fluctuations are set to be zero \(((u'_{Ti}u'_{Vi}) = (v'_{Ti}v'_{Vi}) = (w'_{Ti}w'_{Vi}) = 0\), because of their very low correlation coefficient caused by the high differences in frequency. Consequently the total turbulent kinetic energy is defined as:

\[ k_{tot} = k_T + k_V \]  

RESULTS AND DISCUSSION

In this section the four above mentioned simulations are compared with the measurement to see and understand, how they perform regarding the prediction of relaminarization. In this section, all unsteady results are time averaged over a sufficiently long time interval.

First, the comparability with the measurement should be ensured. Therefore in Fig. 3 the local free stream velocity \( u_\infty \) and the Launder acceleration parameter \( K \) are shown only for one case, since these values agree perfectly for all four cases. \( K \) is defined as

\[ K = \frac{\nu}{u_\infty^2} \frac{du_\infty}{dx} \]
where $u_\infty$ is the local free stream velocity, $\nu$ the kinematic viscosity and $du_\infty/dx$ the streamwise velocity gradient. This acceleration parameter represents a critical value for relaminarization. According to literature, if $K$ exceeds a critical value according to $K > K_{\text{crit}} = 3.0 \cdot 10^{-6}$, relaminarization should most likely occur.

The free stream velocity $u_\infty$ (Fig. 3a) shows, that the simulation is able to capture the experimental results well and also the acceleration parameter $K$ in Fig. 3b gives a very good agreement.

Figure 3: Free stream parameters along the plate comparing the measurement with the simulation results.

To see the differences of the four mentioned simulations at the inlet in Fig. 4 the values of $k_V$, $k_T$ and $k = k_{\text{tot}}$ are given in a bar diagram. The differences between the measurement and the simulations are not surprising. SHF does not consider any unsteady fluctuation but a lower $k$ is set, thus the TKE is too low. On the other side UFF uses the unsteady fluctuations together with the full frequency $k$, thus this simulation has a higher TKE compared to the measurement. Obviously SFF and UHF show a very good agreement to the measurement values.

In order to see the difference between the simulations regarding turbulence along the plate, in Fig. 5a the total turbulent kinetic energy is plotted. For the steady simulations, the shown TKE represents only the $k_T$, because no unsteady fluctuations are computed. The differences between the unsteady and steady curves of the high and full frequency cases are therefore the
Figure 4: Bar diagram of the properties of $k_V$, $k_T$ and $k_{tot}$ measured/set at the inlet.

The turbulent kinetic energy $k_V$ caused by the velocity fluctuations.

It can be observed in Fig. 5a that the full frequency cases SFF and UFF show a very good agreement with the measurement at the beginning of the plate. The SFF solution starts to differ at approximately $x = 850$ mm, where the measurement values rise due to unsteady fluctuations which are not accounted for the steady simulation. On the other hand the UFF CFD result starts to differ at about $x = 550$ mm caused by a too early rise of $k$ compared to the measurement.

The high frequency cases SHF and UHF differ completely from the measurement. This is not surprising for the steady simulation but for the unsteady simulation. Compared to the observations above done with the values at the inlet, the UHF solution should have the best fit to the measurement but it significantly exceeds the measured values. It seems, that the missing turbulence in the CFD equations leads to a reduced damping of unsteady fluctuations, thus to a far too high computed $k_V$.

It can be concluded here, that the “right” value of $k$ in respect to the measurements lies in between the values of the full and high frequency cases for the unsteady simulation. Additionally it can be concluded that a stationary simulation does not address the distribution of the TKE accurately.

In order to compare the four different cases regarding their ability to predict relaminarization, the local skin friction coefficient $c_f$ is compared with the measurement. $c_f$ is defined as

$$c_f = \frac{\tau_W}{0.5 \cdot \rho \cdot u_\infty^2}$$

where $\tau_W$ represents the wall shear and $\rho$ the density of the fluid. In Fig. 5b the $c_f$-value of the simulations together with the measurement is illustrated. At a streamwise position of about $x = 800$ mm the measurement value of $c_f$ starts to decrease. This is a first indication of relaminarization as already shown by Bader et al. [2016]. With a slight streamwise delay, the simulations show the same trend. It can be observed that all simulations agree very well with the measurement up to a position of approximately $x = 1200$ mm. At this position the full frequency solutions SFF and UFF start a retransition to a turbulent boundary layer. The high frequency
Figure 5: Comparison of the total turbulent kinetic energy and the skin friction coefficient along the plate comparing measurement results with values predicted by the four simulations (■ - unsteady; —— - full frequency; – – – - high frequency).

cases SHF and UHF still show a laminar behavior which agrees with the measurement.

Comparing steady and unsteady simulations it can be clearly observed, that the unsteady fluctuations do not influence the prediction of transition and relaminarization. Thus it can be concluded, that only the free-stream turbulence intensity $k_T$ calculated by the turbulence model triggers changes in the state of the boundary layer. So a steady simulation is sufficient to calculate the boundary layer behavior even for the present case with a pulsating separation bubble. Therefore the validity of the model has to be verified, since low frequency unsteady fluctuations may have an effect on the transition and relaminarization process.

SUMMARY AND CONCLUSIONS

In this work, CFD simulations with the transition model $\gamma$-$Re_\theta$ are tested against measurement results. When applying measurement data one should keep in mind that the experimental data contains fluctuations of all frequencies, while in the numerical solution we can differ between a model-related turbulent kinetic energy $k$ and unsteady velocity fluctuations. This may be crucial when using measurement data as boundary conditions for the simulation or comparing experimental with numerical data.
To analyze the best way to apply the turbulent boundary conditions, four different simulations have been analyzed within this work using the full frequency spectrum of the measurement and the high frequency part of the spectrum of fluctuations, respectively. For both boundary conditions steady and unsteady simulations have been performed.

The four simulations revealed some interesting facts:

a) The unsteady simulation with the high frequency fluctuations and the steady state simulation with the full frequency fluctuations show the best agreement with the measurement at the inlet, but

b) the unsteady simulation with the high frequency part shows too high unsteady fluctuations along the plate. This may be caused by a reduced damping by the missing turbulence.

c) Using only the high frequency parts of the fluctuations together with a steady state simulation leads to a too low TKE along the plate, but

d) although the steady simulations do not account for observed unsteady fluctuations, the results of the unsteady and steady simulations show the same behavior regarding transition and relaminarization, thus

e) regarding transition and relaminarization a steady state simulation is may sufficient, although unsteady fluctuations are present and entirely neglected by this simulation.

From these points, we can conclude that low frequency fluctuations, which are only considered by the unsteady simulations, have no influence on the predicted relaminarization by the model. The question arising from this point is, if this behavior is physically correct, since low frequency effects may also influence the position and length of the transitional and relaminarization zone.

Additionally is was found, that the unsteady simulation which the high frequency fluctuations which should be closest to the measured behavior shows a wrong increase fo turbulence intensity.

Further work is necessary to understand the relation between unsteady and turbulent fluctuations and their influence on the simulation of boundary layer behavior. The present paper showed surprisingly, that ”right” turbulence intensity lies just somewhere in between the values resulting from the considerations made within the work.

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