Experimental Investigation of the Aerodynamic Effect of Local Surface Roughness on a Turbine Blade

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ABSTRACT

This paper shows the effect of local surface roughness on the aerodynamic loss behavior of a turbine blade. Non-contact measurements of the surface roughness of turbine blades of a jet engine are conducted. The roughness is quantitatively characterised using a shape and density parameter to parameterise the topology and the average roughness height. An experimental investigation in a linear cascade wind tunnel is conducted in order to identify the contributions of pressure- and friction-losses of the measured surfaces to the overall profile loss increase due to local surface roughness. The results show that the change of profile losses due to local surface roughness is significant. The change in losses is dependent on the roughness height, as well as of the position on the blade of the roughness and the condition of the boundary layer behind. The local pressure gradient at and downstream of the surface roughness is identified as the main influencing parameter besides the roughness height.

NOMENCLATURE

\begin{itemize}
\item $A_f$ the windward wetted surface
\item $A_S$ windward frontal surface
\item $A_{cell}$ area of a single roughness element
\item $A_{f,cell}$ total front surface of a single roughness element
\item $c$ chord length
\item $c_p$ pressure coefficient
\item $h$ surface height
\item $K$ acceleration parameter
\item $k$ surface roughness height
\item $k_s$ sand grain roughness
\item $k_s^+$ dimensionless sand grain roughness
\item $l$ length of windward wetted surface
\item $Ma$ Mach number
\item $n$ number of elements
\item $N$ number of roughness elements
\item $p$ static pressure
\item $p_t$ total pressure
\item $Ra$ average roughness
\item $Rq$ root-mean-square roughness
\item $Rz$ ten-point height
\item $Re$ chord based Reynolds number
\item $S$ area of surface roughness
\item $s$ length of boundary layer flow on the blade surface
\item $S_f$ total front of the roughness area
\item $Sc$ scaling factor
\item $t$ pitch
\item $u$ flow velocity
\end{itemize}

Greek Symbols

\begin{itemize}
\item $\beta_1$ angle of attack
\item $\beta_2$ outflow angle
\item $\zeta$ loss coefficient
\item $\rho$ density
\item $A_s$ shape and density parameter
\item $\lambda$ stagger angle
\item $\tau_w$ wall shear stress
\item $\nu$ kinematic viscosity
\end{itemize}

INTRODUCTION

Due to their high power density and efficiencies, gas turbines will remain the first choice as a propulsion system for aircraft for at least the next few decades. During operation, gas turbines deteriorate because of erosive and corrosive mechanisms. A distinguishing feature of high-pressure turbine blades after operation is an increased surface roughness in comparison to a new part, which is known to increase aerodynamic losses and therefore operational cost.

The effect of surface roughness on fluid flow was first investigated by Nikuradse [1] and Schlichting [2] finding that surface roughness, especially in turbulent boundary layers, leads to a significant increase in losses. One of the major outcomes of this investigation is the model of equivalent sand grain roughness $k_s$, which correlates the skin friction of any roughness type to a sand grain roughness height with the same skin friction.

Since the importance of surface roughness on fluid flow has been known since the experiments by Nikuradse and Schlichting, many studies in the past decades focused on the influence of surface roughness on turbomachinery flow. Speidel [3] and Gersten [4] experimentally investigated surface roughness on turbine cascades with the result that surface roughness influences the boundary layer transitions by moving the point of transition upstream. Furthermore, roughness in the turbulent boundary layer significantly increased the profile losses. Similar results with a maximum increase of profile losses by 11% were reported by Bammert and Fiedler [5], Bammert and Fiedler [6] and Bammert and Sandstede [7], who also...
investigated the effect of surface roughness in a turbine cascade. By applying sand grains onto the blades of an experimental rotating four stage turbine, Bamment and Sandstede [8] measured a decrease of efficiency by 10.5%. This is in good agreement with the results of Boynton et al. [9] who measured an efficiency increase of 2.5% by reducing the blade’s surface roughness of a two stage high pressure turbine by 93%.

In terms of similar results as the studies previously mentioned, the conducted studies can be mainly separated into two parts: The first part are the studies using sand grains on turbine blades in cascade or rotating test rigs [3–8, 10–14]. The second part are studies that investigated the effect of real surface roughness by deterioration or machining of the blades [9,15–21]. The general outcome is that surface roughness can increase losses by up to 40% and only in (rare) special cases has a beneficial influence by suppressing laminar separation bubbles [22–24].

It has been shown by Taylor [25] and Bons et al. [26] that the surface roughness of operated turbine blades is locally inhomogeneous. Aside from the investigations carried out by Yuan and Kind [12] and Zhang and Ligrani [13], none of the studies mentioned considered this aspect. According to Yuan and Kind, local inhomogeneous surface roughness of sand grain type on the suction side of a turbine blade leads to a maximum increase of losses by 36%. Zhang and Ligrani on the other hand, applied sand grains with increasing roughness height from leading to trailing edge onto the pressure side of a high pressure turbine blade. The measurements reveal that surface roughness on the pressure side does not significantly influence the profile losses.

From the investigations carried out so far, it can be seen that there is a link between real surface roughness topology and real surface roughness distribution along the blade’s surface. The current research project aims to identify the loss-causing mechanisms of complex surface roughness, which consists of isotropic and anisotropic roughness and is non-uniform in shape and height along a blade’s surface. The results should be transferable to real turbine blades. The methodology of the research project covers three steps: First a blade for experimental investigations in a linear cascade wind-tunnel has to be designed.

Second, measurements of real surface roughness are carried out. Finally, non-uniform roughness is investigated in a linear cascade wind-tunnel. The blade design was published by Hohenstein et al. [27], and this paper shows the results of surface roughness measurements of operated gas turbine blades, as well as the results of the measurements in the linear cascade wind tunnel. As will be shown in this paper, surface roughness is locally inhomogeneous, and the influence of the roughness on the profile losses is strongly dependent on the location of roughness on the blade’s surface.

**PERFORMED SURFACE ROUGHNESS INVESTIGATION**

In order to investigate the effect of real surface roughness on the profile losses of a turbine profile, the surface roughness of real turbine blades has to be determined. The surface measurements in this investigation were performed with an optical non-contact confocal microscope, in this case a μsurf confocal microscope built by NanoFocus. This system allows the three-dimensional measurement of a surface. It is also possible to perform post-processing on the surface data, filtering or stitching measurements to enlarge the measured region. The functions are used to measure the surface structures of turbine blades from the second stage of a high pressure turbine. The examined turbine blades have been in operation in a real medium-sized aircraft engine. The engine was in flight operation for more than 24000 hours and 9000 cycles [28].

**Surface Measurement Setup**

The measurements were conducted on four regions on the turbine blade suction side. Curtis [29] has shown that 60% of the overall losses can be detected on the suction side. Taylor [25] and others has also shown that the surface roughness of turbine blades after operation is not uniform along chord length. To take this in account, four regions on the suction side level with the mid span were chosen for the measurements. The positions are at the leading edge \( x_{c1}/c = 0, x_{c2}/c = 0.2, x_{c3}/c = 0.5 \) and \( x_{c4}/c = 0.85 \) of the chord length (see Fig. 1). The size of each measurement area is 3 mm by 3 mm and care has been taken to ensure that the direction of the Z dimension correlates to the flow direction in each area. The horizontal resolution is 3.125 \( \mu \text{m} \), and the vertical resolution is 0.2 \( \mu \text{m} \). Post-processing correction of the measured surface was performed before calculating the statistical values. Because of the curvature of the suction side, the surface roughness has to be separate from the suction side shape. Therefore, a second-order polynomial curve is fitted to the raw data, after which the surface is reconstructed using a straight line and the distance of each single value to the curve [25,26].

After separating the shape of the blade, statistical values are then calculated to parametrise the surface roughness. A series of statistical numbers can be calculated [30]. For the present work, the values of the mean roughness height \( R_a \), the root mean square roughness height \( R_q \) and the average peak-to-valley height \( R_z \) are used to parameterise the surface roughness. These values are defined by Thomas [30] for a discrete height profile:

\[
R_a = \frac{1}{n} \sum_{i=0}^{n} |h_i| (1)
\]

\[
R_q = \sqrt{\frac{1}{n} \sum_{i=0}^{n} h_i^2} (2)
\]

\[
R_z = h_{max} - h_{min} (3)
\]

\( R_a, R_q \) and \( R_z \) can only be calculated from two-dimensional data. Therefore the three-dimensional surface data were divided into lines with a wide of 3,125 \( \mu \text{m} \) and a length of 3 mm, and the values were calculated for each line. The mean value of the single calculations is then finally averaged.

To characterise a surface from an aerodynamic point of view, the shape and density parameter \( A_s \) is defined by Sigal [31]:

\[
A_s = \frac{S_f}{S_f^2} \left( A_f \right)^{-1.6} (4)
\]

where \( S \) is the surface roughness area, \( S_f \) is the total front of the roughness area, \( A_f \) is the windward wetted surface of the roughness element and \( A_s \) is the windward frontal surface of the roughness element. The parameter correlates the equivalent sand grain roughness height \( k_s \) to a three-dimensional surface roughness. However, because of the non-uniform and random nature of roughness elements on real surfaces, it is not possible to apply Eq. 4 in this simple form [32]. The field of interest has to be divided in multiple roughness elements (cells) and the calculation of \( A_s \) has to be done for each roughness element (N). Due to these assumptions, Eq. 4 is reformulated as:

\[
A_s = \frac{\sum A_{f,cell} \left( \frac{\sum A_{f,cell}}{\sum A_{f,cell}} \right)^{-1.6}}{\sum A_{f,cell}} (5)
\]

In this case \( S \) will change to \( A_{f,cell} \), as the total front surface of the single roughness element and the frontal surface of the whole roughness in the cell remains the same. By the same orientation of the flow and the Z-direction it is possible to simplify Eq. 5 into a two-dimensional case. The ratio of \( A_{c,cell}/A_{f,cell} \) can be described by the ratio of the horizontal distance \( dx \) and the height difference \( d\Delta h \) and the ratio \( A_{f,cell}/A_{c,cell} \) can be replaced by \( d\Delta h/l_i \) (see Fig. 2) [32]. Eq. 5 will thus change to:

\[
A_s = \frac{\sum dx \left( \frac{\sum d\Delta h}{\sum l_i} \right)^{-1.6}}{\sum d\Delta h} (6)
\]
In order to calculate $k_s$, the correlation

$$
\frac{k_s}{k} = 0.43 \cdot \log(\Lambda_S) + 0.82
$$

(7)

of Bons [32] with a roughness height $k$ is used. In this study the roughness height $k$ is equal to the mean roughness height $Ra$.

Results of Surface Roughness Study

The determined mean values of $Ra$, $Rq$, $Rz$, $\Lambda_S$ and $k_s$ are summarised in Table 1. The results show how the roughness differs along the chord length. At the leading edge, higher values for the roughness are detected. In the middle part of the chord length, the roughness values become smaller at first and then rise slightly to the trailing edge. These results are in good agreement with results of Taylor [25].

Furthermore, the whole qualitative structure of the topological surface changes along the chord. At the leading edge, a mix of holes, deposits and an overall isotropic structure is detected (shown in Fig. 1). At 20% chord length the surface changes to a more homogeneous isotropic structure. At $x_c/c = 0.5$ and $x_c/c = 0.85$ of the chord length the roughness changes to an anisotropic elongated surface structure.

<table>
<thead>
<tr>
<th>Position $x_c/c$</th>
<th>$Ra$ in $\mu m$</th>
<th>$Rq$ in $\mu m$</th>
<th>$Rz$ in $\mu m$</th>
<th>$k_s$ in $\mu m$</th>
<th>$\Lambda_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.0</td>
<td>5.4</td>
<td>28.4</td>
<td>3.7</td>
<td>153.8</td>
</tr>
<tr>
<td>0.2</td>
<td>2.2</td>
<td>2.8</td>
<td>16.1</td>
<td>1.8</td>
<td>237.2</td>
</tr>
<tr>
<td>0.5</td>
<td>1.9</td>
<td>2.5</td>
<td>16.0</td>
<td>1.9</td>
<td>158.1</td>
</tr>
<tr>
<td>0.85</td>
<td>2.3</td>
<td>3.0</td>
<td>18.4</td>
<td>2.1</td>
<td>180.3</td>
</tr>
</tbody>
</table>

Table 1: Mean values of surface roughness measurements

Fig. 1: Examples for typical surface structures on the four measured positions along the chord of the turbine blades

EXPERIMENTAL AERODYNAMIC SETUP TO INVESTIGATE THE EFFECT OF THE MEASURED SURFACE ROUGHNESS

To investigate the effect of the real measured surface roughness on the performance of the turbine profile experiments in the cascade wind tunnel of the Institute of Turbomachinery and Fluid Dynamics were performed. This wind tunnel was previously validated in several experimental investigations of profile losses [33, 34].

The linear wind tunnel (see Fig. 3) is supplied by air from a screw-type compressor. In order to obtain homogenised flow conditions in the test section, the compressed air has to pass through an air cooler, a flow straightener, a settling chamber and a flow conditioner. In the wind tunnel itself the flow traverses a turbulent grid to induce a turbulent intensity of approximately 4%. After passing the turbulent grid, the flow channel changes from a circular to a rectangular shape. In order to reduce endwall boundary layers and secondary flows, a boundary layer suction system is installed around and upstream of the cascade. The cascade itself is installed on a swiveling head to allow the angle of attack to be adjusted. It is also possible to adjust the distance between the side walls to specify a defined cross section size.

The cascade consists of seven blade rows which are split at midspan. The main cascade parameters are given in Table 2. The central blade row contains a test blade with added roughness and a smooth reference blade.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blade rows</td>
<td>$f$</td>
</tr>
<tr>
<td>Inlet Mach-number $Ma_1$</td>
<td>0.1</td>
</tr>
<tr>
<td>Inlet Reynolds-number $Re_1$</td>
<td>125000</td>
</tr>
<tr>
<td>Angle of attack $\beta_1$</td>
<td>$20.62^\circ$</td>
</tr>
<tr>
<td>Outflow angle $\beta_2$</td>
<td>$58.32^\circ$</td>
</tr>
<tr>
<td>Stagger angle $\lambda$</td>
<td>$27.76^\circ$</td>
</tr>
<tr>
<td>Pitch $t$/chord length $c$</td>
<td>0.818</td>
</tr>
</tbody>
</table>

Table 2: Data summary of the blade cascade geometry and aerodynamics [35]
the total inlet pressure $p_{t1}$, the total $p_{t2}$ and static pressure $p_2$ of the exit flow is calculated [27]:

$$\zeta = \frac{p_{t1} - p_{t2}}{p_{t1} - p_2} \quad (8)$$

To estimate an one-dimensional value from the exit flow condition data, an averaging procedure by Amecke [36] is used. To determine the surface roughness effect on the blades aerodynamics, a coefficient is calculated using the difference of the loss coefficients of the test blade $\zeta$ and the reference blade $\zeta_{ref}$ devided by the loss coefficient of the reference blade $\zeta_{ref}$:

$$\frac{\Delta \zeta}{\zeta_{ref}} = \frac{\zeta - \zeta_{ref}}{\zeta_{ref}} \quad (9)$$

Paint tests were performed to visualise and study the boundary layer conditions near the blade surface. For these a mix of 50% turpentine substitute and 50% linseed oil was used. For better visualization, a fluorescent ultra violet (UV) pigment is added to improve the contrast under UV light. The mix is applied to the blade with a paint roller, and the blade is then positioned in the cascade. The cascade runs until the blade has dried, then it is removed and an image of the suction side is taken. For post image evaluation, the blades are always positioned identically, aligned to a grid pattern. The images are taken from an orthogonal position above the blade. This setting allows direct distance measurements on the suction side, based on the blade chord length.

To measure the boundary layer thickness a laser-2-focus system is used. The system contains an ion laser with an optical system to measure the velocity of particles in the flow of the cascade wind tunnel. A seeding reactor produces the particles by generating an oil mist with a particle size of 0.1 $\mu$m to 1 $\mu$m. The oil mist is injected into the flow upstream and in front of the circular to rectangular tube of the cascade wind tunnel. Quartz windows provide a view of the suction side of the test blade. The distance of the two laser foci in the measurement volume is 280 $\mu$m. With this system it is possible to measure flow velocities as near as 100 $\mu$m to the surface of the blade. The position of the measuring plane on the blade is at the same spanwise position from the blade tip as the wake measurements with the pressure probes.

**Roughness Scaling Factor to meet the aerodynamic similarity between the real turbine blade roughness and the cascade blade roughness**

In this investigation the profiles of the cascade wind tunnel are designed to meet the properties of a real high pressure turbine profile from a mid-size aircraft engine. To link the conclusions from the cascade wind tunnel experiments to the real turbine blade, the compliance of the aerodynamic similarity for the surface roughness has to be considered.

Therefore, the surface roughnesses has to be scaled prior to its application on the cascade blades. The scaling factor $S_T$ is estimated based on the sand grain roughness of the real turbine blade roughness $k_s,real$ and the roughness of the scaled surface $k_s,cascade$:

$$S_T = \frac{k_{s,real}}{k_{s,cascade}} \quad (10)$$

At first, the results of $k_{s,cascade}$ are unknown. To correlate $k_{s,real}$ with $k_{s,cascade}$, the dimensionless sand grain roughness $k_s^*$ is estimated by using the local shear velocity $u_z = \sqrt{\tau_w/\rho}$ and the kinematic viscosity $\nu$:

$$k_s^* = k_{s,real} \frac{u_z}{\nu} \quad (11)$$

In order to estimate the aerodynamic properties for the scaling parameter $S_T$, a numerical study was performed. The used Reynolds-Average-Navier-Stokes (RANS) flow solver [27],

**Cascade Wind Tunnel Instrumentation**

A Prandtl probe and a temperature sensor are installed at 0.35 m distance upstream of the cascade to measure the inlet flow conditions. A double pneumatic, three hole wedge-type probe are used to measure the cascade exit flow conditions. The design of the probes allows the measurement of the static and the dynamic pressure of the exit flow. The probes position are 0.3 m downstream of the central blade row, and each probe traverses the wake with a sampling rate of 60 positions along the trailing edges of the cascade blades. One probe measures the test blade, and the other the reference blade (Fig. 4).

From the wake measurement values, a loss coefficient $\zeta$ using the total inlet pressure $p_{t1}$, the total $p_{t2}$ and static pressure $p_2$ of the exit flow is calculated [27]:

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In order to estimate the aerodynamic properties for the scaling parameter $S_T$, a numerical study was performed. The used Reynolds-Average-Navier-Stokes (RANS) flow solver [27],

![Fig. 3: Cascade wind tunnel](image1)

1. Circular to rectangular tube
2. Turbulence grid
3. Variable side walls
4. Inlet measuring plane
5. Swivelling head
6. Blade cascade
7. Outlet measuring plane

![Fig. 4: Double pneumatic three hole wedge-probe behind the test blade and the reference blade](image2)
TRACe, is developed by the Institute of Propulsion and Technology Research Aerodynamics of the German Aerospace Centre in cooperation with MTU Aero Engines. The solver is developed to investigate turbomachinery flows by solving the three-dimensional RANS equations by a finite volume approach.

In this study, only two-dimensional profiles are investigated and have to be transformed into a Quasi-Three-Dimensional (Q3D) setup with inviscid walls at the top and at the bottom. The Q3D-setup is computed in TRACe as a stator without a rotational shape and the analysis is performed at midspan. The flow computation is performed as steady state simulation with an implicit predictor corrector scheme for time integration and the Wilcox turbulence model [37]. The turbulent production term is fixed by using the method as recommended by Kozulovice et al. [38]. The boundary layer flow is computed by using the Low Reynolds method and the first distance to the wall of the profile and the dynamic viscosity $\rho \nu$ is kept smaller than $\nu$ computed by using the Low Reynolds method and the first distance recommended by Kozulovice et al. [38]. The boundary layer flow is computed by using the method as recommended by Kozulovice et al. [38]. The boundary layer flow is computed by using the method as recommended by Kozulovice et al. [38]. The boundary layer flow is computed by using the method as recommended by Kozulovice et al. [38].

Roughness Application on the Test blades

To study the influence of real surface roughness on different position and the overall loss behavior of the test blades, a procedure to apply single surfaces to a smooth test blade is developed. For the application of the roughness the following points are important:

1. Different flow conditions of the real turbines (hot gas) and the experimental setup (air) must to be considered.
2. Blade surface shape has to be obtained.
3. Additional anomalies on the flow caused by secondary effects like abnormal edges need to be minimised.

For the present study, a single real measured surface is selected for each position on the suction side. The surfaces are shown in Fig. 1. The selection criteria were set according to the value of $Ra$ measured overall, and the typical qualitative characteristics for each position as described before. The data for the chosen surfaces are shown in table 4. After the scaling process, the surface is too big to apply them to the specified locations on the blade surface. To fit the surfaces into the prepared slots on the test blade, a 4 mm wide section of the scaled surface is extracted.

To take into account the fact that the blade surface has a curved shape, the extracted part of the surface has to be bent. As aforementioned, the design of the blade suction side is formed by three arcs of constant radius. To avoid discontinuity between the arcs, the geometric boundary conditions were loosened. As a result, it is possible to interpolate every limited part of the suction side with an quadratic polynomial curve.

The test blade is given as a 2D contour discretised by points. To get the shape of the blade contour in the region of interest, the coordinates of the relevant points were taken for a curve fit. A quadratic polynomial is used to interpolate the area of surface application. The resulting curve is used to fit the shape of the blade to the scaled surface data by summing up the values of the surface height and the height of the interpolated blade shape. In Fig. 5, a comparison of a bend and an unbent surface roughness is shown. The bend surface represents superposition of the curvature of the blade and surface roughness. This method ensures that no secondary effects from changing the blade geometry will have an effect on the measurements.

To avoid abnormal edges in the transition form, the surface roughness to the smooth surface of the blade, edges of the cut and bend surface are brought to the same level. To do this, a linear interpolation from the same point from the inner area of the surface normal to the ending edge is performed. The first linear interpolation covers between the inner point and the edge at the zero level of the surface normal to the surface edge. The second linear interpolation covers between the inner point and the end of the surface roughness normal to the surface edge. The distance between each single point of the two linear polynomials is added to the surface measurement. As can be seen from Fig. 6, the result is a continuous equalization of the surface edge and the blade surface and thus an abnormal edge is prevented.

The slots in the test blade are longer than the prepared surface. To fill the slots, the surface is duplicated and the obtained surface segments are arranged back-to-front until the slot is filled. After preparing, the surface data are transformed into a Surface Tesselation Language (STL) model and a laser erosion process is performed as steady state simulation with an implicit predictor corrector scheme for time integration and the Wilcox turbulence model [37]. The turbulent production term is fixed by using the method as recommended by Kozulovice et al. [38]. The boundary layer flow is computed by using the method as recommended by Kozulovice et al. [38]. The boundary layer flow is computed by using the method as recommended by Kozulovice et al. [38]. The boundary layer flow is computed by using the method as recommended by Kozulovice et al. [38].

![Fig.5: Above: Example of a surface without blade shape curvature, below: Superposition of surface roughness and the blade shape curvature](image-url)

Table 3: Summary of scaling factors of the prepared and applied surfaces of the present study

<table>
<thead>
<tr>
<th>Name</th>
<th>chordwise position of roughness $x_c/c$</th>
<th>$Sc$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1b1</td>
<td>0</td>
<td>3.775</td>
</tr>
<tr>
<td>M2b1</td>
<td>0.2</td>
<td>4.239</td>
</tr>
<tr>
<td>M3b1</td>
<td>0.5</td>
<td>5.473</td>
</tr>
<tr>
<td>M4b1</td>
<td>0.85</td>
<td>9.143</td>
</tr>
<tr>
<td>M2b2</td>
<td>0.2</td>
<td>8.987</td>
</tr>
<tr>
<td>M3b2</td>
<td>0.5</td>
<td>20.066</td>
</tr>
<tr>
<td>M4b2</td>
<td>0.85</td>
<td>14.995</td>
</tr>
</tbody>
</table>

Table 4: Parameters of the applied surfaces of the present study

<table>
<thead>
<tr>
<th>Position of roughness $x_c/c$</th>
<th>0</th>
<th>0.2</th>
<th>0.5</th>
<th>0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Ra$ in $\mu m$</td>
<td>7.7</td>
<td>2.6</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>$Rq$ in $\mu m$</td>
<td>10.8</td>
<td>3.2</td>
<td>3.5</td>
<td>3.1</td>
</tr>
<tr>
<td>$Kc$ in $\mu m$</td>
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<td>17.3</td>
<td>21.7</td>
<td>20.7</td>
</tr>
<tr>
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<td>2.2</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>$\Lambda_s$</td>
<td>257.0</td>
<td>118.7</td>
<td>419.2</td>
<td>453.3</td>
</tr>
</tbody>
</table>
Fig. 7: Paint test on the suction side of the smooth test blade: The transition is caused by a separation bubble at $0.55 \leq c_x/c \leq 0.75$. From the paint tests, it is also obvious that boundary layer located 31 mm towards the side walls from the midspan of the cascade conditions are present at the measurement plane of the pressure probes tailboards.

Fig. 8. Periodic flow conditions at the outflow were achieved using numerical profile pressure distributions of $c_p$ which are shown in Fig. 7. The investigation of the effects of surface roughness was conducted for an inflow Mach number $Ma_1 = 0.1$, and an outflow Reynolds number of $Re_2 = 242,300$. The desired inlet flow angle was adjusted and validated by comparing the experimental and numerical profile pressure distributions of $c_p$, which are shown in Fig. 8. Periodic flow conditions at the outflow were achieved using tailboards.

Paint tests were used to validate that two-dimensional flow conditions are present at the measurement plane of the pressure probes located 31 mm towards the side walls from the midspan of the cascade. From the paint tests, it is also obvious that boundary layer transition is caused by a separation bubble at $0.55 \leq x_c/c \leq 0.75$, see Fig. 7.

Fig. 6: The effect of edge manipulation, above: A comparison of the 3D simulation of the surface roughness with and without manipulated edge region, below: 2D surface with linear interpolation and the edge region performed to form the surface in a probe plate. The blank probe plate is an aluminium plate with the form and length of the slots in the test blades.

RESULTS OF AERODYNAMIC INVESTIGATION

The investigation of the effects of surface roughness was conducted for an inflow Mach number $Ma_1$ of 0.1, and an outflow Reynolds number of $Re_2$ of 242,300. The desired inlet flow angle was adjusted and validated by comparing the experimental and numerical profile pressure distributions of $c_p$, which are shown in Fig. 8. Periodic flow conditions at the outflow were achieved using tailboards.

Paint tests were used to validate that two-dimensional flow conditions are present at the measurement plane of the pressure probes located 31 mm towards the side walls from the midspan of the cascade. From the paint tests, it is also obvious that boundary layer transition is caused by a separation bubble at $0.55 \leq x_c/c \leq 0.75$, see Fig. 7.

The influence of surface roughness on the integral aerodynamic profile losses

To avoid geometrical tolerances in the blades affecting the measurements of the profile loss, each of the blades was measured before roughness was applied. The blades profile losses were measured relative to a reference blade, to take into account deviations of ambient and flow conditions on different days. The change of pressure loss is therefore evaluated by means of:

$$\frac{\Delta \zeta}{\zeta_{ref}} = \left(\frac{\Delta \zeta}{\zeta_{ref}}\right)_{rough} - \left(\frac{\Delta \zeta}{\zeta_{ref}}\right)_{smooth} \quad (13)$$

The Influence of surface roughness on the aerodynamic loss behavior is shown in Fig. 10. The following is observed:

1. Roughness at the leading edge $M1b1$ has only a minor effect, leading to a small increase profile loss $\Delta \zeta/\zeta_{ref}$ by $1.46\% \pm 0.026\%$.

2. Roughness at a chord length $x_c/c$ of 0.2 leads to a distinct result. On one hand, for a small roughness height $k^+_s = 0.80$, the pressure losses $\Delta \zeta/\zeta_{ref}$ are reduced by $-0.98\% \pm 0.06\%$ (configuration $M2b1$). On the other hand, an increase in losses $\Delta \zeta/\zeta_{ref}$ by $1.79\% \pm 0.03\%$ is observed for a roughness height $k^+_s = 2.63$.

3. A significant increase of profile losses is observed when roughness is applied at $x_c/c = 0.5$. The investigated configurations lead to an increase of $\Delta \zeta/\zeta_{ref}$ by $10.54\% \pm 0.12\%$ (configuration $M3b1$) and by $12.47\% \pm 0.04\%$ (configuration $M3b2$).

4. The effect of local surface roughness in the turbulent boundary layer at $x_c/c = 0.85$ is less than at $x_c/c = 0.2$ but still significant. An increase of losses caused $\Delta \zeta/\zeta_{ref}$ by $5.19\% \pm 0.05\%$ (configuration $M4b1$) and $7.18\% \pm 0.03\%$ (configuration $M4b2$) is observed.

Influence of surface roughness on boundary layer transition

The addition of surface roughness alters the boundary layer transition, causing a change in the integral aerodynamic loss behaviour. This can be clearly seen from the paint tests given in Fig. 9. Visible is the suction side of the cascade blade with the smooth reference blade on top of Fig 9, and blades with local surface roughness from leading to trailing below.

For all cases, except the one where roughness is applied at
$x_c/c = 0.5$ chord length (configuration M3b2), the separation of the flow at $x_c/c = 0.55$ is clearly visible. Neither a change in the location of flow reattachment nor changes in the flow structure can be observed when roughness is applied at the leading edge (configuration M1b1), compared to the smooth reference case.

The same cannot be said however, when roughness is applied at $x_c/c = 0.2$. The point of flow separation remains the same, but reattachment occurs further upstream. This is caused by disturbances induced in the boundary layer by the surface roughness. Downstream of the roughness, streaks are visible. These are approximately constant in spanwise direction until $x_c/c \approx 0.34$ and start to widen afterwards. This is caused by the damping of the disturbances in the front part of the blade with an accelerated flow until $x_c/c \approx 0.34$ and an amplifying of the disturbance by the decelerated flow at $x_c/c > 0.34$. Through the triggered boundary layer transition, the flow reattaches further upstream and increases the length of the turbulent boundary layer. In the case of the small roughness height at $x_c/c = 0.2$ (configuration M2b1), the reduction of the length of the flow separation prevails against the negative effect of an increased turbulent boundary length, leading to a reduction of profile losses. In the case of an increased roughness height (configuration M2b2), the negative effect of an increased turbulent boundary length prevails against the reduction of the length of the flow separation and therefore the overall profile losses increase (Fig. 10).

When roughness is applied at $x_c/c = 0.5$ (configuration M3b2), this changes even more. Flow separation is suppressed, and the transition mode changes from separation-induced transition to bypass transition. The length of the turbulent boundary layer is increased by approximately 40%, which causes a significant increase of profile losses of more than 10% (Fig. 10).

For roughness applied at $x_c/c = 0.85$ (configuration M4b1), the paint test upstream of the roughness does not reveal any differences in the flow compared to the smooth reference case. Neither disturbance in the boundary layer nor a change of the location and extension of the separation bubble are visible. Therefore, the measured increase of profile losses occurs due to a roughness caused by increased in turbulent dissipation (Fig. 10).

The laser-2-focus measurements of the boundary layer velocity given in Fig. 11, confirms this. The edge of the boundary layer is set to the height normal to the surface where the velocity reaches 99% of the local free stream velocity. The separation bubble is clearly

![Fig.9: Paint tests on the suction side of the test blade with different roughness configurations](image)

![Fig.10: Above: Change of profile losses $\Delta \zeta / \zeta_{ref}$ dependent on the roughness height and position, below: Change of profile losses $\Delta \zeta / \zeta_{ref}$ dependent on the acceleration parameter $K = (\nu / u_i^2) (du_0/ds)$ [35]](image)
visible in the front part of the figure at $0.55 \leq x_c/c \leq 0.75$. In the rear part of the blade, a strong increase of the boundary layer’s thickness by about 40% compared to the smooth reference case indicates a significant increase of wall normal exchange of momentum. The mixing of high and low momentum flow leads to the observed increase in profile losses by $\Delta \zeta / \zeta_{ref} \approx 5.19\% \pm 0.05\%$ (configuration $M4b1$) and $\Delta \zeta / \zeta_{ref} \approx 7.18\% \pm 0.03\%$ (configuration $M4b2$) although boundary layer transition is not altered.

**Coupled influence of pressure gradient and local surface roughness**

As previously shown, roughness-induced disturbances within the boundary layer alter the location and mode of transition from laminar to turbulent boundary layer flow. The local profile pressure gradient has a comparable strong effect on the change of profile losses as the height of the roughness. Given in Fig. 10 is the change of profile losses dependent on the acceleration parameter $K$ and non-dimensional roughness height $k^+$. Only cases where local surface roughness is applied in the laminar boundary layer are considered.

A split of the increases of profile losses at $K \approx 2 \times 10^{-4}$ is visible: a moderate increase of profile losses for an accelerated flow ($K \geq 2 \times 10^{-4}$) is measured. On the other hand, a strong increase at the blade’s part with an decelerated flow ($K < 2 \times 10^{-4}$) is observed. This clearly indicates that the dampening effect of an accelerated flow on roughness-induced disturbances is as important as the roughness height itself.

**CONCLUSIONS**

In this study characteristics of suction side surface roughnesses from real and operated high pressure turbine blades from an aircraft engine are determined and quantified. The results show that the local surface characteristics, such as shape and height, differ along the suction side from the leading edge to the trailing edge. Additionally, this work introduces a new method which allows the application of the measured real surface structures to test blades in a cascade wind tunnel. Thereby, it is shown that the applied local surface structures have distinct effects on the loss behaviour of the test blade.

The results further show that these effects are not necessarily correlated to the roughness height:

- High roughness structures at the leading edge have a minor influence on the loss behaviour
- Smaller structures along the chord have a larger effect on the loss behaviour
- Roughnesses in the area of transition and in the turbulent boundary layer cause major changes in the losses
- Mostly the measured losses were increased by the applied roughnesses. However, in this study and for the present pressure distribution, a local roughness which was applied in front of a separation decreases the size of the separation and thereby lowers the measured aerodynamic loss in one case

More generally, this study confirms that there is a complex system of effects from the local surface roughnesses on the local flow, depending on the local flow conditions at a real turbine blade. Because of the distinct boundary layer flow conditions combined with transitional effects on a turbine blade, the prediction of the correct loss behaviour is complex and has to be the objective of further investigations.

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**Fig.11**: Velocity profiles on the suction side in the area of transition of the smooth test blade and roughness $M4b1$ [35]
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