AN ADVANCED AXIAL-SLOT CASING TREATMENT ON A TIP-CRITICAL TRANSONIC COMPRESSOR ROTOR
PART 1: UNSTEADY HOT WIRE AND WALL PRESSURE MEASUREMENTS

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ABSTRACT
The application of casing treatments to compressor stages has proven suitable to achieve an extended operating range towards lower mass flow rates and to increase the stage pressure ratio. The responsible effect of the casing treatment on the blade passage flow is the reduction of blockage in the tip region mainly caused by the tip leakage vortex. In transonic compressors the tip leakage flow interacts with the shock induced by the subsequent blade. The position and strength of this shock effects the behavior of the vortex and can lead to higher blockage. At highly throttled operating points the shock detaches from the blade leading edge. Hence, the distance between tip leakage vortex development and the shock interaction is reduced. Aims of this investigation are to determine the effect of an advanced axial slot casing treatment on the shock detachment and to estimate the recirculation activity inside the slots.

A casing treatment was applied on a modern one and a half stage high speed test rig with steady and unsteady instrumentation. The test rig allows the direct comparison with the conventional smooth wall configuration. Static wall pressure in the blade tip region was measured using unsteady pressure taps to resolve the shock structure close to the casing. Inside one casing treatment slot a hot wire probe was used to measure the recirculation velocity depending on the operating point. Additionally a five hole probe was used to measure the rotor outflow. The results show an increased operating range of the axial compressor towards lower mass flow rates along with a higher stage pressure ratio. A reduced detachment distance of the shock compared to the smooth wall configuration is observed at low mass flow rates. The dependency of the recirculation activity on the shock position is derived from the data. Over a wide range of mass flow rates the velocity inside the slot rises with the detachment of the shock and hence the pressure ratio. Only at highly throttled operating points the recirculation velocity decreases while the pressure ratio still rises. This is a possible indicator for repeated recirculation of flow through adjacent slots. The measurements are used as a validation for numerical simulations presented in Part 2 of this publication, showing a good agreement in the observed flow features including shock position. A comparison of numerical and experimental pressure distributions is given and the results are analyzed with similar methods to quantify the shock detachment and strength.
INTRODUCTION

A general aim in the development of aerospace propulsion systems is the reduction of weight. This influences the design of each component of an engine, including the compressor. The weight of modern compressors amounts up to 50 percent of the engine’s mass. A possible solution to reduce weight is the reduction of the number of compressor stages. Since modern engines with high turbine inlet temperatures require a high overall pressure ratio of the compressor, the reduction of stages necessitates an increased loading of each stage. Especially at part speed with low mass flow rates the load on front stages of a compressor is increasing. These circumstances can lead to compressor stall or even surge when the mass flow in a single stage falls below a certain value. Hence, modern compressor stages need to provide a high pressure ratio over a wide range of mass flow rates.

A possibility to extend the operating range of a compressor rotor is the application of casing treatments (CT) influencing the flow in the rotor tip region. These systems have proven suitable especially on rotors which show tip critical behavior, where the source of stall is located in the tip region close to the casing. This behavior is typical for highly loaded front stages of transonic high pressure compressors with a complex flow structure in the tip region. The tip leakage flow forms a vortex traveling downstream through the blade passage. This vortex forms a zone of blockage for the main flow and can be a reason for stall inception. The influence of the tip clearance, and hence the tip leakage flow, on the performance of a transonic compressor has been investigated by numerous researchers, particularly by Hah et al. (2004), Hoeger et al. (2000).

In transonic rotors, this vortex has to cross the shock of the subsequent blade and tends to increase in size due to the higher pressure downstream the shock, eventually leading to vortex breakdown. Casing treatments influence the development of the tip leakage vortex with the aim to prevent exceeding growth. Axisymmetric casing treatments like circumferential grooves above the rotor influence the development of the tip flow directly, locally reducing the driving pressure ratio over the blade tip and dampening the relative velocity of the tip leakage flow. This prevents a large inclination of the tip leakage vortex towards the leading edge of the adjacent
blade and hence reduces blockage. Recent investigations have shown a larger extension of the operating range with non axisymmetric CTs like axial slots compared to circumferential CTs. Axial slots additionally modulate the inflow to the rotor periodically and remove low momentum fluid in the blockage zone to reinject it upstream of the rotor. A numerical analysis can be found in Hembera (2008), Wilke and Kau (2004), Legras et al. (2011). The axial Mach Number in the tip region is increased which has influence on the shock position, reducing the tendency of the shock to detach from the leading edge. If the shock remains attached, the tip leakage flow has a longer distance to mix with the main flow before the interaction with the shock occurs. This can prevent subsequent growth of the vortex.

Objective of Part 1 of this publication is to analyze the influence of an advanced axial slot casing treatment on the shock position in a modern transonic compressor since it is seen as an indicator for the blockage caused by the tip leakage vortex using unsteady wall pressure measurements. A method to derive the shock position from the wall pressure data was developed and successfully applied. Additionally, velocity measurements inside a casing treatment slot were carried out to provide information about the activity inside the cavity and to validate numerical simulations presented in Part 2 of this publication. Therefore a hot wire probe was introduced into a CT cavity at a position where high velocity amplitudes were suggested. The interdependency of recirculation activity and shock position was derived.

To adapt CTs to modern compressor designs or to develop matching systems of rotor and CT it is necessary to perform CFD calculations to estimate the performance. These simulations are very challenging, especially with non axisymmetric CTs, which require time resolved calculations.

Part 2 of this publication shows results from numerical simulations, addressing the influence of recirculation on tip leakage flow directly since insight into the complex flow structure is possible. A validation of these simulations is given through direct comparison with measurements shown in Part 1.

**Shock detachment**

The relative position of the shock to the blade leading edge is a very sensitive parameter that depends on various factors. For a transonic compressor with inlet Mach numbers of about 1.2-1.4, the shock remains attached to the blade leading edge from the near choke point until at least the design point. For the investigated rotor, the highest efficiency achieved is the point where the passage shock has turned from oblique to normal and starts to detach. If the rotor is throttled further towards stall, the shock detaches by a certain amount, which is currently not predictable.

The detachment distance was investigated thoroughly for single airfoils and blunt bodies, exemplarily by Bölcs and Suter (1986), Bailey and Sims (1963), Leyva (1999). They all concluded that a dependency on the up-stream Mach number, the body (blade) thickness and the blade tip angle exists. If the shock detaches, a subsonic region appears between the blade leading edge and the shock. The detachment distance increases while throttling and has a growing subsonic region which transports information about downstream pressure events, such as blockage induced by the tip leakage vortex. Downstream pressure information is transported through the passage and around the blade leading edge in the detached case, thus influencing the shape and position of the bow shock wave traveling upstream. Additionally, the tip leakage flow expanding on the suction side close to the leading edge appears as an obstacle to the main flow, and is comparable to a larger body or blade thickness that is linearly increasing the detachment distance.

One possibility to enhance compressor stability without CT is the blade leading edge forward sweep. Its effectiveness can be explained by the increased distance between the tip leakage vortex development and interaction with the shock. Upstream of the interaction the vortex accelerates in an axial direction through interaction with the main flow. Numerical investigations show that higher axial
momentum of inflow prevents an eventual vortex breakdown that may occur through the pressure rise across the passage shock (Schlechtriem and Lötzerich, 1997). For a constant blade pressure ratio, the shock detachment distance acts as an indicator of the structure of the blade tip flow. Hence, a reduced detachment distance for a given mass flow is equivalent to a more stable flow structure and may be of value as it is connected to the blockage in the blade tip region.

**Measurement Setup**

The Darmstadt Transonic Compressor (Fig. 1) was designed as a test rig for a single-stage, high-pressure compressor with axial inflow. A new stage equipped with variable inlet guide vanes (VIGV) was commissioned to determine the influence of the associated disturbances. The test rig is electrically driven with controlled shaft speed. A steady instrumentation is applied to measure the performance of the setup. Therefore, the operating point can be identified using inlet and outlet temperature and pressure as well as applied shaft power. Radially distributed instrumentation downstream of the stage provides information on the outlet flow while traversing the stator. To avoid clocking effects, the VIGV can be traversed circumferentially, synchronously to the stator. A conventional five hole probe with a head diameter of 3 mm is used to measure the rotor outflow. The investigated rotor is representative for a front stage of a state of the art transonic high pressure compressor, showing tip critical behavior in the smooth wall configuration. The casing treatment was developed as part of a project at the Institute for Flight Propulsion of TU München (Hembera (2008)). Design intend was an extension of the stall margin without decreasing efficiency.

For the CT setup 18 sensors (Kulite XCS-062 diff.) were inserted equally spaced between two CT-slots at constant circumferential position, see Fig. 2 (a). Five probes were located upstream the blade leading edge. A hot-wire probe (Dantec 55P11/10) was inserted inside the casing treatment slot. Hot wire probe and five hole probe were calibrated in a free stream channel (five hole probe Ma 0.1 to Ma 0.8; hot wire probe 10m/s - 180m/s). To ensure that position and orientation of the hot wire probe coincides with the region of highest velocity inside the slot, the results from the numerical simulations described in Part 2 were considered. The measurement position lies in the area, where the recirculated flow is reinjected, see Fig. 2 (a). The unsteady instrumentation was recorded simultaneously at a rate of 500kHz.

Mechanical stress of the blades was monitored via strain gauges applied to rotor and stator. Inflow and shaft speed were corrected to achieve similar inlet Mach numbers to compare different operating points. The inlet mass flow was normalized using total inlet temperature and pressure; shaft speed is corrected by the inlet temperature and humidity. The maximum shaft speed of the test rig is limited to 20,000 rpm.
To determine the operating range of the compressor, the mass flow is reduced until stall occurs. The last stable operating point where continuous measurements can be performed with IGV and stator traversing, is referred to as near stall (NS). Since the last stable operating point is influenced by the casing treatment, a distinction is made between near stall smooth casing (NSSC) and near stall casing treatment (NSCT).

**Results of Smooth Casing Measurements**

For the smooth casing configuration, an increasing tip leakage vortex was observed by Stereo Particle-Image-Velocimetry (SPIV) measurements while reducing the mass flow in the compressor. A schematic of the measurement setup and the flow structures is given in the upper part of Fig. 3 (a). Fig. 3 (b) shows the results of these measurements carried out for the smooth wall configuration at 92% span at NSSC condition. A large blockage area was created in the blade passage. The tip leakage vortex structure is visible in the radial velocity component, colored on the right side of the figure. The associated boundary of this vortex is also shown on the left of the figure, colored by the axial Mach number, and clearly depicting the blockage downstream of the shock at this specific channel height. It was also possible to determine the shock position relative to the rotor blade by analyzing the relative Mach number, see Fig. 3 (a). Further information on the setup can be found in Brandstetter et al. (2011). Based on these results, it was assumed that the application of an axial slot casing treatment should be successful for this specific compressor, since the rotor shows typical tip-blockage behavior.

![PIV Smooth Casing](a)

![92% Span PIV Velocity NSSC](b)

**Figure 3:** Particle Image Velocimetry measurements at NS for the smooth casing configuration (Brandstetter et al. (2011))
Results of Casing Treatment Measurements

Steady performance

A five-hole probe was used at the operating points DP, NSSC and NSCT to achieve time-averaged flow values downstream of the rotor. Results are shown in Fig. 4. The axial Mach number profiles as well as the flow angle $\alpha$ at DP appear similar, proving that the influence of the CT at this operating point is negligible. The most obvious difference between the two configurations is visible in the outer 20% of the flow channel for the NSSC point, where the axial Mach number is significantly increased through the casing treatment. The flow angle profile shows that the higher axial Mach number is connected with a decreased deviation in the blade tip region. At each measured channel height 400 pressure values were averaged; the average standard deviation of the probe measurements amounts to 0.6° in flow angle and 0.008 (NS) / 0.005 (PE) in axial Mach number.

The measurement of stage efficiency and stage pressure ratio shows an increased total pressure ratio for both operating points compared to SC, DP (+0.2%) and NSSC (+2.6%), while the isentropic stage efficiency at NSSC is increased by about 1.5%. At DP, the measured efficiency was also increased by a lower value through the application of the casing treatment, which lies within the measurement repetition accuracy of the test rig. Fig. 4 shows the operating point NSCT with a significantly reduced axial Mach number compared to the NSSC point, proving the extension of the operating range towards lower mass flow. The average deflection in the subsonic region is increased by about 5 degrees, emphasizing the possible blade load reserves of the smooth wall configuration. The corresponding mass flow rates can be found in Fig. 6 (a).

Continuous Measurement

To determine the exact shock position for specific operating points a mass flow was adjusted until steady operating conditions were reached. The unsteady instrumentation data was then recorded for 1,000 rotor revolutions. Fig. 5 shows pressure contours of these measurements during two blade passages. Each blade passage was evaluated separately to localize significant values. Local maxima of the chord wise pressure gradient were a robust indicator for shock detection. The superimposed crosses in the pressure contour figures show the position of detected gradient maxima. For each detection point, the static pressure rise in the chord direction was extracted. This could be used to distinguish between a shock and a subsonic pressure rise and to identify the static shock pressure ratio at the casing wall. Figure 6 (a) shows the ensemble averaged shock positions of these measurements,
while the error bars are defined by the standard deviation during the 1000 recorded revolutions for each operating point. In order to describe the shock contour, the gradient detection points were connected by a curve fit. The intersection of this curve with the extension of the blade chord is defined as SP. The value shown equals the distance of this position to the blade leading edge, normalized with the blade chord length at tip, see Fig. 5 (f). Negative values describe a detached shock.

**Transient Measurement**

To acquire information about the compressor and CT behavior during a transient reduction of mass flow, the test rig throttle was continuously closed from near choke to stall while the unsteady pressure probes and the hot wire probe were recorded simultaneously. The procedure to measure the shock position was used to identify the associated operating point during transient measurements. The measurement of the transient mass flow with conventional rig instrumentation is too slow and inaccurate since it requires a relatively long measurement time to stabilize. The method was calibrated using continuous measurements described above to achieve a correlation between conventionally measured mass flow and the unsteadily measured shock position. It enables to determine a time resolved operating point when exemplarily approaching rotating stall. To stabilize the method against natural shock vibration and detection inaccuracy, a sliding median filter was applied to average the detections for each rotor revolution. Figure 6 (b) shows the results for the pressure ratio over the CT slot in the upper figure.

The wall pressure in the axial area, where the flow is presumably induced into the slots is designated as fill pressure ($fp$), the pressure in the upstream part of the slots (reinjection area) designated reinjection pressure ($rp$), see (Fig. 2 (b)). The difference of these values indicates the driving force for the CT activity. In Fig. 6 and 7 the slot pressure difference is made dimensionless with the reinjection pressure $rp$. The lower part of Fig. 6 (b) shows the velocity measured inside the slot. In each case, the maximum, the minimum and the average for each revolution is marked. The time-resolved recirculation velocity and slot pressure ratio for 12 different shock positions (marked with vertical lines) is shown in Fig. 7.

At high mass flow rates ($DP$ and $PE$), the CT does not significantly influence the blade tip flow structure (Fig. 5). The shock position, shape and strength do not vary until the shock starts to detach. At these operating points the axial Mach number profiles (Fig. 4) are quite similar, which is important for eventual stage matching problems that might occur through CT application. Despite the weak influence on the main flow, the recirculation velocity reaches about 50% of its maximum value at $PE$. As far as the tip leakage vortex trajectory is derivable from the wall pressure measurements, no difference is observable. When further throttling the mass flow until NSSC is reached, the recirculation velocity increases, corresponding to the slot pressure ratio. During this process, the shock
Figure 6: Comparison of Shock Position/Strength and Recirculation Velocity. Values (a) in Relation to respective Design Point CT - Numerical Results from Part 2 of this publication

Figure 7: CT-Activity over Rotor Pitch - Transient Measurement
detachment is reduced in the CT configuration, as can be seen in Fig. 6 (a). Near stall, the smooth casing configuration shows a sudden decrease in shock pressure ratio even though the detachment distance increases. Since the shock pressure ratio corresponds to the Mach number, it is assumed that a sudden change of blockage establishes due to an increased vortex size, eventually forcing a vortex breakdown. This degree of shock detachment is not reached with casing treatment, nor is there a sudden breakdown of the shock pressure ratio at NSCT.

The five-hole probe measurements show almost equal axial Mach numbers between DP and NSSC at 95% - 99% span with CT. The high recirculation activity reduces the blockage of axial mass flow in the outer span regions. Since no stall occurred with casing treatment at this operating point, the stage could be throttled further than NSSC while still increasing its pressure ratio. From NSSC equivalent mass flow to NSCT the recirculation velocity starts to decrease slightly even though the slot pressure ratio rises. This behavior was not expected and did not appear in numerical calculations. In the time-resolved velocity in Fig. 7, the velocity in the NSCT case is 60% of the maximum case while the pressure profile shows a steady rise. An oscillating disturbance is superimposed with a significant content of the third blade passing harmonic, as can be seen in the frequency spectrogram in Fig. 8. The dotted red line marks the time, when the blow off valves downstream the stage were opened to avoid compressor damage due to high blade vibration amplitudes.

This behavior could have a number of possible causes. At the inlet of the CT slots, a separation bubble could establish due to the high incidence at low mass flow. This separation would cause a reduced recirculation velocity; hence, the axial velocity of the jet would be reduced. The filling of subsequent slots would include high entropy fluid that has already been recirculated. This process could reach a steady state with a given amount of fluid that is not transported downstream immediately after recirculation. A rotor tip bound vortex structure upstream the shock would be the result near stall, which is never the case for the smooth casing configuration as could be seen in the PIV measurements. Since the number of axial slots per rotor passage lies between 2.5 and 3, the energy content of the third blade passing harmonic could be explained by this theory. Harmonic resonance of the cavity due to its size is unlikely. This interpretation, sketched in Fig. 9 (b), could not be proven exactly using available data and is the subject of further investigation.

The reduced shock detachment with CT measured contrasts with investigations of axisymmetric casing treatments (Rabe and Hah, 2002), showing no significant influence on the relative shock position. Figure 9 (a) illustrates the different shock shapes and travel length of the tip leakage vortex, comparing CT and SC configuration. Fig. 10 shows pressure contours extracted from numerical simulations, described in Part 2. Comparison with the experimental data demonstrates the predictability of the CT influence. The flow structure in the blade tip region matches remarkably well for the operating points shown; only the shock detachment is underestimated in the calculations. However, the difference in shock position between the configurations at the NSSC point (Fig. 6 (a)) is also present in the simulations. Hence, the stabilizing effect of a shock located further downstream is considered. Since the exact value of this parameter influences the CT activity (as seen in the measurements), the focus of following investigations should be on these phenomena in order to improve prediction of compressor stability and efficiency with casing treatments.

CONCLUSIONS

The most significant difference between the smooth casing and the casing treatment configurations is reduced blockage in the blade tip region. The operating range of the compressor is increased significantly. The blockage could not be measured directly through the used instrumentation but the effects of blockage on shock position. The reduced blockage is connected with a reduced detachment of the blade leading edge shock with CT. Based on these results, it is assumed that the influence of
the CT on the compressor is a combination of two effects: the removal of fluid with low momentum and the reduction of shock detachment. The ejection of fluid downstream of the passage shock reduces the associated blockage, which leads to a higher axial Mach number. The removed fluid is accelerated through the slot pressure ratio and re-injected in a positive axial direction. Due to the reduced blockage and the higher upstream velocity, the shock position remains closer to the leading edge. This process enables the tip leakage vortex to absorb more energy from the main flow before passing the shock, hence reducing the tendency to break down. The recirculation velocity demonstrates predictable behavior until NSSC; for the highly throttled NSCT point, a reduced recirculation is observed. At the Design Point, the CT shows low influence and allows application to existing stages without stage matching problems. Regarding the throttled operating points, the skewed pressure and velocity profiles have to be considered.

The measurement setup with combined unsteady hot-wire and pressure measurements allows the characterization of the effects due to a casing treatment on a transonic compressor. The automatic detection of the shock detachment distance from unsteady wall pressure data was suitable for identifying an operating point during transient measurements. This procedure might be very useful for investigations close to the surge limit. The commonly used mass flow rate is difficult to measure exactly during transient measurements near stall. It may also be used as a validation criterion for numerical simulations.

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REFERENCES

References


