Flow Structure within an Aggressive S-Shaped Intermediate Compressor Duct

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Abstract. As part of Clean Sky 2 (Engines ITD), a working group, formed by the DLR Institute of Propulsion Technology, MTU Aero Engines and GKN Aerospace, is setting up a complete compression system module (LPC/ICD/HPC). The aim of the project is to shorten the intermediate compressor duct (ICD), which connects the low pressure compressor (LPC) and high pressure compressor (HPC). This leads to a reduction of the axial length and weight of the overall engine and thus a reduction of the specific fuel consumption. In order to identify measurement-technologies and mitigate risks for this experimental set-up, a non-rotating testrig was set up in advance to investigate two different test vehicles. In a first step an ICD demonstrator was set up, which had a reduced axial length of 25%, compared to currently operating designs. This design predicted no separation or performance losses inside of the aggressive s-shaped contour. In a second step another demonstrator was installed with an even shorter axial length of 50% axial length reduction, compared to todays state of the art configurations. In this demonstrator the design was chosen to exceed the functional limit according to today's CFD prediction and thus explore the potential for further length reduction in the future and to create a data base for numerical tool validation. The two configurations were tested at DLR Cologne. The test channel offers the possibility to use a variety of different measurement techniques to determine the flow behavior inside the ICD. This paper presents the oil streak pattern taken on the hub area between the struts and the ones taken on the pressure and suction side of the outlet guide vanes (OGV- LPC) for both demonstrators.

Keywords

Intermediate Compressor Duct, Oil Streak Pattern, Outlet Guide Vane, Flow Structure

INTRODUCTION

The axial length reduction of the compressor system provides the technical capability to improve the specific fuel consumption of an aircraft engine. Inside of the compressor system, between the Low Pressure Compressor (LPC) and the High Pressure Compressor (HPC) is the Intermediate Compressor Duct (ICD). The ICD offers the potential of an axial length reduction. The cross section of the ICD has the shape of a swan neck, as it leads the flow from the higher LPC mid radius to the lower HPC mid radius. Ortiz Duenas et al. [1] described the variation of axial length for a strutfree duct, where a length reduction of 26% is possible without significant increase of duct losses. For a struted duct, Stuerzebecher et al. [2] showed that the reduction of the axial length is limited as aerodynamic performance losses increase at a certain point. It is the aim of this project to define the optimum of the length reduction. Aerodynamic performance losses can be tolerated if the maximum reduction of specific fuel consumption (SFC), due to engine weight and nacelle drag reduction is achieved.

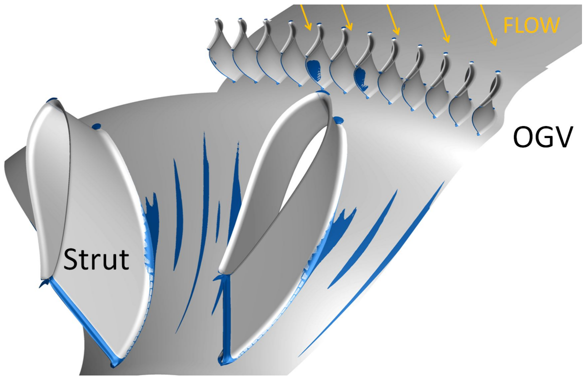

Figure 1. ICD SEPARATION ZONES Vx = 1.5 m/s

Nevertheless, flow separation would lead to a blockage and therefore to a throttling effect of the LPC and a distorted HPC and must be avoided at any operating conditions. The most sensitive regions inside the ICD are shown in Fig. 1. The blue areas are the locations where the axial velocity is lower than 1.5 m/s and are an indication for potential flow separation.

Wallin et al.[3] described in his work those locations of flow separation for this ICD campain. Two main parts are the ones where flow separation most likely occurs. Firstly the ICD itself, when the gradient of the radial reduction is too high and the air does not follow the contour of the swan neck any more. And secondly the outlet guide vanes of the low pressure compressor, when the vane loading gets too high and separation begins. In the ICD campain, two ICD demonstrator were tested:

1. Build 1.0 Demonstrator

This demonstrator called Build 1.0 is designed to be separation free in the aerodynamic design point, but with a relative axial length reduction of 25%.

2. Build 1.1 Demonstrator

This demonstrator has a reduction 50% compared to current stare of the art applications and is designed in a way that flow separation slightly occurs.

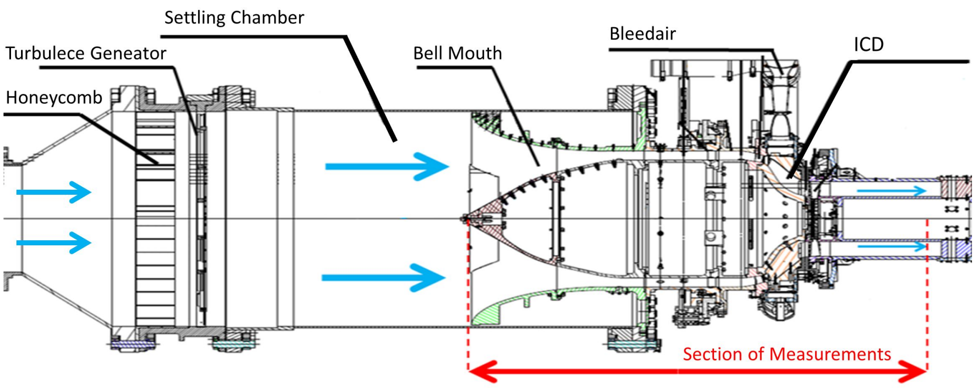

Figure 2. ICD TESTRIG

With the help of the test results from both setups, it is planned to design an ICD for the complete compression module (LPC/ICD/HPC). In the last decades, many studies focused on the investigation an characterization of the flow field inside a compressor cascade. Herzig, Hansen and Castello [4] published in 1954 a substantial study of the visualization of secondary flow in compressor cascades using oil streak pattern. Dong et al. [5] worked on three dimensional flows and losses in axial compressors and visualized the flow with the help of oil streak pattern. Schulz et al. [6] used the oil streak patter in his study to characterize flow structures and the influences of rotor-stator interactions on flow separation in stator region. This paper presents results of the taken oil streak pattern in the ICD campaign and provides the visual evidence, that the OGV and hub region is free of flow separation in Build 1.0. For Build 1.1 this paper presents the evidence that the flow on the OGV and hub region is highly loaded and separates.

1. TESTBED DESCRIPTION

Figure 2 describes the testbed. The incoming flow is lead into the settling chamber by a diffusor. Behind the diffusor, a honeycomb flow straightener reduces radial flow components. To simulate the turbulence level of an engine a turbulence generator is installed. The turbulence level can be adjusted by adding different sword like obstacles in the settling chamber. The turbulence level is about 1.5%. After passing the settling chamber the bell mouth begins to accelerate the flow. Inside the inlet plane (see Fig. 3), the flow is measured with the help of boundary layer rakes and the entry Mach number is calculated.

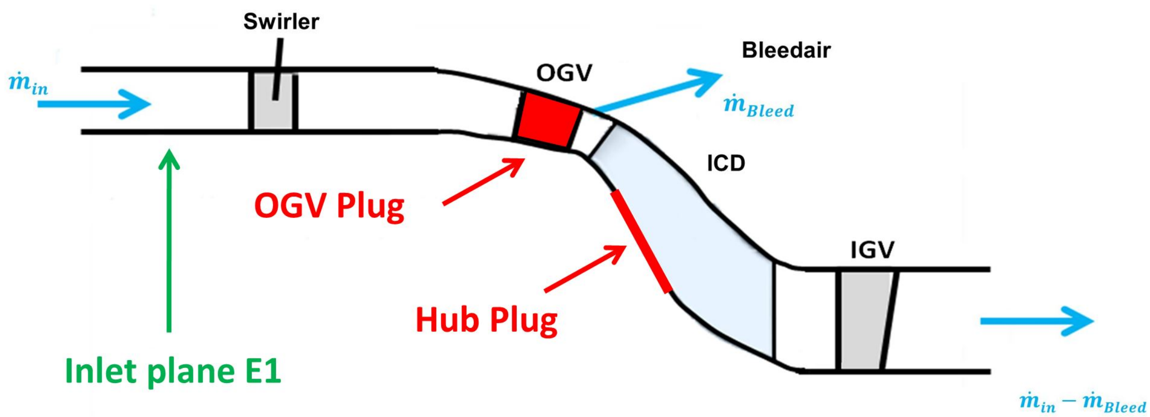

Figure 3. ICD TESTSECTION

Table 1. RIG SPECIFICATIONS

	max	min
Inlet Reynols number	5,500,000	650,000
Inlet Mach number	0.4	0.05
Pressure level abs.	225 kPa	65 kPa
Massflow	30 kg/s	-
Bleed massflow	40%	-

To simulate the last stage of the low pressure compressor a movable swirler row leads the flow to a defined circumferential angle. The movable swirler row allows for a substantial variation of the OGV incidence. The following LPC-OGV row is part of the demonstrator and leads the flow staggered optimally around the following ICD struts. Here the testrig offers the possibility to pull out a plug of 2 OGV blades for the oil streak pattern. Between two ICD struts, on the hub and in the middle of the radial height reduction, the rig offers a second possibility to pull a plug for oil streak patterns. Behind the ICD struts, a row of inlet guide vanes accelerate the flow, to take into account the upstream effect of a high pressure compressor which is not present here. Behind the HPC-IGV the flow leaves the testrig. A bleed port between OGV and ICD at the shroud takes out a massflow of bleedair, which can be defined precisely to simulate different engine settings. The main caracteristics of the testrig are described in Tab. 1.

OGV PLUG
To apply the oil paint the rig provides a removable plug with two OGVs (see Fig. 3 and 4). For easier painting and better analysis these can be separated. The vanes are painted in black for a better contrast. The oil paint is green for the hub and casing, white for the pressure and suction side. Threrfore secondary flow effect can than be located easily. The plugs are laser melted and then finished by a milling process. Finally the OGV plug is polished.

HUB PLUG
The plug in the ICD hub region is located in between of two struts (see Fig. 3 and 4). The plug was inserted during the milling process of the flow path, so no step is produced, which could take an influence on the flow. Before testing, the plug was also painted in black, for a better contrast.

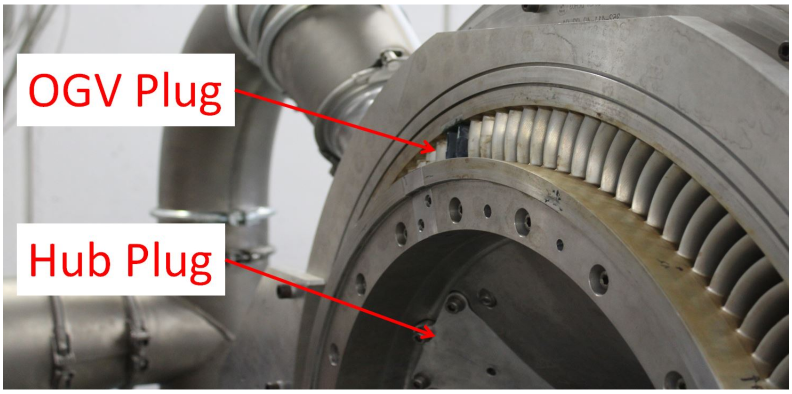

Figure 4. LOCATION OF PLUGS

Table 2. DEFINITION OF OPERATING POINTS

OP	Build	Ma	Swirler
1 ADP	1.0	nominal	nominal
2 ADP	1.0	reduced	increased
3 ADP	1.1	nominal	nominal
4 ADP	1.1	reduced	decreased

EXPERIMENTAL APPROACH
The viscosity of the oil paint is determined in pre-tests, taking temperature and mach number into account. The paint is applied carefully on the plugs, taking care that no streaks are created in direction of flow. As soon as the oil paint has been applied, the plugs are re- installed in the testbed and the channel is closed. This procedure needs to be performed fast, so that the oil paint does not dry out. The desired operating points (described in Tab. 2) are set as quickly as possible. With the help of a borescope the distribution of the oil paint is observed. After approximately 10 minutes the flow streaks distribute over the whole plug and the testrig is shut down immediately, so that lower flow velocities do not influence the pattern. When the channel is under ambient conditions again, the testrig is opened and the plugs are removed carefully. With a high resolution camera the oil streak pattern pictures are taken.

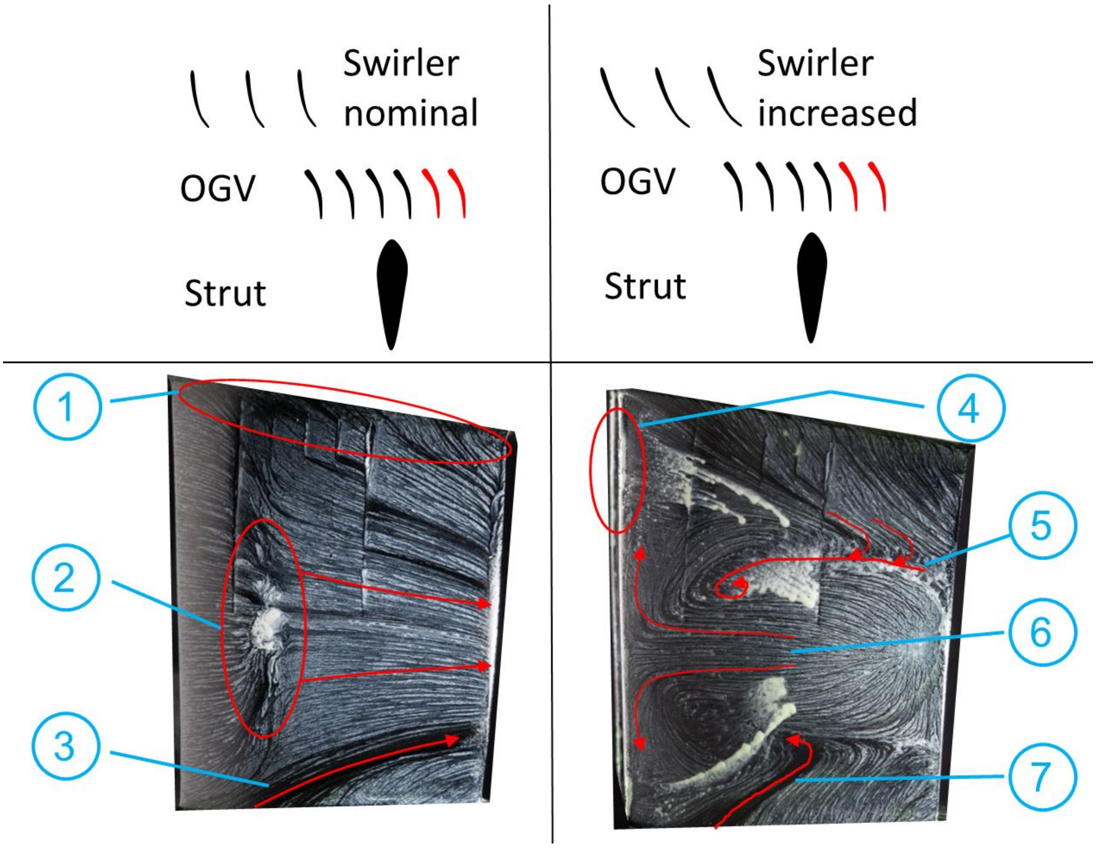

Figure 5. OGV SUCTION SIDE BUILD 1.0 ADP

2. OIL STREAK PATTERN BUILD 1.0

In order to interpret the effects in a three-dimensional flow from the oil streak pattern, an analysis of the flow topology is necessary. For this Lighthill [7], Tobak and Peake [8][9] and Dallmann [10] give a detailed description of the theory of the topology in a separated flow.

To show that flow separation occurs on the OGV at the aerodynamic design point, two swirler settings are used. On the left upper side of Fig. 5, the swirler setting is shown with a nominal setting. The Mach number is set to the nominal case. The two OGV marked in red describe the position of the OGVs where the paint is applied. In the lower left picture the result of the oilstreak pattern is shown with the nominal swirler setting on the suction side of the OGV. The red lines an circles describe aerodynamic effects. The blue lines and numbers are used only for pointing to the red lines and circles. Some milling marks are visible but have only a minor influence on the flow structure, as the vanes are polished. The flow enters from the left side. A secondary flow is visible on the hub and tip region (1) and (3) as the oil paint color used on the casing is green. In (2) a separation bubble marks the the region where the laminar flow gets turbulent. The hole vane provides an attached flow. So in that operating point no separation is caused by the OGV.

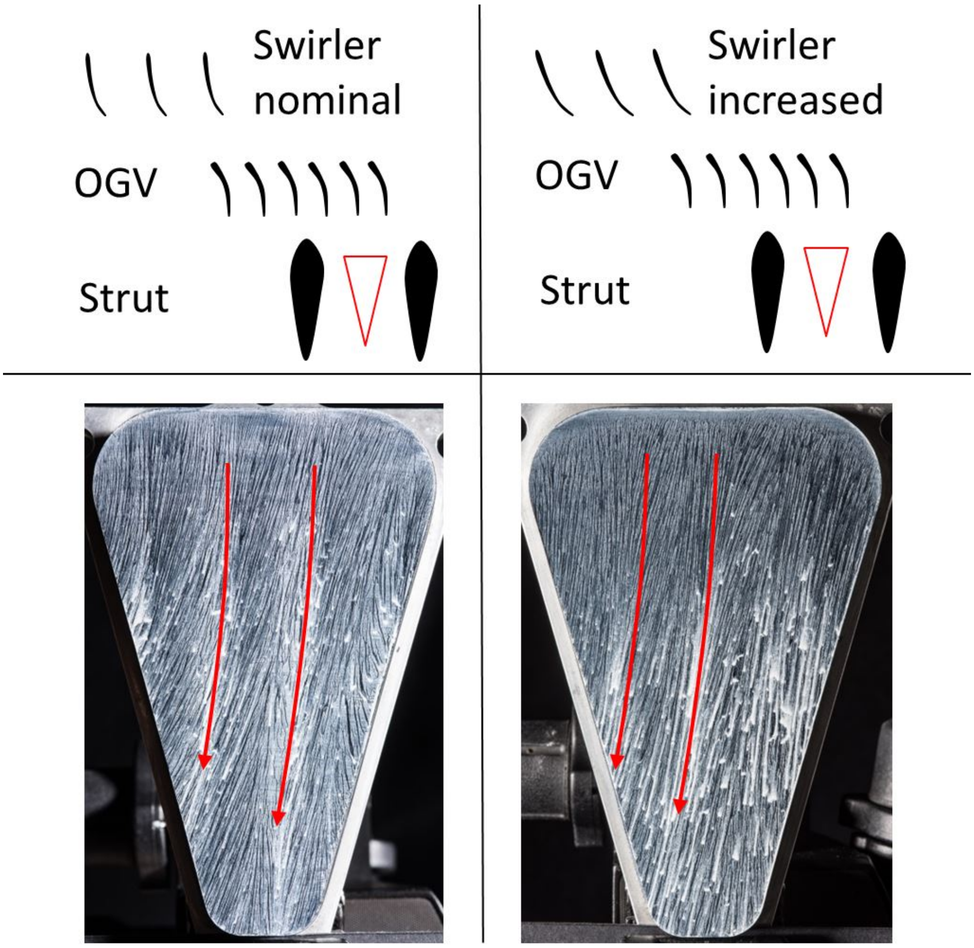

Figure 6. HUB BUILD 1.0 ADP

To check the contrary, the swiler angle is changed to an increased angle. In this operating point the Mach number is slightly decreased, but at a higher pressure level to gain the same Reynolds number. The upper right part of figure 5 shows the different setting between the nominal and increased swirler angle. The oil streak pattern are very different to the ones at nominal swirler angle. At (4) a separation bubble can be identified very close to the leading edge. The white paint a bit more downstream is the amount of paint collected by this separation bubble. When shutting the testrig down, the accumulated paint is released and deployed on the vane. In (5) a separation line can be identified and ends up in a detached swirl. This is the border where the flow reverses, as seen in (6). The secondary flow in (7) also ends up a in separation line and reverses. Therefore the vane is detachsed and produces aerodynamic losses. During the test a fluctuating noise could be heard. This type of sound points to a separation in the channel.

Figure 6 shows the corresponding results from the hub plug of Build 1.0 ADP in nominal and increased swirler angle. The upper part describes the swirler setting an the location of the hub plug in the red triangle. In the oil streak pattern the wakes of the OGV can be seen where the paint accumulates and forms a white line. In Fig. 6 these wakes are marked with red arrows. The difference between both swirler settings is mainly the offset of the OGV wakes. This is due to the different OGV loading and therefore deflection. But on both images, no separation can be detected. Even knowing that the flow on the OGV at increased swirler angle, detaches. One possible explanation is that knowing the geometry of the flow path, the smallest cross section is in between OGV and the first bend of the swan neck. Therefore the flow might reattach, due to the flow acceleration.

3. OIL STREAK PATTERN BUILD 1.1

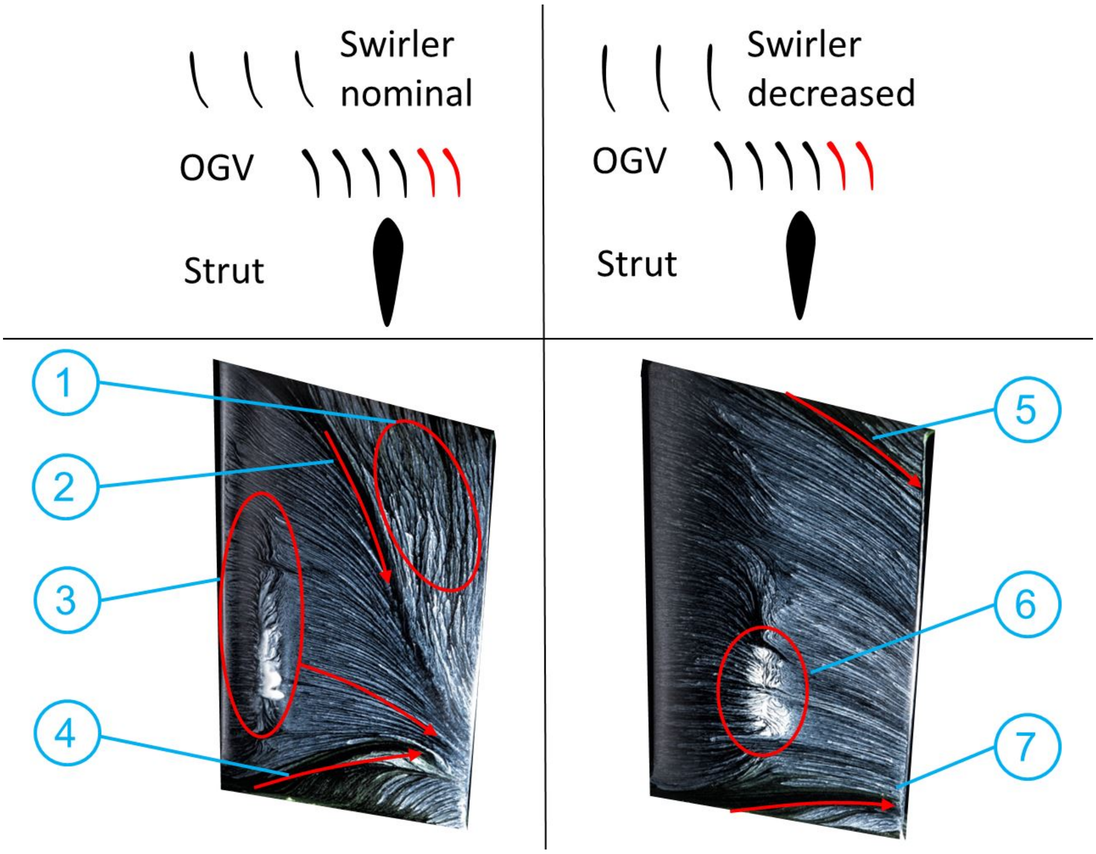

Figure 7. OGV SUCTION SIDE BUILD 1.1 ADP

In order to identify new potentials for even shorter ducts and needs for new CFD Tools the ICD Build 1.1 is designed with an axial length reduction of 50% and separation is predicted via previous CFD calculations. The separation of the OGV at the aerodynamic design point at nominal Mach number can be seen on the left side in Fig. 7. The area in (1) is detached. The secondary flow of casing (2) and hub (4) can be identified by the green oil paint, which deploys over the whole vane. A separation bubble can be seen in (3), where the laminar flow changes into a turbulent flow. When the swirler angle is set to the decreased position, the vane attaches (see right side of Fig. 7). The secondary flow in (5) and (7) also is visible but not as strong as can be seen on the left side of Fig 7. A separation bubble, where the flow changes from laminar to turbulent, can also be identified in (6).

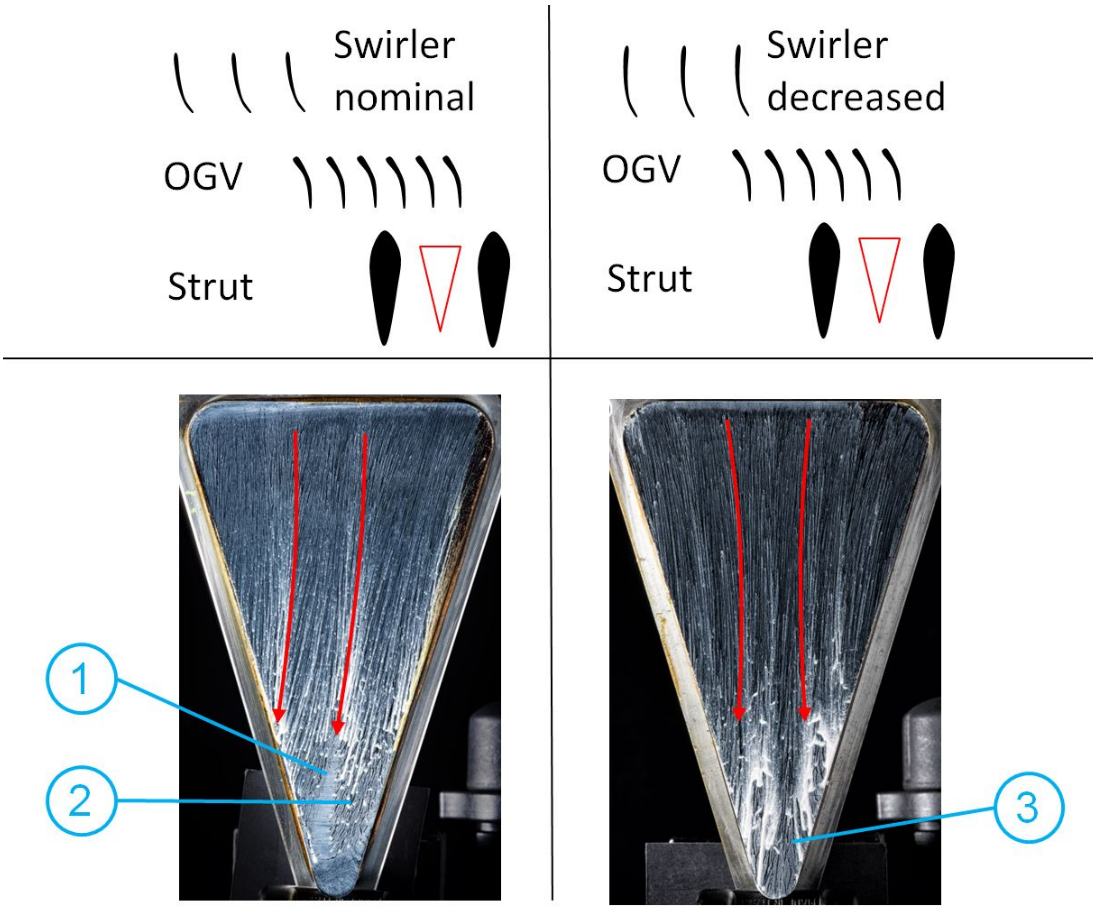

Figure 8. HUB BUILD 1.1 ADP

The ICD Build 1.1 is designed in such a way, that flow separation might occur also in the hub region. Due to the aggressiveness of the duct, the flow velocity in the curvature of the hub region is low. This causes a high streamwise pressure gradient and the flow tends to separate. This effect can be seen in Fig. 8. On the left side of the figure the hub plug at ADP (nominal Mach number) and nominal swirler angle is shown. The red arrows indicate the swirler wakes and therefore the flow direction. In the lower part of the oil streak pattern, the movement of the oil paint does not pass through the whole plug. The swirler wake provides a very low axial velocity, so that an area of the initial pattern before testing (1) can be seen. Right next to the wake the movement of the oil paint is very low with varying circumferential components (2), compared to the pattern in the upper region of the plug. Nevertheless no flow reverse can be identified. A flow reverse would be identified by the fact that the oil paint accumulated at the left and right edges of the plug would be sucked into the center. This leads to the conclusion that the hub region is highly loaded and the wall shear stresses are very low but no complete separation occurs. The same indications shows the plug under decreased swirler angle and the reduced Mach number on the right side of Fig. 8. One difference is the wake distribution of the swirler wake due to the different swirler angle (compare red arrow directions). In the lower part of the right picture at (3), a the low movement with circumferential components can also be identified as in (2), which is a indication of a starting separation and low wall shear stresses. The accumulated but not reversed oil paint at (3) supports the indication of low shear stresses.

4. CONCLUSION

For further data analysis it is important to know, if and where flow separation occurs inside the ICD. With the oil streak pattern it can be shown that Build 1.0 is free of separation on the OGV. In addition, the swirler angle can be changed so that separation on the OGV is forced, due to high blade loading. In Build 1.1 the channel behaves the other way around. In the design point flow separation occurs on the OGV. By reducing the swirler angle, the flow attaches due to the decreased OGV loading. In all four conditions shown, the hub is separation free, but in Build 1.1 the lower hub shows first tendencies to detach and low wall shear stresses are observed.

ACKNOWLEDGMENT

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Unions Horizon 2020 research and innovation programme under grant agreement No CS2-Engines ITD-2014-2015-01.

ABBREVIATIONS

ADP Aerodynamic Design Point
DLR German Aerospace Center
HPC High Pressure Compressor
ICD Intermediate Compressor Duct
IGV Inlet Guide Vane
LPC Low Pressure Compressor
OGV Outlet Guide Vane
OP Operation Point

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