Planning of a compressor rig test with advanced inflow distortion simulation

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Abstract

The objective of the project is the generation of detailed experimental data to validate CFD of distorted intake flows and their interactions with the fan. Distortions as seen on engine installed on an aircraft in flight shall be simulated and analysed in a laboratory environment. The challenge is to combine realistic distortion patterns with a fan stage in laboratory environment for high fidelity measurements. In the first part of the project the focus was on the design of distortion generators placed upwind of the fan stage in the compressor test rig of the TU (Technische Universität) in Darmstadt, Germany. In cooperation with UniBW (University of Armed Forces) in Munich, distortion generating elements were defined with the aid of numerical simulations and PIV tests. The compressor will be run at two speed lines with and without distortions. At selected points, supplementary details of the distortion will be measured using PIV systems from the UniBW in Munich, a traversable Kulite pressure probe and total pressure rakes.

Nomenclature

M Mach number
CDI Circumferential Distortion Indicator
CFD Computational Fluid Dynamics
DFG Deutsche Forschungsgemeinschaft
DS Distortion Simulator
PIV Particle Image Velocimetry
RDI Radial Distortion Indicator

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1 Introduction

The presented work was carried out within the DFG Research Group "Simulation of wing and nacelle in stall conditions". Rolls-Royce leads the transfer project TP B5 and will perform a test which provides experimental data. The aim is to validate numerical methods for prediction of intake distortion during high incidence or cross wind and the associated interactions with the fan. To support the sub-projects dealing with simulation of distorted fan flow intake distortion similar to those that occur at high incidence are generated. The numerical modelling of the engine fan flow when subjected to asymmetrical flow enables the identification of issues at the boundary of flight conditions such as at high incidence angles or high crosswind in the early stages of the development of new modern light weight fan geometries. Hence complex engine and expensive flight testing can be reduced. Furthermore it is necessary to expand the existing experimental database with data from a coupled system (intake and fan) and to implement modern optical measurement techniques to obtain the required local flow measurements needed to validate numerical methods. The experimental data as well as the understanding from the coupled CFD will be used to improve the Rolls-Royce simulation methods. The conclusions from the DFG sub-project dealing with turbulence in the atmosphere will enable further understanding related to the characteristics of atmospheric disturbances and their influence on intake flows.

2 Intake Distortion Fan Interaction

2.1 State of the Art

During flight maneuver as well as in crosswind conditions, the engine intake stall results in highly inhomogeneous flows being subjected on the fan or even results in the intake flow completely separating. The design rules and the fundamentals of separated flow phenomenon of engine intakes are described in [1, 2]. More recent work for the A340/Trent 500 [3] and the NIMROD/BR710 [4] highlights the industry working procedures with respect to the use of numerical methods (CFD) and experimental investigations. Details of the particularities of ground effects during crosswind and the interaction with the fan can be found in [5]. Similarities with the fundamental phenomenon seen on an airfoil have been observed such as the growth of the boundary layer with high pressure gradients, shock induced separation as well as transitional separation with reattachment. The fan feeds energy into the internal flow and interactions occur between the separation (inhomogeneity) of the flow and the energy fed back by the fan (boundary condition). The efficiency and the working line of the fan as well as the local mass flow through the fan during separation are altered due to these intake/fan interactions. It is widely accepted that these factors weaken the separation. This flow behavior has also been underlined by numerical simulations [6, 7]. Hence it is assumed that intake model testing without a fan representation is conservative considering the strength/magnitude of the separation. This usual assumption should be verified by intake separation measurements in the presence of a fan and by the comparison to measurements ignoring the influence of the fan. Furthermore such results can be used to validate coupled numerical solutions. Comparisons between low turbulent wind tunnel test results and free field measurements introduce questions relating to the read across of onset off boundary layer separation. Obviously interactions with the atmosphere play a similar role as they do for airfoils. The design of an engine nacelle starts with the sizing of the diameter of the intake relative to the maximum engine intake flow in the flight envelope. The Mach number at the smallest diameter section (intake throat) should always be clearly below M = 1 at design conditions. The contraction ratio from highlight to throat then governs both the behavior during high incidence or in crosswind conditions and the external dimensions of the nacelle. The contraction ratios are governed by manufacturer specific recommendations with small variations. Nacelle shapes, similar to ellipses and their aspect ratio vary only slightly from model to model and change only circumferentially for underwing applications with high incidence angle requirements. Profiles and parameters are based on comprehensive tests by Rolls-Royce in the late 60s as mentioned in [1] and project to project experience. Due to the high risks associated to engine development (late restrictions to the operating procedures due to distorted intake flows) numerical methods today are used mainly during the analysis phase of the classical designs and experiments are still preferred for new designs.

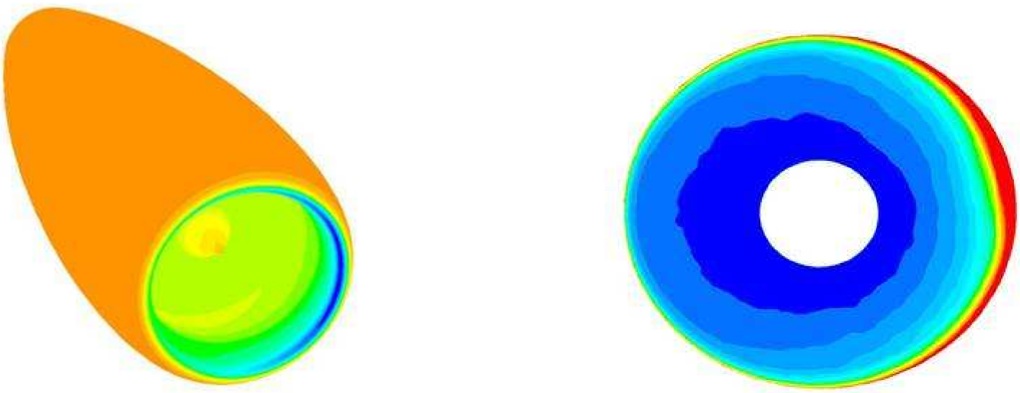

Figure 1: Disturbed flow in an isolated engine intake under crosswind from right (left figure: static pressur, right figure: total pressure loss at the fan face)

Figure 1 shows an engine nacelle in crosswind computed using a RANS code without representation of the fan. The figure on the left illustrates the increase in pressure that indicates highly supercritical flows on the internal surface. The figure on the right illustrates the total pressure at the end of the intake diffuser (fan face). The total pressure losses due to the weakening boundary layer can also be identified on the external section. During the latest Rolls-Royce Deutschland projects an inverse design approach for the external nacelle aerodynamic lines has been followed by implementing a Navier-Stokes code developed with DLR [8, 9]. However the design of the internal aerodynamic lines follows the classic procedure. The computation of the boundaries of the incidence capability (onset of separation) is obtained using a coupled potential code with boundary layer calculations and flow transition predictions. The distortion levels caused by intake flow separation in crosswind that are required to determine the stability boundary of the fan are obtained experimentally at model scale in the ONERA F1 wind tunnel (see figure 2) without fan representation or by testing at full scale in presence of a crosswind blower (see figure 3).

The crosswind engine test with the fan which represents the baseline configuration for certification determines the limits of the coupled intake/fan system and results in the engine release for flight testing. The loads and vibrations (oscillations) of the fan blades as well as the engine stability are the measurement parameters used to establish the limits. Physical flow phenomena are not measured. At present it is not possible to numerically compute these limits quantitatively. Continuous validation of numerical methods is required as well as the support by fundamental experiments. Transonic compressor test beds such as the rig constructed at the TU in Darmstadt are available for such experiments [10, 11].

Figure 2: Model scale intake test in crosswind without fan in the ONERA F1 wind tunnel at full scale Reynolds numbers

Figure 3: Engine test in crosswind at Rolls-Royce Stennis test facility

2.2 Relevance in Engine Design

Distorted flow in the intake of an aircraft engine cause the fan blades and core compressor stages to run in off design conditions. The fan and compressor is designed in the first place for homogeneous distribution of static and dynamic pressure of the oncoming flow. The design thus focuses on unsteady rotor stator interactions. Due to distortions in the intake flow this may be overlayed by either spatially distorted intake flow or unsteady distortions in the intake. Both are time variant in the rotating frame of reference of the rotating fan/compressor blades. Local significant changes in pressure ratio/mass flows and/or velocity triangles can cause mechanical excitation of the blades, stall or compressor surge.

For certification of the engine installed on a specific aircraft it has to be shown, that the engine is operating stable and without hazardous blade/disc stresses at all conditions within a specified operation envelope. Critical conditions are in flight situations with high angle of attack and/or yaw angles and ground operation in crosswind. Distortions can be caused by external sources such as the wing, fuselage or ground vortices and by flow separating in the intake.

Thus the position of the engine on the aircraft relative to possible sources of distortion, the sizing of the intake throat and the local aerodynamic contouring of the intake can avoid intake distortions. The distortions interact with the fan and are possibly modified by the presence and reaction of the fan. This phenomena is not well understood and simulation techniques are rare. This needs to be improved to lower development risk and to avoid need of too much conservatism in the design of the isolated components.

2.3 International Standards

An engine is certified according to the rules described in CS-E500/650 and the aircraft for FAR25-939. These regulations describe, that the engine needs to be free of hazardous stresses and operable in all relevant conditions. The certification rules do not go into technical details of how this has to be done.

Common practise is to use distortion descriptors for the interface of intake and fan. Thus the fan and intake can be tested isolated against the specified and agreed distortion levels ahead of expensive flight testing. A variety of distortion descriptors are given in ARP1420 [2]. They are mainly divided into radial total pressure shape variation (RDI) and circumferential spatial harmonic distributions (CDI).

Tests at Rolls-Royce in the 1960s [1] have shown that circumferential distortions in a 60 degree segment cause the worst effects on compressors. Therefore the DC60 which is a special form of CDI is used since for engine certification.

2.4 Engine and Rig Testing

During flight testing (in flight and ground handling) it is demonstrated that the engine works properly within given flight envelope and crosswind limitations. In addition the fan blades and disc are instrumented with strain gauges to show that the stress stay within the endurance limits.

For risk mitigation engine and aircraft compatibility can be shown in advance by engine testing with simulated distortions. In flight distortions are measured with an instrumented through flow nacelle installed on an aircraft wind tunnel model. The tests are performed for high speed and low speed with flaps and spoilers. The distortions are specified in terms of DC60.

The isolated intake is model tested in high angle of attack conditions and crosswind to prove the sizing and aerolines fulfill the specifications. The instrumentation allows to specify RDI and CDI values.

The fan may be tested in model scale using distortion screens. The screens simulate spacial distortions in total pressure, mainly in terms of RDI (boundary layer) and DC60.

3 Experimental Setup

3.1 Transonic Compressor Rig

The TU Darmstadt single stage transonic compressor rig is operated as open circuit (Fig. 4). Ambient air is sucked into a settling chamber. From there the air is directed into the compressor via a calibrated nozzle to measure the mass flow rate. After passing through the compressor the air is exhausted to ambient through a ring diffuser and a throttle. An 800 kW D/C-drive linked to a planetary transmission and a torque-meter drives the compressor rotor. Its external diameter is 0.38 m and its hub to tip ratio is 0.51. A mass flow of 16.0 kgs and a pressure ratio of 1.5 can be achieved. The mechanical shaft speed limit is $20,000$ rpm. Hence the typical flow conditions of an engine fan stage can be obtained.

Total pressure and total temperature rakes as well as static ports are fix mounted downstream of the compressor section. Radially traversable probes may be inserted at different axial and circumferential positions. Darmstadt-Rotor-1 (Fig. 6) will be used in this project together with the Darmstadt-Stator-1. This rotor was developed by *MTU AeroEngines* as a baseline design for the test rig in the early 1990s [10, 11]. It represents a typical, highly loaded rotor with sixteen radially staged controlled diffusion airfoils.

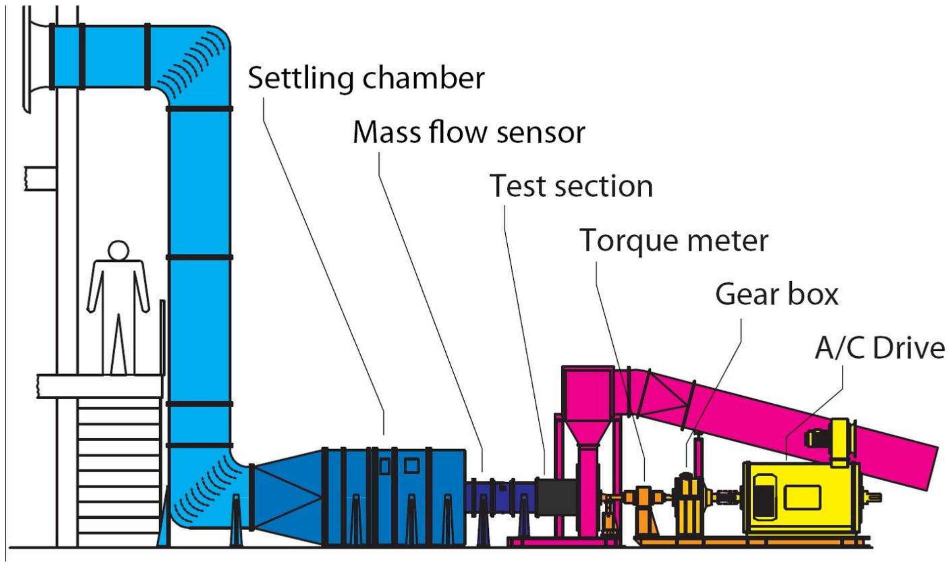

Figure 4: Transsonic compressor rig at the TU Darmstadt

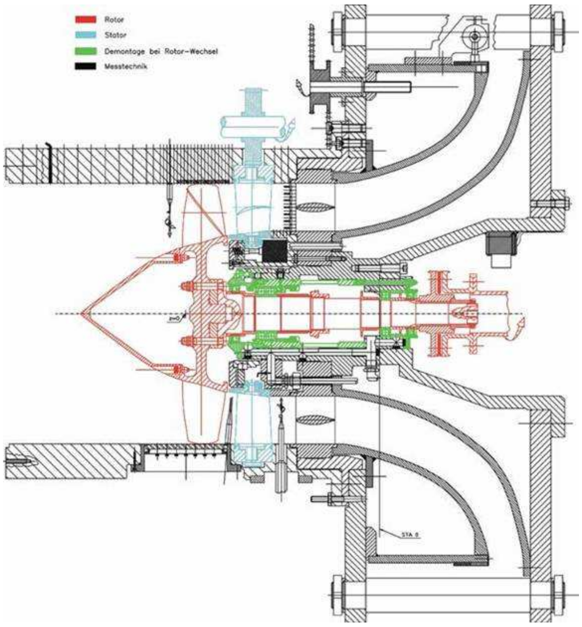

Figure 5: Details in a vertical cut of the compressor

Figure 6: Titanium blisk Rotor 1

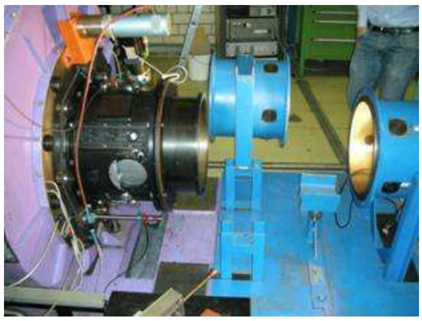

Figure 7: Removable onflow section into the compressor

3.2 Distortion Simulator

The design of an appropriate distortion simulator has shown to be more difficult than expected. It is usual praxis in civil engine design to use distortion screens in front of compressors which generate a total pressure loss (steady state) in the shape of a circumferential segment or radially in the shape of a boundary layer (see figure 8).

The DFG project deals with stall in distorted atmospheric onflow which includes highly dynamic effects. Therefore the focus of the authors is vortex shedding from lip separation, similar to boundary layer shock interaction of an airfoil with separation (i.g. OAT15A airfoil [12]). The separation in the intake (isolated, without compressor) is studied in more detail in the EU project ATAAC (Advanced Turbulence Simulation for Aerodynamic Application Challenges). Unsteady DES simulation will be available at the end of the ATAAC project. It is expected, that vortical flow is shed from a separation bubble. A subsonic separated nacelle intake is investigated within the DFG project by the UniBW (University of armed forces in Munich), the same group which will perform the PIV measurement in the TU Darmstadt rig.

The first design was a backward facing step in the tube in front of the rotor. Numerical

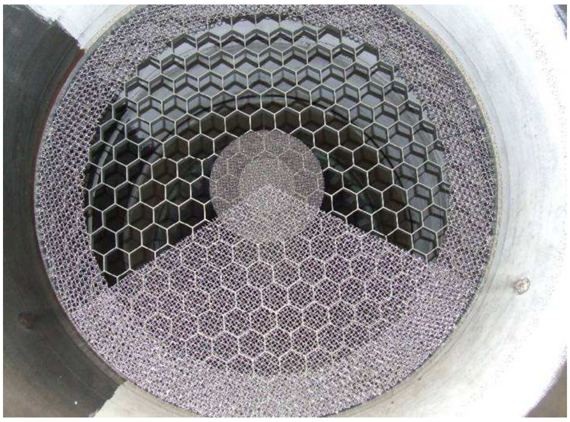

Figure 8: Distortion screens used to provide total pressure loss patterns in terms of CDI and RDI

simulations have shown that due to the Reynolds numbers and the accelerating flow in front of the rotor the recirculation zone is small and quite stable. Distortions in terms of DC60 are lower than -0.1 and will not cause significant effects on the rotor. The total pressure distribution calculated by CFD (URANS) is shown in figure 9.

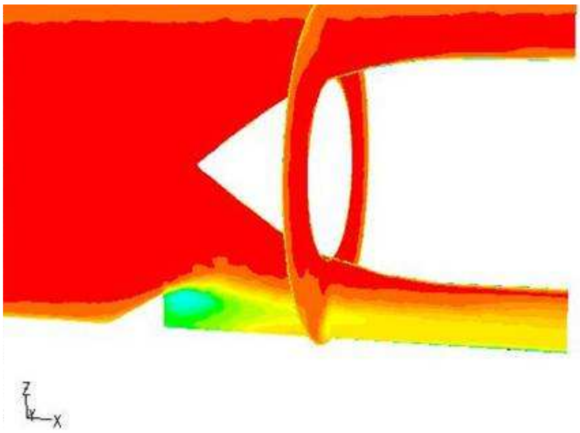

Figure 9: Total pressure simulated by CFD of a backward facing step type distortion generator implemented in the TU Darmstadt compressor rig

The second design is the so called “Wirbel-Blende” which is shown in figure 10.

It is basically a hexahedron in crossflow. The hexahedron is curved parallel to the duct walls and extends 60 degree in circumferential direction. With the aid of analytical methods the dimensions were set by UniBW such that a 400 Hz vortex shedding is expected. A pre test with a straight hexahedron performed by UniBW in a transonic wind tunnel using the PIV technique has verified the design. Vortices were shed at a frequency of 400 Hz and were still visible 200 mm downstream of the distortion generator. There is still a risk that vortices will not be shed as expected because the design in the compressor rig is curved and the flow accelerates. In order to mitigate the risk numerical simulations were started. Due to high dependencies on the mesh the frequency found in the wind tunnel test could not be reproduced until today. The numerical work is ongoing.

As a fall-back a second distortion simulator was designed and investigated in the wind tunnel. It is a half delta wing which generates a longitudinal vortex. From aircraft and engine

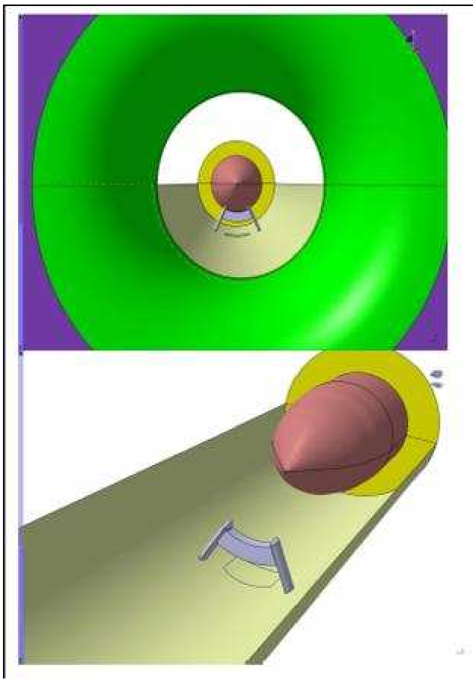

Figure 10: "Wirbel-Blende" or vortex generator

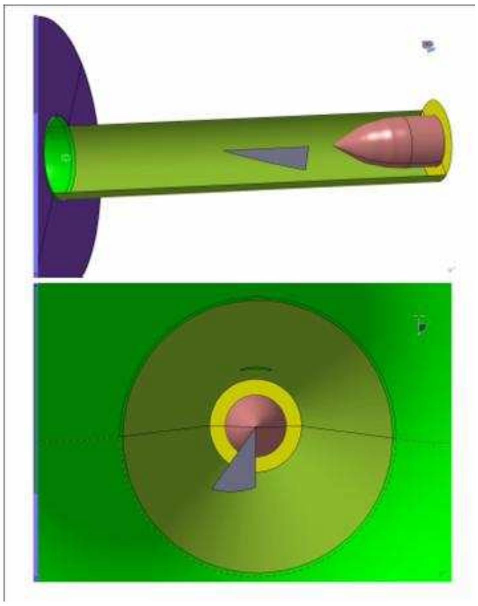

Figure 11: Delta wing

tests it is known that vortices are generated by flaps/spoilers on the wing or arise from boundary layers on the ground (ground vortex) or the fuselage. This kind of distortion is simulated with the half delta wing. It is assumed, that this design will work properly and reduce the risk of not generating any distortion affecting the rotor during the test campaign.

3.3 Measurements

The compressor rig provides a standard instrumentation for measurement of the compressor characteristics. This includes the measure of mass flow through the compressor and total pressure and temperature in front and behind the compressor stage. Total values in front of the rotor are taken in the settling chamber. Behind the stator and in front of the struts five total pressure and temperature rakes are located at different circumferential positions. They are distributed such, that they provide a representative circumferentially averaged total pressure behind the stator guide vanes instantaneously. To get a more accurate averaged total pressure the stator can be rotated. This rotation needs additional time (20 minutes) for each stabilized point on a rotor speed line.

The standard measurements of the rig deliver:

- Mass flow
- Inlet total pressure and total temperature
- Total pressure and temperature behind the stator
- Rotational speed
- Torque

To enable the measurements in front of the rotor and downstream of the distortion simulator the compressor rig needs to be equipped with additional probes and access for PIV. Figure 12 shows a sketch of the planed modifications and measurement planes.

A quartz glass for PIV access will be placed in the casing between the distortion generator and the rotor (see figure 13). A radially movable total pressure probe will also be placed between distortion simulator and rotor. This enables the measurement of the distorted flow in front of the rotor with the rotor present. The circumferential position of the pressure probe is fixed and therefore the distortion simulator will be movable in circumferential direction.

The distorted flow will be measured:

- At a fixed circumferential position of distortion relative to the stator rakes, PIV and pressure probe will measure radial and circumferential profile of the distorted flow (distortion simulator and stator will move synchronously)
- The pressure probe moves radially
- The PIV sheet will be located in the middle of the "Wirbel Blende" (radial cut, axial&radial coordinates)

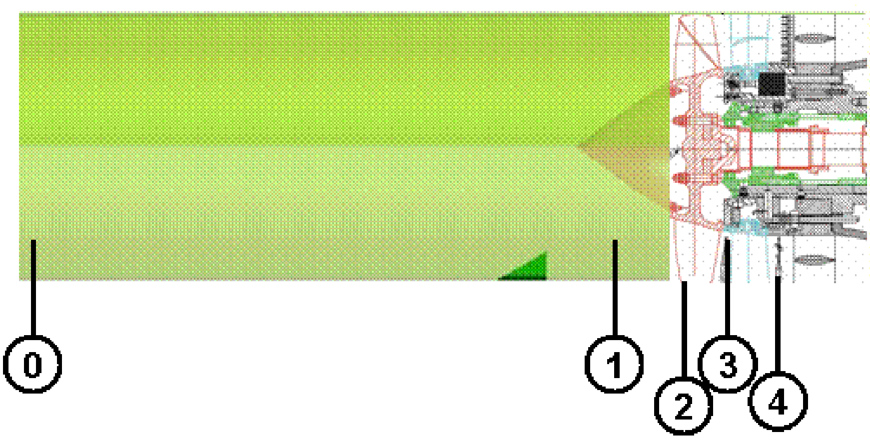

Figure 12: Schematic view of the TUD compressor rig showing new parts and measurement sections

Station	Description	Traverse
0	Undisturbed inflow P_t, T_t	none
1	Distortion, Kulite and PIV	Kulite: radial
2	Tip-Timing	none
3	-	Optional Kulite radial
4	After stage	2 Rakes, rotation

3.3.1 Pressure Probe

Within this project a time-resolved pressure probe requires designing and manufacturing. The probe will be housed in a prismatic body to enable radial positioning. Using a piezoresistive

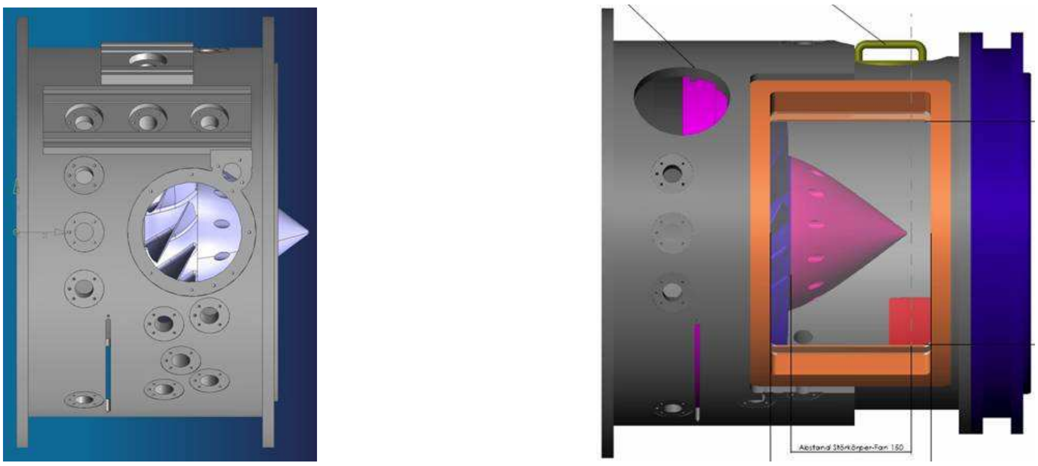

Figure 13: Original rotor casing (left) and new design (right) with PIV access (window made out of quartz)

sensor in the middle it is possible to measure the pressure up to 100 kHz. Two static pressure holes on both sides of the probe will enable to calculate the static pressure and the whirl angle of the flow. During the measurement campaign the probe is traversed radially at different angular positions of the distortion simulator resulting in a complete measurement of the distorted flow past the distortion simulator.

3.3.2 PIV

Laser measurement techniques that measure the flow in the gap between the blade and the measuring section have been attempted/proven at the TU Darmstadt. For the new configuration the flow forward of the rotor shall be measured. In cooperation with UniBW a glass section will be included in a similar manner to that of the rotor section into the intake of the rotor to enable optical access (See figure 14).

The PIV system was tested with two representative distortion simulators in the transonic wind tunnel at UniBW. It has been shown that time resolving unsteady PIV needs light intensities which are hard to get in the TUD compressor rig. It was therefore decided to use stereoscopic PIV which will deliver time averaged axial, radial and circumferential velocity components in a radial cut between the distortion simulator and the rotor face. These time averaged velocities will be used to validate numerical methods. For security reasons the PIV will be remote controlled from the control stand outside of the room where the compressor rig is located.

3.3.3 Tip Timing

During the test the blade vibrations will be monitored by a tip timing system. The operating points of the compressor were chosen such that they are not close to a critical vibration mode. Nevertheless torsional and flap modes will be monitored during the test to avoid harmful blade vibrations during the test with significant inlet distortions.

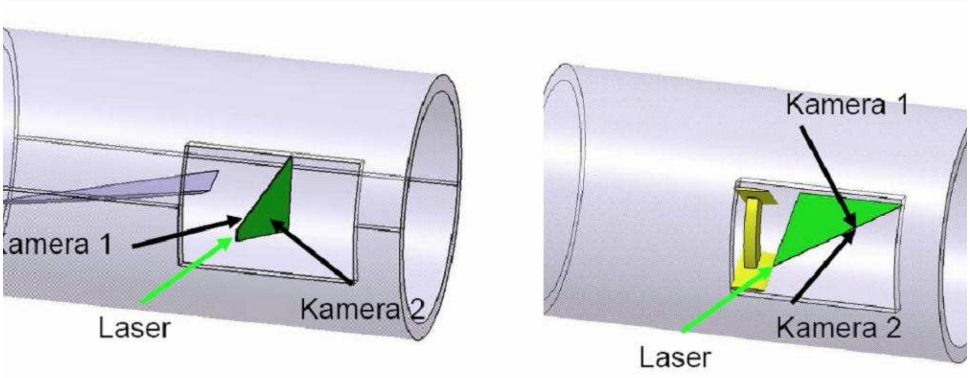

Figure 14: Sketch of the PIV setup showing the laser sheet

4 Test Plan

4.1 Overview

The test rig provides a broad mapping of the fan compiled from pressure ratios plotted against mass flow and the corresponding coefficients and rotational speeds. Further speed lines are included up to the surge line at different flows. Comparisons of the map with and without distortion are made. The objective is to capture the displacement of the surge line due to distortion. Regions that portray blade vibrations that could lead to blade rupture are excluded.

4.2 Configurations

For repeatability of former test campaigns and comparison with the main test the compressor will be tested with the new casing but without distortion simulator at some limited conditions where data exists with the original casing.

The second configuration is the vortex generator as shown in 10. The focus will be on this configuration since it is assumed that it is most representative for lip separation.

Due to risks related to this configuration a third configuration was designed and will be used if the vortex generator fails or if test time is left after the test of the vortex generator. The third configuration is the delta wing as shown in figure 11. The half span delta wing will generate a longitudinal vortex which is representative for distortion sucked in from outside of the intake (i.g. ground vortices).

4.3 Test Conditions

The rig will be tested at rotor speeds of 65% and 100%. Most of the data from former tests are available for those speeds. These speeds are also most suitable to avoid blade vibrations. By varying the mass flow the rig can be run along a speed line to pressure ratios up to the stability line. In the present test we will focus on two pressure ratios on both speed lines, which results in four conditions where the complete test and measurement program should be performed.

Pre tests with distortions will be performed to define the points close to the stability line of the distorted compressor. These points should be close enough to the stability line to show some effects in the compressor flow and possible interaction with the disturbance. On the other hand any risk to harm the rig needs to be avoided and a certain stability/repeatability for the flow is needed for the detailed high quality measurement aiming at CFD validation. The other points will be placed in a region typical for design conditions with relevant pressure ratios and stable flow through the compressor.

4.4 Test Program

Using the distributed rakes behind the rotor stage the pressure ratio can be determined without traversing for standard flow conditions. As such the rig will be rerun along the stability line for comparison of the new casing with the standard one. When the rakes (more precisely the stator) need to be traversed circumferentially to capture the pressure ratio in case of inhomogeneous flow behind the stage, especially for disturbed flow, each condition needs about one hour. Two to four detailed measurements of the pressure ratio will be needed to find and fix the high pressure conditions on each speed line for disturbed flow, were Kulite and PIV measurements will be performed. For identifying the stability it may not be necessary to rotate the stator 360°.

The pressure losses due to rotor and stator (behind the compressor stage) will be measured without distortions for validation of the numerical simulations of the baseline undistorted compressor stage at the four identified points. This will also be the baseline for comparison with the distorted total pressure profiles behind the stage. The stator should be rotated by 90° at least.

Measurements at all four points will then be performed with a distortion simulator which generates vortex shedding at a frequency of about 400 Hz. Due to the presence of circumferential distortion the stator needs to be rotated together with the distortion by 360°. This corresponds to a 360° traverse of the total pressure rake. The position of distortion relative to the stator is fixed.

At the four conditions the flow field in front of the rotor will be measured with the Kulite probe and the PIV system. The Kulite will be traversed in radial direction and the distortion simulator together with the stator in circumferential direction. The Kulite will thus perform unsteady measurement of total pressure over a to be defined time period at different radial and circumferential positions behind the distortion simulator.

In case of the PIV only the mid plane will be measured. Therefore nothing needs to be rotated in this case.

	description	time	comments
1	Run 2 speed lines	4 h	No rotation, comparison with former tests
2	Identify test points on speed line	8h	Rotate stator and DS (360° or less) and identify high pressure points close to stability line with distortion
3	Compressor characteristic baseline	4h	Measure pressure ratio and mass flow for four conditions in undisturbed flow (Rotate stator 90° min)
4	Compressor characteristic disturbed	4h	Measure pressure ratio and mass flow for four conditions in disturbed flow (Rotate stator and DS 360°)
5	Kulite tests	1 days	Kulite measurement for disturbed flow, rotate DS and move Kulite
6	PIV Measurements	2 days	PIV measurements for disturbed flow, no rotation.

5 Conclusion

The test planning is progressing well. The hardware design is finished and fulfills the need of optical access and traverse of the pressure probe. The test will deliver unsteady data in an axial cut and spatial distribution of the mean velocity field in a stream wise cut. This will support the validation of unsteady CFD simulation of the coupled system. The rig with the new hardware offers the possibility of further measurements between rotor and stator and unsteady PIV upstream of the rotor. About two weeks additional test time would be necessary to perform these additional tests.

A distortion simulator with vortex shedding is the baseline. Since the unsteady CFD of the distortion simulator within the rig was not finished before the hardware manufacturing had to be started a second simulator was designed and can be used in case the baseline does not generate sufficient distortion in the rig environment. The pre tests in the transonic windtunnel at UniBW successfully proved the basic design of the simulators and the PIV setups for stereoscopic and time resolving PIV.

Acknowledgments

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