5th International Conference on Experimental Fluid Mechanics ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

Implementation and Experimental Verification of Active Flow Control by Jet Injection over a Coanda Surface in a Multi-Stage High-Speed Axial Compressor

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Abstract

Back in 2009, an until then successful method of implementing **A**ctive **F**low **C**ontrol (AFC) in the stator vanes of a high-speed 4-stage axial compressor failed for the first time, and the accident damaged almost the entire compressor blading. The AFC was implemented by the injection of high momentum fluid through a span-wise slot near the trailing edge of the vanes suction side. Downstream of the injection gap, the Coanda effect is used to prevent the separation of the flow.

As a result of the failure, the design and manufacturing process of the AFC vane were revised without making any changes in the 3D flow design in order to maintain the initial aerodynamic design intent. The new set of re-designed vanes was produced and successfully implemented into the first stator vane row of the 4-stage high-speed axial compressor to continue the AFC investigation.

First experimental results of the first stage AFC show that the overall compressor performance was maintained with respect to the isentropic efficiency and the total pressure ratio. However, on the other hand, the outlet flow angle of the AFC vane can be adjusted by means of different AFC **m**ass **f**low **r**atios (mfr).

1 Introduction

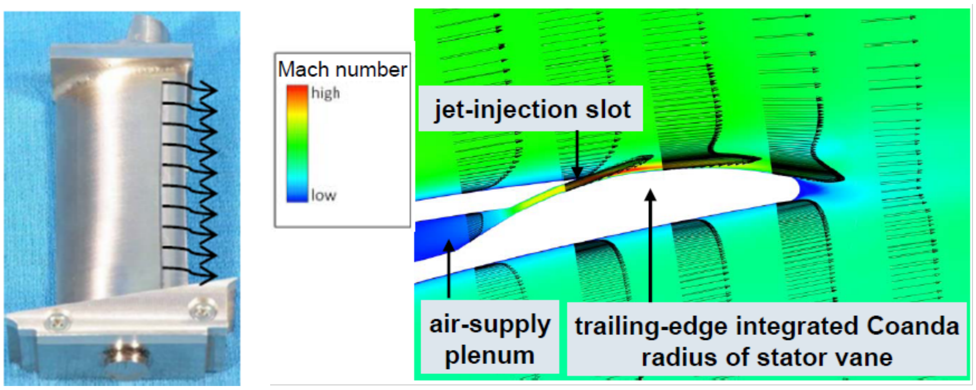
In March 2011, the Advisory Council for Aeronautics Research in Europe (ACARE) released the new vision ”Flightpath 2050”. This sets the goals for future innovations in aviation relative to the capabilities of typical new aircraft in the year 2000:

- carbon dioxide (CO2) emission reduction by 75%,
- nitrogen oxides (NOx) reduction by 90%,
- noise reduction by 65%, and
- ensuring recycling capability of air transport systems.

In aviation, different approaches to reach these goals are currently being investigated, including maintaining high power density at off-design conditions.

In aircraft engines, the axial compressor supplies highly pressurized air during the flight phases (e.g. taxiing, take off, climb, cruise, descent, landing approach, and landing), and therefore must cope with a wide operating range. The compressor is usually the limiting factor of the aircraft engine and off-design operation is particularly challenging for compressors. A traditional approach to handle a wide operating range is the use of variable stator guide vanes, but these vanes are associated with a number of considerable disadvantages (e.g. many parts, high weight, high complexity). The latest approach for ensuring the operability of the compressor and improving compressor performance is **A**ctive **F**low **C**ontrol (AFC) by jet injection, for which no moveable parts are needed.

The feasibility of AFC by jet injection is documented by multifarious authors. The injection of high momentum fluid near the trailing edge of a compressor stator vane has been demonstrated in previous investigations at the Institute of Turbomachinery and Fluid Dynamics. Guendogdu et al. (2008) and Vorreiter and Seume (2015) implemented an AFC stator vane equipped with jet injection and a Coanda radius near



(a) Outlet flow path at the AFC stator vane

(b) Numerical investigation of the jet injection

Figure 1: Jet injection over a Coanda radius (Siemann et al. (2017), edited from Vorreiter et al. (2012))

the trailing edge of the first stage in a four stage compressor rig (see Fig. 1(a) and 1(b)). Injecting 0.5 % of the compressor inlet mass flow maintained the outlet flow angle, despite a reduced vane number by 20 %, from 30 in the reference configuration to 24. A brief overview of newest numerical predictions, re-designed manufacturing and the latest comparison of numerical calculation and experimental investigation are given in this paper.

2 AFC by Jet Injection

The performance capability of compressor blades arises from the effective turning angle, which is the difference between the inlet angle of the flow β_1 and the outlet angle of the flow β_2. The higher the targeted turning, the higher is the tendency that the flow separates from the blade profile, which results in a significant decrease in performance. Guendogdu et al. (2008) and Vorreiter et al. (2012) described an approach to inject high momentum fluid in a stator near the trailing edge (see Fig. 1(a)) by guiding a secondary air flow through an inner plenum of the vane (see Fig. 2). The injected jet follows the blade surface along a Coanda radius at the trailing edge, which in turn leads to an adjustable outlet angle depending on the strength of the jet, defined by the AFC mfr

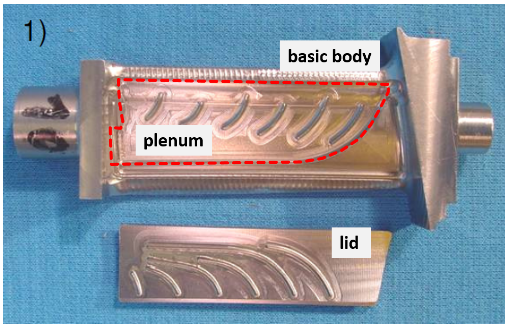


Figure 2: Former Coanda vane during manufaturing (edited from Guendogdu (2009))

$$mfr = \frac{\text{AFC mass flow}}{\text{compressor mass flow}}. \tag{1}$$

The enhanced turning allowed the outlet flow angle referred to the reference design blade number at the same time to be maintained, which then enabled the reduction of the number of blades by 20 % in the first stator row. Further numerical studies (Opitz (2017)) for the reference design number of blades predict a significant influence on the outlet flow angle β_2 at different mfr (see Fig. 3). Without any moveable parts inside the flow path, the outlet flow angle is varied by injected air supplied by an external secondary system. Higher

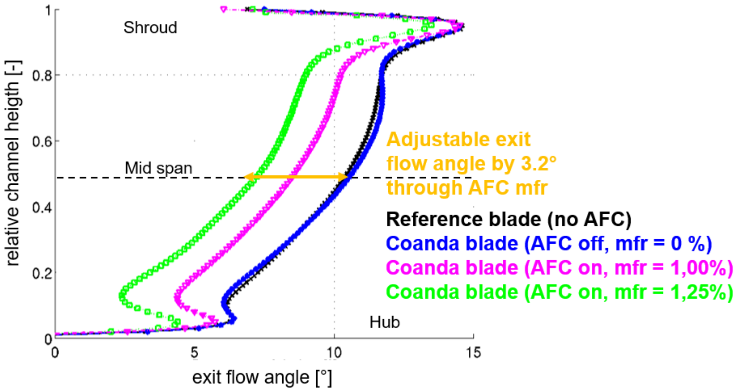
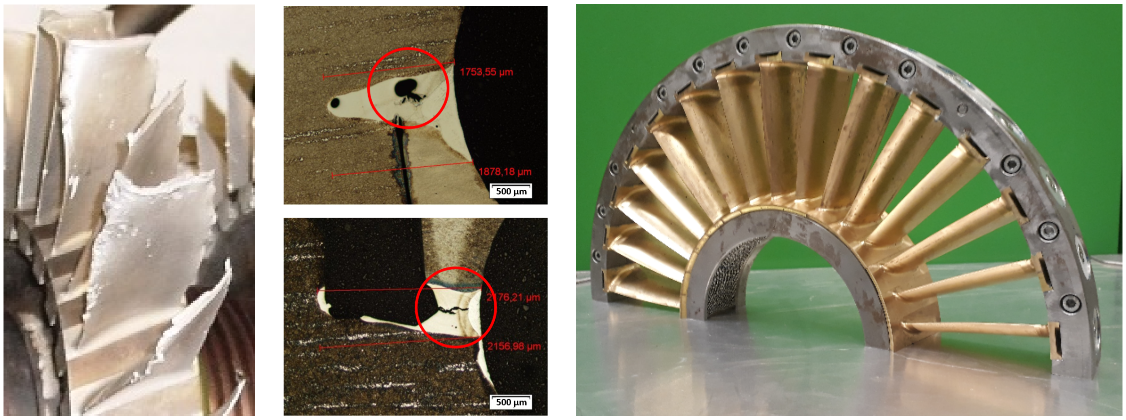


Figure 3: Different outlet flow angles by varying injected mass flow rate (edited from Siemann et al. (2017))

loaded compressor designs allow for higher pressure ratio and efficiency, at the cost of narrowed operability margins. The AFC by injection is intended to be used for stage matching during off-design operations to support the operability margin.

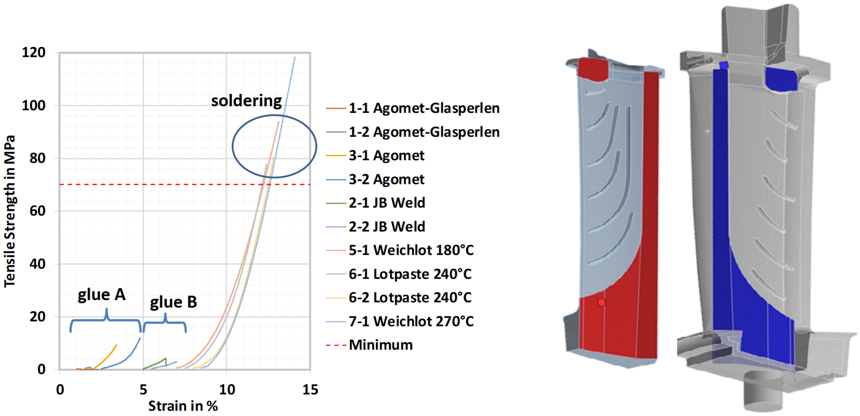
3 Failure Analysis and Re-Design of the AFC vane

As mentioned, a previous attempt of AFC implementation failed. The error pattern led to the conclusion that at least one lid of an AFC vane initially detached during operating at 17, 100 rpm and consequently triggered a chain reaction throughout the entire compressor. The free lid in the first stage caused further damages in other AFC vanes, and the resulting loose parts followed the flow path through the three stages downstream and damaged almost every blade (see Fig. 4(a)) and vane. Examinations of the vane probes with a welded connection between the basic body and the lid revealed defects in the weld (see Fig. 4(b)), and consequently, welding was excluded from the manufacturing possibilities to connect the body and the lid. The search for alternative manufacturing strategies also put rapid prototyping into focus, but nowadays it is not applicable due to the strength and surface quality requirements inside the plenum and the necessary reworking of the outer geometry. Therefore, two alternative joining methods, soldering (brass vanes) and gluing (aluminum vanes), were considered replace welding (steel vanes). Tensile tests (DIN 50125 and DIN ISO EN 4136) were conducted to identify the appropriate method. The results (see Fig. 5(a)) revealed gluing as unsuitable (< 20 MPa) and soldering as feasible (> 80 MPa) under real conditions regarding the required tensile strength (> 70 MPa). One strict boundary condition in the re-design process was to keep the



(a) Damaged rotor blades (b) Welding defects (c) Mounted AFC stator vane ring

Figure 4: Faillure analysis and final re-design



(a) Tensile strength tests (b) Re-designed vane

Figure 5: Re-design process of the AFC vane

existing 3D design and dimensioning of the AFC vane unchanged, including the inner plenum. As the two-part design had to be maintained, adjustments of the parting line were the only way to fulfill the geometrical requirements, namely shape and surface quality. Besides the necessary changes, the re-designing offered the possibility to solve some issues of the former design, which the technicians had to deal with at the milling machine. Some edges, grooves, indentations and faces are simplified to improve accessibility and prolong the service life of the milling tools, which led to the current design as shown in Fig. 5(b). The contact areas for the connection between basic body and lid were significantly enlarged to increase the capability to withstand tension stress. The height of the lid was increased, to ensure it reaches beyond the flow profile into the hub and shroud contour to allow for the mounting of additional screws and safety pins. The longer lid also ensures that it cannot leave its mounting location in the stator row ring even if the joint connection should fail.

The final manufacturing process starts with the two blanks, which are roughed into a workpiece with a raw outer surface, but with the final plenum contour and final contact areas. Soldering paste is applied to the contact areas, and the two parts are assembled and fixed with clamp devices for the next process step. The full package is heated in a soldering furnace to melt the soldering paste, while the clamps ensure the correct position and gap size. After a cooling slowly, the soldered brass parts are milled to the final contour and mounted to the full stator vane ring (see Fig. 4(c)), which is implemented into the first stage of the 4-stage axial compressor rig.

4 Performance of the AFC vane

The numerical performance prediction of the reference vane configuration and the AFC vane configuration without jet injection is verified in the experimental investigation (see Fig. 6). Even the slightly thicker design of the trailing edge of the AFC vane does not cause a significant reduction of the isentropic efficiency in the range from the **A**erodynamic **D**esign **P**oint (ADP) towards the ”choke line”. This confirms the aerodynamic design, which aims to maintain the aerodynamic behavior of the AFC vane without injection in respect to the reference design. Only in the operating range towards lower mass flow (”stall line”) than ADP, the efficiency of the reference slightly exceeds the AFC configuration due to the aforementioned thicker trailing edge. The AFC does not show major effects in the total pressure rise of the compressor. In fact, the pressure ratio at ADP is the same for the reference configuration, the AFC configuration without, and with jet injection. Only towards a higher compressor mass flow, the pressure rise increases slightly by 1.5 %.

However, a closer look on the experimental results of the AFV vane performance reveals the numerically predicted shift of the outlet angle β_2 depending on the injected mfr (see Fig. 7). The turning of the AFC vane increases with rising AFC mfr, but the numerically predicted effect exceeds the experimentally measured results.

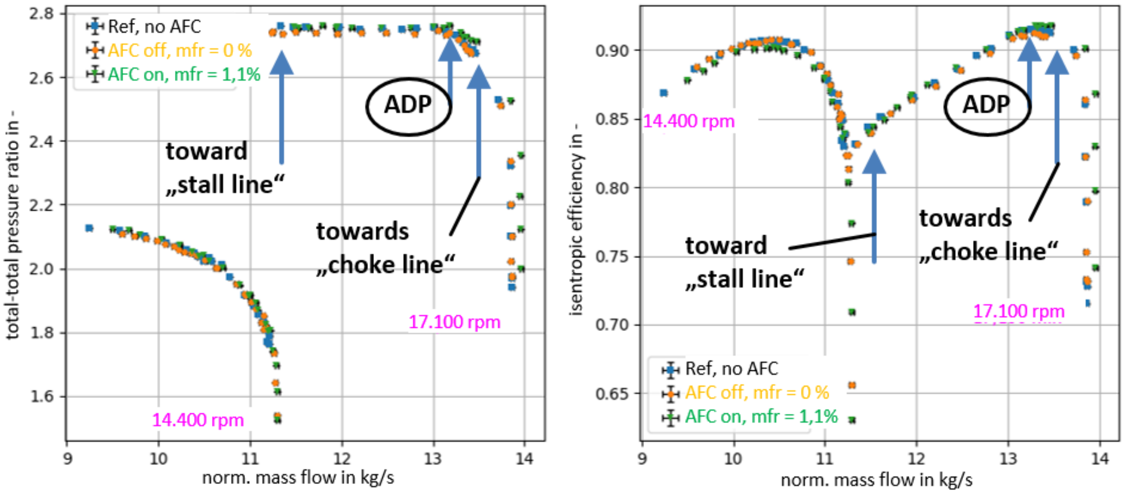


Figure 6: Speedlines of the reference and AFC (mfr off=0.0 % and mfr on=1.1 %) configuration at 14, 400 rpm and 17, 100 rpm aerodynamical speed

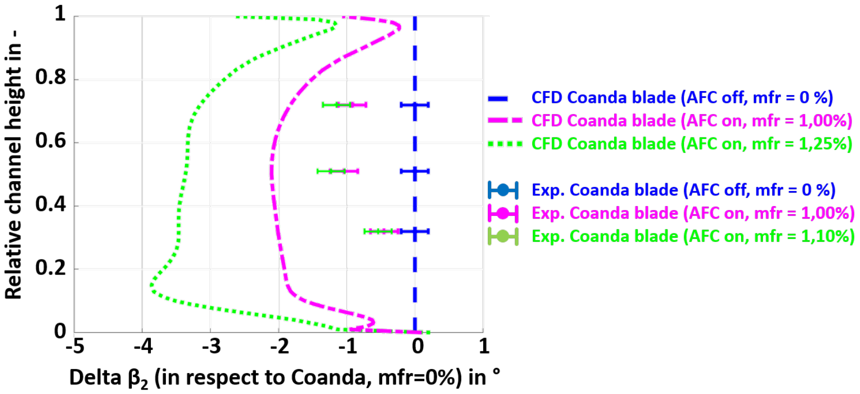


Figure 7: Experimental results of the outlet flow angle β_2 compared to numerical prediction

5 Conclusions

Active **F**low **C**ontrol is demonstrated using hollow stator vanes in a soldered two-part design. This approach does not require moveable parts inside the flow path. In the axial compressor, the AFC vanes achieve increased turning by increasing the outlet flow angle through injecting a small portion of the compressor flow through a 0.2 mm thin slot. The experimental results verify that the efficiency and total pressure rise of the AFC configuration without jet injection matches that of the reference configuration. For this reason, the flow does not require an active adjustment due to AFC at the **A**erodynamic **D**esign **P**oint (ADP). At ADP, injecting 1.1 % of the compressor mass flow achieved a 0.5 % increase in pressure ratio.
AFC by injection was found to be applicable to reduce the number of vanes in one stage but was not proven to be suitable for eliminating an entire stage of the compressor. Contrary to the initial assumption, that a stage could be eliminated thanks to a significant increase in pressure rise at the ADP, the main potential of AFC by injection over a Coanda radius near the trailing edge of the compressor stator vane is that...

(1) the pressure rise was increased at off-design conditions without a loss in efficiency, in the present case mass flows higher than at the ADP,

(2) a reduced number of vanes and thus solidity is feasible without loss in pressure rise and efficiency at the ADP, thereby reducing cost and weight, and

(3) no loss in efficiency occurs at operating points at which the AFC is not used.

Acknowledgements

This paper presents scientific result of a research project, sponsored by the German Research Foundation (DFG) under Grant No. SE 1023/12-02.

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