ABSTRACT
To reduce the specific fuel consumption of future turbofan engines via increased propulsion efficiency, the bypass ratio is increased by lowering the fan hub-to-tip ratio. Based on a comparison of fan configurations for an ultra-high bypass ratio (UHBR) engine the effects of an increasing bypass ratio on the downstream near hub flow are presented. In order to evaluate the increasing amount of near hub flow associated with a reduced fan hub-to-tip ratio, the splitter is lowered at radial height. Numerical simulations of three different UHBR configurations of the fan were conducted and compared with fan configurations of the V2500 fan rotor. The results of the numerical flow simulations show, that the near hub flow is dominated by secondary flow effects. By increasing the bypass ratio, the fan wake is affected negligibly for both fan configurations. The interaction of the secondary flow and the core stator of the UHBR fan, combined with a reducing annulus cross section, is found to have a detrimental effect on the downstream stator. The findings of this paper provide a better understanding of the near hub flow sensitivities towards increasing bypass ratios of future turbofan engines.

INTRODUCTION
Recent design trends are proposing to increase the engine bypass ratio by reducing the hub-to-tip ratio. Near hub fan flow dictates the core compressor inflow and thereby the core efficiency. The goal is to minimize the loss of the near hub fan section, keeping the pressure ratio high. Lowering the hub radius leads directly to decreasing hub circumferential speeds. While trying to maintain high work, the required flow turning of the rotor at the hub increases. In practise a compromise between high pressure ratio and reasonable flow turning is mostly chosen, leading to a non-uniform flow distribution. The downstream low-pressure compressor or booster is thereby subjected to a flow dominated by stronger fan wakes and secondary flow phenomena, resulting in higher stagnation pressure losses.

Zamboni and Xu (2012) showed via a simple cycle analysis that these near hub stagnation pressure losses become more significant with increasing bypass ratio. The uniformity of radial distribution of the near hub flow plays a decisive role as the flow interacts with the downstream splitter and the core inlet guide vane (IGV). General theories of secondary flow effects can be found in literature (Horlock and Lakshminarayana, 1973). Furthermore, the core flow performance is strongly impacted by the interaction between fan wake and splitter. Goyal and Dawes (1993) present the effect of a splitter on the comparison between measured and predicted flow. They state that near hub flow of the fan wake gets affected by the presence of a splitter. The fan total pressure ratio differs around 2.6% in the near hub region at design point (DP) and a bypass ratio of 4.6. Investigations on simulations of fan-bypass configurations made clear, that the splitter flow incidence caused by variation in bypass ratio can affect the downstream flow significantly. Depending on the incidence flow, the boundary layer is increased and the core flow is subjected to a highly non-uniform flow (Dawes, 1991).

In this paper the effect of increasing bypass ratio on the near hub flow is investigated by increasing the hub-to-tip ratio of the core flow section. In particular, the interaction between the near hub flow and the splitter and the influence of the partial increasing near hub flow in the core section will be analysed. To determine the major causes for the effects, the UHBR configuration is compared with the V2500 fan configuration.

FAN CONFIGURATIONS
For research of the fundamentals on an environmental friendly future regional aircraft, an UHBR engine was designed within the framework of the Coordinated Research Centre 880 (Giesecke, 2018). The UHBR engine was designed at top of climb conditions with a bypass ratio of 17. The design process and off-design behaviour of the fan stage can be found in (Giesecke, 2017). In total, the UHBR fan
configuration consists of 19 fan blades, 55 outlet guide vanes (OGV) and 103 inlet guide vanes (IGV). A zoomed in meridional view of the configuration is shown in Figure 1.

![Figure 1 Meridional view UHBR fan](image1)

The main flow is divided by a splitter, which is positioned in typical distance of about $\Delta x_S/l=0.1$ behind the fan trailing edge (Grieb, 2009). With a hub-to-tip ratio of $\nu=0.35$ at fan leading edge and a fan total pressure ratio of $\pi_t=1.46$, the fan rotor achieves a polytropic efficiency of $\eta_p=88.65\%$ at top of climb condition (TOC). The latter values are determined from the evaluation planes at fan leading (LE) and trailing edge (TE). Depicted as dashed lines in Figure 1, the evaluation plane is defined at 6% of the fan chord length ($\Delta x_{chord}$) upstream and downstream of the corresponding fan edge.

![Figure 2 Meridional view V2500 fan](image2)

The V2500-A1 turbofan engine is part of the International Aero Engines V2500 aircraft engine family. Owning a research engine of this type, the Institute of Jet Propulsion and Turbomachinery also has a fan model of the V2500-A1 engine (Spuhler et al., 2019). The fan model consists of 22 fan rotor blades and a downstream splitter at 0.17 relative axial distance ($\Delta x_S/l$) behind the fan trailing edge as shown in Figure 2. For better visual comparison the scale of Figure 1 and Figure 2 is the same. The downstream OGV and IGV are not included yet. The characterising parameters of the fan rotor are given in Table 1. The values correspond to the design point of the V2500 fan rotor at cruise condition.

<table>
<thead>
<tr>
<th>Table 1 Fan parameters</th>
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<tbody>
<tr>
<td><strong>Type</strong></td>
</tr>
<tr>
<td>UHBR fan</td>
</tr>
<tr>
<td>V2500 fan</td>
</tr>
<tr>
<td>DP</td>
</tr>
<tr>
<td>TOC</td>
</tr>
<tr>
<td>Cruise</td>
</tr>
<tr>
<td>$\nu_{fan}[-]$</td>
</tr>
<tr>
<td>0.35</td>
</tr>
<tr>
<td>0.30</td>
</tr>
<tr>
<td>$\eta_{p, fan}[-]  %$</td>
</tr>
<tr>
<td>88.65</td>
</tr>
<tr>
<td>92.03</td>
</tr>
<tr>
<td>$\pi_t [-]$</td>
</tr>
<tr>
<td>1.46</td>
</tr>
<tr>
<td>1.62</td>
</tr>
</tbody>
</table>

The fan total pressure ratio over the relative channel height shows a similar distribution for both fan rotors as depicted in Figure 3. Overall, the V2500 fan provides a higher total pressure ratio indicating a more aerodynamically loaded fan blade.

![Figure 3 Fan total pressure ratio](image3)

**METHODOLOGY**

The complicated and time consuming method of designing a fan for a corresponding hub-to-tip ratio and bypass ratio limits the possibility of obtaining a preliminary assessment of the near hub flow. However, there is the aim for an improved coupled fan-booster design for UHBR engines. Using a simplified approach for generating different bypass ratios in a fan configuration, the effect on the near hub flow will be investigated. The splitter is lowered at radial height keeping the hub-to-tip ratio of the fan rotor section constant.

![Figure 4 Radial offset splitter](image4)
This will reduce the area of the core section according to the continuity equation. The radial offset $\Delta r$ is calculated using Equation (3) and (4).

$$\Delta r = r_{\text{Splitter, BPR}} \sqrt{\frac{\rho_{\text{BPR}} \cdot v_{\text{BPR}}}{p_{\text{BPR}}}} + r_{\text{Hub}}$$  \hspace{1cm} (3)

$$r_{\text{Splitter, BPR}} = \frac{m_{\text{BPR}}}{\sqrt{p_{\text{BPR}} \cdot v_{\text{BPR}}}} + r_{\text{Hub}}$$  \hspace{1cm} (4)

The variable $r_{\text{Splitter, BPR}}$ defines the radius for the splitter at the desired bypass ratio. Being a compressible system, the density $\rho_{\text{BPR}}$ and the velocity $v_{\text{BPR}}$ are not constant with an increasing bypass ratio. The corresponding values are obtained due to an iterative process. In total, three different UHBR configurations of the fan are studied in this paper with a bypass ratio of 17 (reference), 20 and 25. The meridional view for the three bypass ratios is shown in Figure 4. The V2500 fan rotor is also investigated at three different bypass ratios generated using the same method. The corresponding bypass ratios are chosen to show the same percentage variation as the UHBR configuration and are 5.4 (reference), 6.5 and 8.0.

**NUMERICAL SETUP**

The computational mesh was generated with the commercial mesh generator AutoGrid 5 by NUMECA. The grid is divided in different blocks. With an O-mesh around the blade surfaces merged with four surrounding H-meshes, the blade-to-blade mesh was formed. For the region close to the splitter a C-mesh was used. At all walls the average $y^+$ is about 1. The required mesh density was determined using the grid convergence index (GCI) to ensure mesh independent results (Celik et al., 2008). With a GCI of about 0.04% the results can be stated mesh independent. The mesh size for the UHBR fan rotor is about $8.8 \times 10^6$ cells with 181 cells in radial direction in a one pitch periodic domain as shown in Figure 5. The V2500 fan rotor is meshed with about $5.1 \times 10^6$ cells. The quality and density of the V2500 mesh used was investigated in (Koch, 2015).

All simulations of the present paper were done using the 3D RANS solver TRACE Version 9.1.519 by the German Aerospace Center (DLR). TRACE has been developed and validated for turbomachinery flows using several turbulence models (Becker et al., 2010; Nürnberg, 2004; Schönweitz et al., 2016). In this case, the Wilcox k-ω turbulence model is used (Wilcox, 1988). All CFD calculations are done at steady state. The solver settings are summarized in Table 2.

<table>
<thead>
<tr>
<th>Table 2 Numerical solver settings</th>
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<tbody>
<tr>
<td><strong>Inlet</strong></td>
</tr>
<tr>
<td>UHBR Fan</td>
</tr>
<tr>
<td>V2500 Fan</td>
</tr>
<tr>
<td><strong>Outlet</strong></td>
</tr>
<tr>
<td>$p_{1,2}$, $T_{1,2}$, $\alpha$, $\beta$</td>
</tr>
<tr>
<td>$p_{1,2}$, $T_{1,2}$, $\alpha$, $\beta$</td>
</tr>
<tr>
<td><strong>Wall treatment</strong></td>
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<tr>
<td>Low-Reynolds</td>
</tr>
<tr>
<td>Low-Reynolds</td>
</tr>
<tr>
<td><strong>Rotational speed</strong></td>
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<tr>
<td>3074</td>
</tr>
<tr>
<td>4652</td>
</tr>
<tr>
<td><strong>Row Interface</strong></td>
</tr>
<tr>
<td>Mixing Plane</td>
</tr>
<tr>
<td>-</td>
</tr>
<tr>
<td><strong>Turbulence model</strong></td>
</tr>
<tr>
<td>Wilcox k-ω</td>
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<tr>
<td>Wilcox k-ω</td>
</tr>
</tbody>
</table>

Figure 6 depicts the stations where the boundary conditions are applied. The rotor domain has one inlet boundary at station 2, while the exit boundaries are divided by the splitter. The UHBR Fan is linked to a downstream stator both in the bypass and in the core section. Thereby, the pitch-wise mass flow averaged fluid properties of the fan wake are passed to the downstream row. As outlet boundary conditions, a circumferentially mass flow averaged static pressure is set at midspan. In case of the UHBR fan configuration the outlet conditions are applied behind the stator vanes at station 13 and 23 respectively, as shown in Figure 6. The outlet boundaries for the V2500 fan are at station 12 and 21, because of the omitted vanes.

**Figure 6 Meridional view of numerical domain**

When simulating the different configurations, the outlet static pressure boundary was adapted to ensure an equal fan wake profile for the corresponding mass flow for the respective bypass ratio. In order to numerically resolve the viscous layer at the wall boundaries, the Low-Reynolds wall treatment was chosen (Wilcox, 1994). This is particularly important in the case of increasing bypass ratios where the percentage of fan near hub flow increases within the core section. The numerical calculation was assumed to be converged when the RMS residuals for mass flow and pressure reached a stable level of less than $10^{-5}$ and the RMS of the polytropic efficiency was less than $10^{-4}$ over the last 2000 iterations.
RESULTS AND DISCUSSION

3D Flow Topology of the UHBR Fan

To visualise the secondary flow phenomena, the turbulent kinetic energy $k$ is used indicating areas of high turbulence in Figure 7. The iso-surfaces show the typical secondary flows such as the tip leakage vortex that rolls up on the suction side of the rotor blade. A horseshoe vortex is normally built up at the hub leading edge. However, the concentrated vortex is too close to the surface and is rapidly diffused by viscous and Reynolds stresses because of the sharp leading edge (Bradshaw, 1987). The vortex origin is barely visible and indicated in Figure 7. Due to a pressure gradient, mixing of the suction and pressure side flow occurs at the trailing edge forming a so-called trailing edge vortex. This wake flow, characterised by low velocity and high total pressure, interacts with the splitter as shown in Figure 7. Depending on the wake flow splitter interaction, the near splitter flow is affected. Because of the high hub-to-tip ratio in the core section, the radial flow distribution gets influenced due to blockage. Another vortex that originates from the fan rotor is the corner vortex at the edge between trailing edge and hub. This vortex directly flows into the core passage and affects the downstream core stator. On the downstream shrouded OGV and IGV the same vortices can be determined, apart from the tip leakage vortex. The turbulent kinetic energy also indicates small corner separations on the hub kink at the fan trailing edge, which could influence the downstream booster.

Zamboni and Xu (2014) emphasised that the hub end wall curvature and the contraction of the annulus cross section have a significant impact on the near hub fan flow. The data depicted in Figure 8 shows the near hub turbulent kinetic energy at the UHBR fan trailing edge for the three investigated bypass ratios.

![Figure 7 Secondary flow visualisation](image)

![Figure 8 Turbulent kinetic energy at UHBR fan TE](image)

Only 20% of the relative channel height is shown in the A-A cuts, with the upstream fan trailing edge being outlined. Additionally, the relative velocity streamlines are plotted. They clearly visualise the corner vortex at the hub. Overall the velocity streamlines move downwards in hub direction with increasing bypass ratio. This minor radial redistribution has no significant impact on the secondary flow topology. From the turbulent kinetic energy contour it can be seen, that the area of turbulent kinetic energy is growing slightly with an increasing bypass ratio. The distance between splitter nose and fan trailing seems to be wide enough, so that the fan flow is not affected by the flow interaction at the splitter. In addition to the observation of Zamboni and Xu (2014), a contraction of the annulus cross section has no tremendous impact on the near hub fan flow upstream of the splitter. Figure 9 shows the normalised total pressure $p/p_{\text{mean}}$ close behind the splitter nose for each UHBR fan bypass configuration. Additionally, the meriodional velocity streamlines are depicted. It can be seen, that the splitter contour faces a nearly axial flow. Therefore, lowering the splitter contour in radial direction does not change the incidence angle effectively. The values of normalised total pressure do not change at their absolute position.
However, the increasing percentage blocking and viscous effects on the no-slip wall the contour topology changes slightly. The results show, that the UHBR fan does not react sensitively to an increasing bypass ratio. Accordingly, the fan values of the fan parameters from Table 1 remain the same.

The highly non-uniform fan wake and the vortices proved to be uncritical for the UHBR fan splitter interaction.

**Impact of the Near Hub Flow on the IGV**

The downstream IGV is subjected to the near hub flow in a bypass configuration. It was designed for the reference bypass ratio of 17. When the splitter is lowered in radial height the IGV is simply cut at the corresponding span. Since the core flow is not significantly affected by the lowered splitter, an IGV redesign is not required. However, with an increased hub-to-tip ratio of the core section, the relative proportion of boundary layer and corner vortex along the span is increased. In Figure 10 the meridional view of the IGV is shown. The evaluation planes at IGV leading and trailing edge are defined at $\Delta x_{\text{plane}}=6\%$ of the IGV chord length. To understand the overall effect of increasing bypass ratio on the IGV the total pressure loss $\zeta_{\text{rel},\text{abs}}$ is analysed. The comparison of the IGV flow turning $\Delta \beta$ will provide information about the flow angles.

In Figure 11 the total pressure loss and the flow turning are presented respectively. The data depicted is pitchwise mass averaged and spanwise plotted. For better comparison the relative channel height was chosen.

**Figure 10 Meridional view IGV**

**Figure 11 IGV total pressure loss and flow turning**

From the total pressure loss plot at the top it can be seen, that the distributions of the curves coincide fairly well. While the
total pressure loss has higher values for increasing bypass ratio over most parts of the channel height, the total pressure loss decreases with increasing bypass ratio from about 50 to 70 percent relative channel height. At a relative radial height of about 30 and 90 percent the maximum difference in total pressure loss is present. Looking at the flow turning, the regions of higher total pressure loss coincide with the regions of higher flow turning for increased bypass ratio. These deviations are traced back to the minor radial flow redistribution at the IGV inlet and the contraction of the flow field.

**Figure 12 Total pressure loss at IGV TE**

Figure 12 shows the total pressure loss contour at the IGV trailing edge with the corresponding suction side surface streak lines. It can be seen, that the area of low total pressure loss is deformed due to the contraction of the annulus cross section. As the percentage amount of boundary layer increases the flow with high kinetic energy is condensed in the mid span passage area, leading to a spike of low total pressure loss in circumferential direction at those heights. This explains the lower total pressure loss for increasing bypass ratio at 50 to 70 percent relative channel height in Figure 11. At the trailing edge near hub contour a small reduction of the high total pressure loss area is shown. The reason for this is a less loaded IGV which can be seen by the straitened streak lines for increasing bypass ratio. However, the percentage area of high total pressure loss at the trailing edge increases by up to 7% for increasing bypass ratios. Overall, the IGV is affected by blockage effects due to percentage increased boundary layer and corner vortices as well as the contraction of the cross section. This is in accordance to the findings of Zamboni and Xu (2014). With an increase in bypass ratio from 17 to 25 the total pressure loss increases up to 10% integrated over the total channel height. Because of the small percentage affected area of the bypass section and the missing corner vortex, the OGV total pressure loss only differs up to 0.5%. Generally, the bypass section seems not to be sensible to an increasing bypass ratio by lowering the splitter.

**Effect on the V2500 fan**

The UHBR fan has shown no high sensitivity for increasing bypass ratios. However, the splitter interacts with an almost axial flow and the UHBR fan blade is loaded conservatively. To investigate not only a various operation point but also a different fan design and hub contour, the V2500 fan is analysed. In Figure 13 the near hub suction side streak lines of the UHBR fan and V2500 fan are presented at the corresponding design point. It can be seen, that the streak lines of the V2500 fan get highly deflected towards the bypass section, while the UHBR fan streak lines only show a minor deflection at splitter height. This indicates a larger corner separation at the V2500 fan trailing edge compared to the UHBR fan.

Additionally, the downstream flowing fan wake interacts with the splitter at a certain incidence angle. The hub contour also supports a non-axial flow at the near hub region. This suggests that the V2500 fan wake splitter interaction differ from the UHBR fan configuration and that the V2500 fan might react different to an increasing bypass ratio. Figure 14 shows the near hub turbulent kinetic energy at the V2500 fan trailing edge for the three investigated bypass ratios. Starting from hub, 60% of the relative channel height is shown in the A-A cuts to capture the affected fan wake area. The relative velocity streamlines are plotted and the upstream trailing edge is outlined. As already seen in the surface streak lines the radial velocity at the V2500 fan near hub trailing edge is a dominant velocity component. The corner vortex almost
dissipated up to the evaluation plane showing no swirl in the streamlines. Unlike the UHBR fan, there is no kink in the hub contour at the fan trailing edge, which enhances the corner vortex. An increasing bypass ratio results in rising values of turbulent kinetic energy. The main topology of the fan wake is not changed at the evaluation plane in accordance to the results of the UHBR fan. With that, the effect of increasing bypass ratio on the fan parameters is negligibly small. As stated by Dawes (1991), the splitter flow incidence can affect the downstream flow significantly.

The main topology of the fan wake is not changed at the evaluation plane in accordance to the results of the UHBR fan. With that, the effect of increasing bypass ratio on the fan parameters is negligibly small. As stated by Dawes (1991), the splitter flow incidence can affect the downstream flow significantly.

Figure 14 Turbulent kinetic energy at V2500 fan TE

In Figure 15 the meridional velocity streamline and the normalised total pressure \( \frac{p}{p_{\text{mean}}} \) for each V2500 fan configuration is depicted. Although the flow incidence of the V2500 splitter differs clearly from this of the UHBR splitter, the core flow is affected similarly. The general effect on a downstream IGV is expected to be the same as for the UHBR fan configuration, because of a percentage increased boundary layer or and the contraction of the cross section. The extent of influence is still to be investigated.

Figure 15 Splitter flow interaction V2500 fan
CONCLUSIONS
The effect of increasing bypass ratio of UHBR fans on near hub flow by lowering the splitter has been investigated. The near hub fan wake is characterised by a highly non-uniform flow and secondary flow phenomena. Therefore, the UHBR fan wake splitter interaction was analysed for bypass ratios of 17, 20 and 25. The results show, that the fan interaction behaviour is uncritical to an increasing bypass ratio. The fan performance is not affected. This allows for neglecting the radial splitter position when designing the fan blade. However, the axial distance between fan trailing edge and splitter nose was not studied in this paper.

The downstream core stator is affected by the 3D flow path and by the contraction of the annulus cross section. An increasing bypass ratio from 17 to 25 leads to an increase in total pressure loss of up to 10% due to percentage increased boundary layer and trailing edge vortices. The downstream bypass section is not affected remarkably by the increasing bypass ratio. These findings should be considered during compressor design.

Despite the other bypass ratio, design and hub contour, the V2500 fan shows similar fan wake splitter interaction effects. This confirms the results obtained from the UHBR fan configurations.

Future work needs to investigate the near hub flow behaviour at off-design conditions as the rotor-stator interaction as well as the fan wake splitter interaction will be affected. The next step will be unsteady simulations of the UHBR fan configuration to resolve rotor-stator interactions. Furthermore, the leakage flow between the stationary and the rotating hub can be considered, as it increases the blockage in the core stator.

NOMENCLATURE

Geometric and Flow Quantities

\( \alpha \)  flow angle (radial)
\( \beta \)  flow angle (circumferential)
\( \rho \)  density
\( \zeta_{\text{abs}} \)  total pressure loss coefficient
\( \eta_{\text{p}} \)  polytropic efficiency
\( \kappa \)  isentropic exponent
\( \nu \)  hub-to-tip ratio
\( \pi \)  total pressure ratio (\( \pi_{\text{t}} = p_{\text{t,2}}/p_{\text{t,1}} \))
\( \Delta \beta \)  turning (\( \Delta \beta = \beta_{\text{f,2}} - \beta_{\text{f,1}} \))
\( \Delta \)  radial offset
\( \Delta x \)  axial distance
\( h \)  specific enthalpy
\( H \)  channel height
\( i \)  incidence
\( k \)  turbulent kinetic energy
\( l \)  chord length
\( m \)  mass flow
\( p \)  static pressure
\( \rho \)  total pressure
\( r \)  radius

\( T \)  temperature
\( v \)  absolute velocity
\( x,y,z \)  coordinate system

Indices

1  inlet
2  outlet
abs  absolute
p  polytropic
ref  reference
S  splitter nose (axial position)
t  total

Abbreviations

BPR  bypass ratio
CFD  Computational Fluid Dynamics
DLR  German Aerospace Centre
DP  design point
GCI  Grid Convergence Index
IGV  inlet guide vane
LE  leading edge
OGV  outlet guide vane
PS  pressure side
RANS  Reynolds-averaged Navier-Stokes
SS  suction side
TE  trailing edge
TOC  top of climb
TRACE  Turbomachinery Research Aerodynamics

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