

Adaptation of a Transonic Test Turbine Facility for Experimental Investigation of Aggressive Intermediate Turbine Duct Flows

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ABSTRACT

The design of aero engines with a further increased bypass ratio will lead to low pressure turbines of lower speed and larger diameters. The flow leaving the high pressure turbine has to be guided to an entry at a greater diameter safely without any separation or flow disturbances. To save weight and costs this intermediate turbine duct has to be as short as possible. One goal of the EU-project AIDA (Aggressive Intermediate Duct Aerodynamics, Contract: AST3-CT-2003-502836) is to provide insight to these problems by doing cooperative CFD work and measurements by the partners.

To investigate the limits of such a non-separating high diffusion duct flow a detailed test arrangement under engine representative conditions is necessary. Therefore, the continuously operating Transonic Test Turbine Facility (TTTF) at Graz University of Technology has been adapted:

An aggressive (high diffusion) intermediate duct is arranged downstream of a new designed HP turbine stage providing an exit Mach number of about 0.6 and a swirl angle of -14 degrees. A second LP vane is located at the end of the duct and represents the counter rotating low pressure turbine at larger diameter. A following deswirlor and a diffuser are the connection to the exhaust casing of the facility. The aerodynamic design was done by MTU Aero Engines.

Detailed measurements will be performed with conventional (pressure and temperature probes) as well as with optical measurement techniques (triggered three-component stereoscopic Particle-Image-Velocimeter, 3C-PIV, two-component Laser-Doppler-Velocimeter, 2D-LDV) at different operating conditions to gain a unique database for intermediate turbine duct flows.

The inner wall of the turbine intermediate duct is equipped with large windows to provide optical

access to the whole flow field. A laser light sheet visualization and an oil film visualization of the surface flow are also possible. Both stators are fully rotatable to adjust the circumferential measurement position without moving the optical setup.

NOMENCLATURE

Symbols

AR	[-]	= $A_{\text{exit}}/A_{\text{inlet}}$ area ratio
α	[deg]	swirl angle
C	[mm]	chord length
c_{ax}	[mm]	axial velocity
d_{TE}	[mm]	trailing edge thickness
h	[mm]	average blade height
H	[J/kg]	enthalpy
l	[mm]	axial duct length
l/h_{inlet}	[-]	dimensionless duct length
T	[K]	temperature
u	[m/s]	circumferential velocity
$\Delta H/T$	[J/(kg K)]	specific turbine work
$\Delta H/u^2$	[-]	loading coefficient
c_{ax}/u	[-]	flow coefficient
t/C	[-]	pitch to chord ratio
h/C_{ax}	[-]	aspect ratio
Ma	[-]	Mach number
Re	[-]	Reynolds number

Abbreviations

AIDA	Aggressive Intermediate Duct Aerodynamics (EU-project)
ADP	aero design point
LP	low pressure
HP	high pressure
CFD	computational fluid dynamics
TTTF	transonic test turbine facility
3C-PIV	Particle-Image-Velocimetry
2D-LDV	Laser-Doppler-Velocimetry

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INTRODUCTION

In multi-spool jet engines the low-pressure (LP) system has a much lower rotational speed and larger radius than the high-pressure core system. Therefore, S-shaped transition ducts are necessary to connect the large-diameter LP system to the small-diameter HP system.

Demands on improved efficiency and reduced noise levels lead to engines with very high by-pass ratios. This trend towards engines with large fans and small high-pressure-ratio cores gives larger radial differences and a need for more aggressive intermediate ducts to connect the different modules.

Figure 1 shows an example for an intermediate turbine duct (ITD) of a recent jet engine. It is obvious that more aggressive and shorter ducts can help to reduce the length and the weight of the engine significantly. It becomes clear that new aggressive duct designs are an enabling factor for future generations of efficient low-noise ultra-high-by-pass-ratio commercial jet engines

To investigate the flow physics in aggressive intermediate turbine ducts and the interaction between the neighbouring components a detailed test arrangement under engine representative inlet conditions is necessary. Therefore, the continuously operating Transonic Test Turbine Facility (TTTF) at Graz University of Technology has been adapted.

The flow field and interaction mechanisms that occur in low-aspect-ratio high-pressure turbine stages are highly three-dimensional due to the effects of secondary and tip-leakage flows. In recent years increased research work has been performed in high-speed engine representative facilities to investigate these interaction mechanisms, e.g. [1], [2] and [3]. Where the investigations in [1] and [2] were carried out in short duration test facility, the flow measurements of [3] were gained in the continuously operating facility presented in this paper. Less research work has been published describing the development of the exit flow from a transonic turbine stage within an inter-stage diffuser, e.g. [4], [5] and [6].

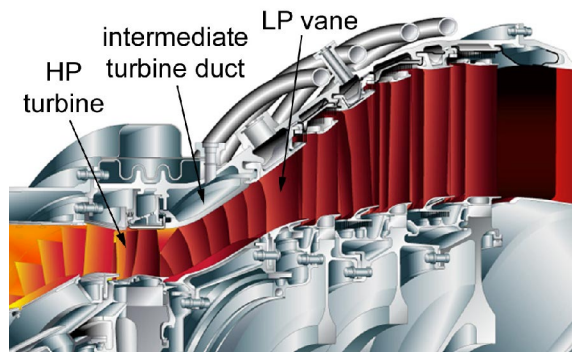


Fig. 1: Intermediate turbine duct (PW6000)

The AIDA project tries to eliminate this lack of information by building up an engine representative test rig within the TTTF of Graz University of Technology. This rig consists of a transonic high-pressure turbine together with an aggressive intermediate turbine duct and the first vane row of the downstream arranged low-pressure turbine. The continuously operating test facility allows besides the use of conventional and fast response aerodynamic probes the application of modern laser-optical measurement techniques, e.g. three-component stereoscopic Particle-Image-Velocimetry [7], for investigation of the unsteady interaction between the components. Therefore, the whole intermediate turbine duct is fully optically accessible through window inserts in the inner wall of the flow channel.

The investigation will allow the development of a new class of very aggressive intermediate ducts and will help to establish validated analysis methods and “CFD Best Practice Guidelines” for duct flows.

TEST FACILITY

The transonic test turbine facility (TTTF) of the Institute for Thermal Turbomachinery and Machine Dynamics at Graz University of Technology is a continuously operating cold-flow open-circuit plant which allows the testing of turbine stages with a diameter up to 800 mm in full flow similarity (corrected speed and pressure ratio) due to its modular design. All casing parts are split horizontally for easy maintenance and quick modification of the test setups. An overhung-type turbine shaft allows an easy disk assembly without dismantling the bearings. The facility is also equipped with cooling air flow supply for vanes, blades and cavities.

The facility is driven by pressurized air delivered by a separate 3 MW compressor station in the second basement of the institute. This compressor station consists of two centrifugal compressors and two screw compressors which can be connected together with two coolers to 14 different types of operation (serial, parallel and mixed types, with and without cooling and/or intercooling).

The shaft power of the test stage drives a three-stage radial brake compressor. This brake compressor delivers additional air mixed to the flow from the compressor station and increases the overall mass flow (see Fig. 2). The air temperature in the mixing chamber (turbine stage inlet) can be adjusted by the coolers between 40 °C to 185 °C. The maximum shaft speed of the test rig is limited to 11550 rpm. Depending on the stage characteristic a maximum coupling power of 2.8 MW at a total mass flow of 22 kg/s can be reached. Detailed information on the design and construction of the facility can be found in [8], on the operation in [9].

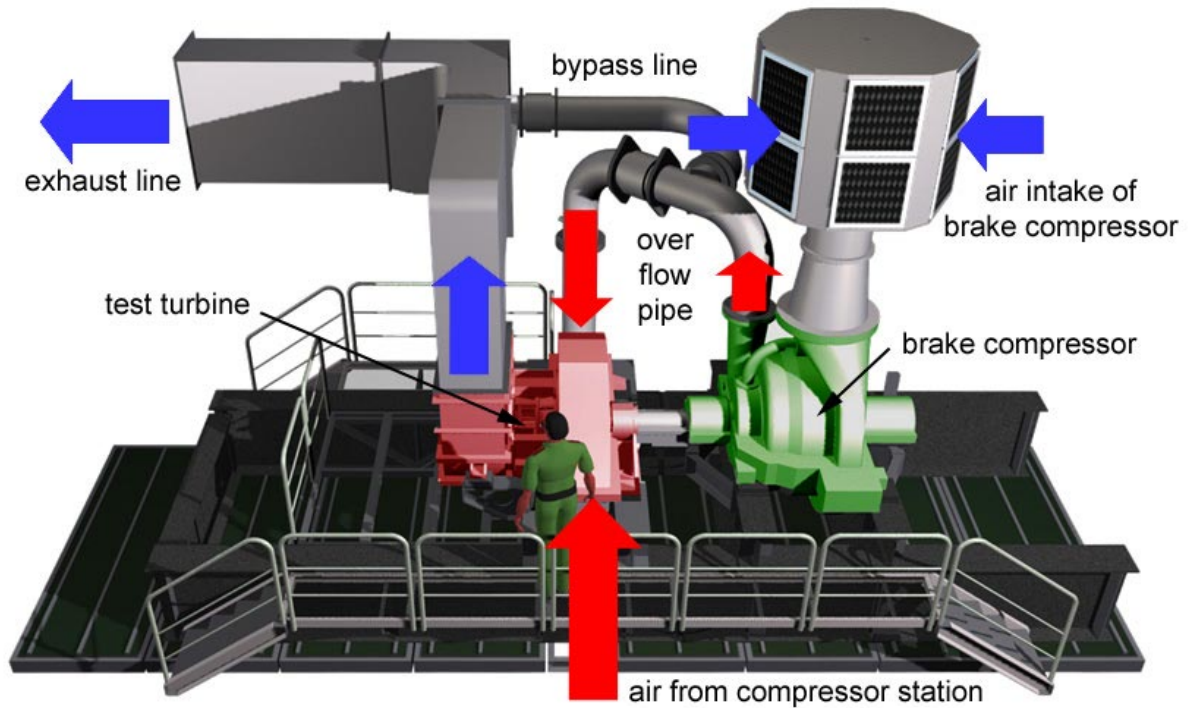


Fig. 2: Transonic Test Turbine Facility (TTTF), general arrangement

TURBINE STAGE

The objective of this new well performing HP turbine is to produce engine like inlet conditions for the downstream component, the intermediate turbine duct (ITD). The inlet flow of the ITD can be described as strongly transient with periodically impinging wake structures from the passing rotor blades, three-dimensional and highly turbulent.

Table 1 explains the HPT main parameters. The stage pressure ratio is about 3.2. This is combined with a stage reaction of 0.46 based on the enthalpy. The blading has transonic conditions on the suction surface of the airfoils and at the exit of the blade rows. The turbine is choked for the whole operating area in the turbine map to be investigated.

The blade hub to tip ratio is approximately 0.76 which is within the range of real aero engines. The ITD inlet Mach number is adjusted to 0.6 and represents realistic duct inlet conditions of modern jet engines with a single stage HPT. The inlet swirl angle is about -14 degrees measured from the engine axis. For simplicity reasons the HP turbine setup was designed uncooled.

The Reynolds number level based on the chord length is here typically high and correlates with the HPT inlet pressure level and will be in a similar range like for aero engines at take off condition.

Table 1: HPT main parameters

Aero Design Point HPT			
mass flow	[kg/s]	15,94	
total temperature inlet	[K]	425	
total temperature exit	[K]	320,3	
total pressure	[Pa]	350000	
$\Delta H/T$	[J/(kg K)]	254	
$\Delta H/u^2$	[-]	1,6	
c_{ax}/u	[-]	0,64	
stage pressure ratio	[-]	3,16	
degree of reaction	[-]	0,46	
power	[kW]	1720	
HPT Blade Exit			
R_{Hub}/R_{Tip}	[-]	0,76	
$Ma_{exit,absolute}$	[-]	0,6	
α_{exit}	[deg]	-14	
speed	[rpm]	11000	
$R_{blade,inlet}$	Hub	[mm]	204
	Tip	[mm]	251
$R_{blade,exit}$	Hub	[mm]	192
	Tip	[mm]	251
blade height	[mm]	53	
blade tip clearance	[% span]	1, 2 & 3	

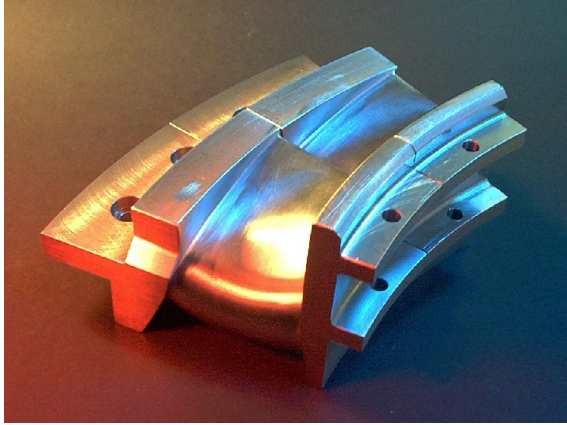


Fig. 3: HP vanes of new designed turbine stage

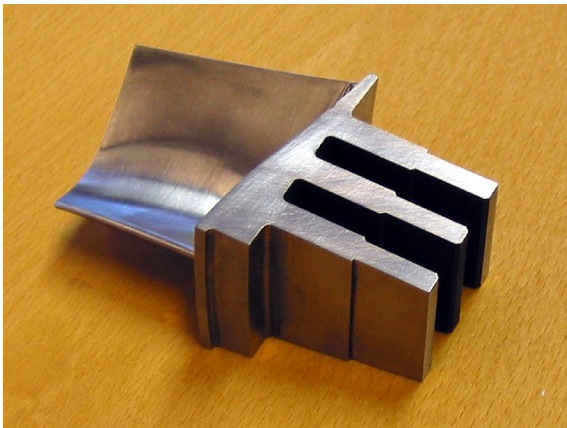


Fig. 4: HP blade of new designed turbine stage

There are 24 HP vanes, 36 rotor blades and 48 LP vanes (see Table 2), consequently the blade count ratio is 2-3-4 which eases CFD modelling of this test arrangement.

The number of airfoils of the vanes and blades were kept equal to the former investigated test stage of Graz University of Technology. So the fixations and the whole disk design could be done in a similar way. Figure 3 and 4 show the HP vanes and blade respectively. A plug-in blade foot connection is used for mounting the blades onto the rotor disk, see Fig. 4 and 5. The blades of the unshrouded rotor are equipped with plenum tip seals.

The HP vanes are fitted into a fully rotatable casing to change the relative position between vanes and the applied optical measurement system which is fixed in space during measurement.

The HPT Blade vicinity is equipped with interchangeable liner rings. These rings will provide the opportunity to change the tip clearance from 0.5 mm to 1 mm and 1.5 mm (1 %, 2 % and 3 % relative tip clearance) to study the influence of this variation on the intermediate duct flow, see Fig 5.

Table 2: Blading design parameters

	HP vane	HP blade	ITD	LP vane
blade count	24	36		48
t/C	0.89	0.76		0.88
b (mm)	67.9	51		44.3
d_{TE} (mm)	1	1		1
h_{exit} (mm)	47	58		63
h/C_{ax}	1.1	1.2		2.0
Re_C	$2 \cdot 10^6$	$1 \cdot 10^6$		$0.5 \cdot 10^6$
Ma_{inlet}	0.1	0.48	0.6	
Ma_{exit}	1.05	1.07		
α_{inlet}	0	34.4	-14	
α_{exit}	67.6	-57.2		-44.7
flow turning	67.6	91.6		

INTERMEDIATE TURBINE DUCT

The target is to provide engine like intermediate duct flow conditions and to perform high quality measurement to get a detailed understanding of the duct flow phenomena. Therefore the main component of the test setup is an aggressive high diffusion intermediate turbine duct assembled downstream of the transonic turbine stage. The vanes of the following counter rotating low pressure turbine are mounted at the end of the ITD. The plan is to use a basic aggressive duct design and further a super aggressive design which should produce a separated flow condition. This paper describes the test setup of the basic aggressive design.

The duct area ratio AR is approximately 1.5 and a non dimensional duct length l/h_{inlet} of 2 is used. Figure 5 shows that the designed duct geometry is well above the classical limit by Sovran and Klomp [10]. The ITD is designed very steep with 48 degrees at the inner contour and with 38 degrees at the outer contour measured to the engine axis. The aerodynamic design was done including the HPT, the LP vane and the deswirlers. One result is given in Fig. 5 where only the ITD plus LP vane is shown. The Mach number contours illustrate that the velocities go down at hub and tip, but no separation with a back-flow region occurs. This demonstrates the high diffusion design of this very short aggressive duct.

The main task of the following LP vane is to provide an engine like radial mass flow distribution which would be unrealistic without the blockage effect of this vane. The blade count of 48 was chosen to improve the performance of CFD calculations (see Table 2).

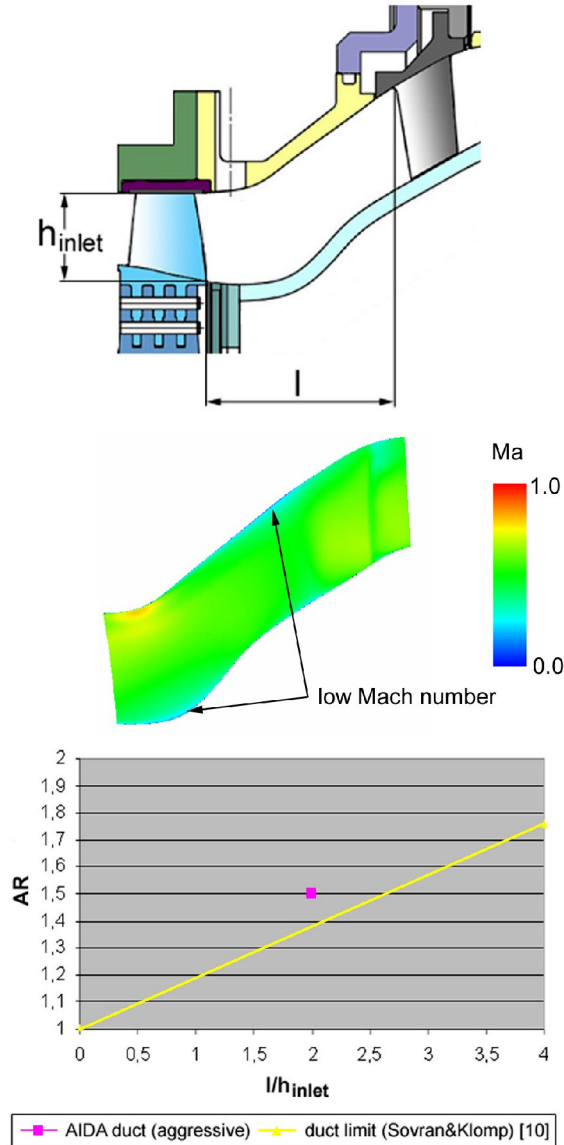


Fig. 5: Aggressive intermediate turbine duct design

TEST RIG AND INSTRUMENTATION

Figure 6 shows a meridional section of the TTTF together with the AIDA test rig. The flow direction is from the left to the right. The blade counts and the profiles are also given at the bottom.

The incoming air is accelerated by the HP vanes in circumferential direction and impinges on the HP rotor with the cylindrical outer contour. Then it is guided by the intermediate turbine duct to the vanes of the counter rotating LP turbine assembled at a larger radius. There it is accelerated again and turned in the opposite circumferential direction. A downstream deswirler turns the flow back and recovers some pressure. The air leaves the facility through the diffuser and the exhaust casing.

The TTTF is designed for the application of the most common optical and conventional measurement and flow visualization techniques. Therefore the facility is equipped with two fully rotatable gear rings. These gear rings are necessary for turning the stationary blade rows during operation in order to change the circumferential measurement position, while the often relatively large measurement system stays fixed in space. A clocking investigation can also be realized easily by variation of the relative vane-vane position.

There are interfaces for inserting probes, probe rakes or small windows at three different axial positions at several circumferential locations in the outer casing of the AIDA test setup (see Fig. 6, marked with "1", "2" and "3"). Furthermore the rig is equipped with static pressure taps around the circumference of the inner and outer casing at the indicated measurement planes ("1", "2" and "3") as well as upstream and downstream of the LP vane. Pressure taps are also arranged in several meridional planes inside the ITD at the inner and outer wall (see Fig. 6) to get the pressure distribution over the duct there.

Area traverses by means of pneumatic five-hole-probes with thermocouple will be performed at quite a few axial positions to get the pressure loss and the total temperature distribution. The probes and the traverse gears are mounted inside the inner liner of the IDT to protect the sensitive flow at the outer wall from disturbances by the probe fixation. In addition to that unsteady measurements with the support of the University of Cambridge by means of fast response aerodynamic probes will be carried out at position "3" (duct inlet) and several planes within the duct.

Instrumentation for the determination of the duct flow characteristics has to meet not only high demands on accuracy and repeatability but requires higher numbers of channels, too. Therefore the measurement system is made up by ten multi channel pressure transducers PSI 9016 with a total amount of 160 channels and an accuracy of 0.05 % and four National Instruments Field Point FP-TC-120 eight-channel thermocouple input modules and one FP-RTD-122 resistance thermometer input module.

The National Instruments Field Point FP-TC-120 thermocouple input modules suffer from low accuracy. The limiting factor is the built-in thermistor which measures the reference temperature of the junctions. To overcome this problem the FP-TC-120 modules are used as A/D voltage converters only whereas the cold junctions are placed in isolated isothermal copper blocks. The temperatures of the blocks are measured by means of Pt 100 sensors with the FP-RTD-122 resistance thermometer input module. After calibration of the whole measurement chain the repeatability was better than 0.1 °C.

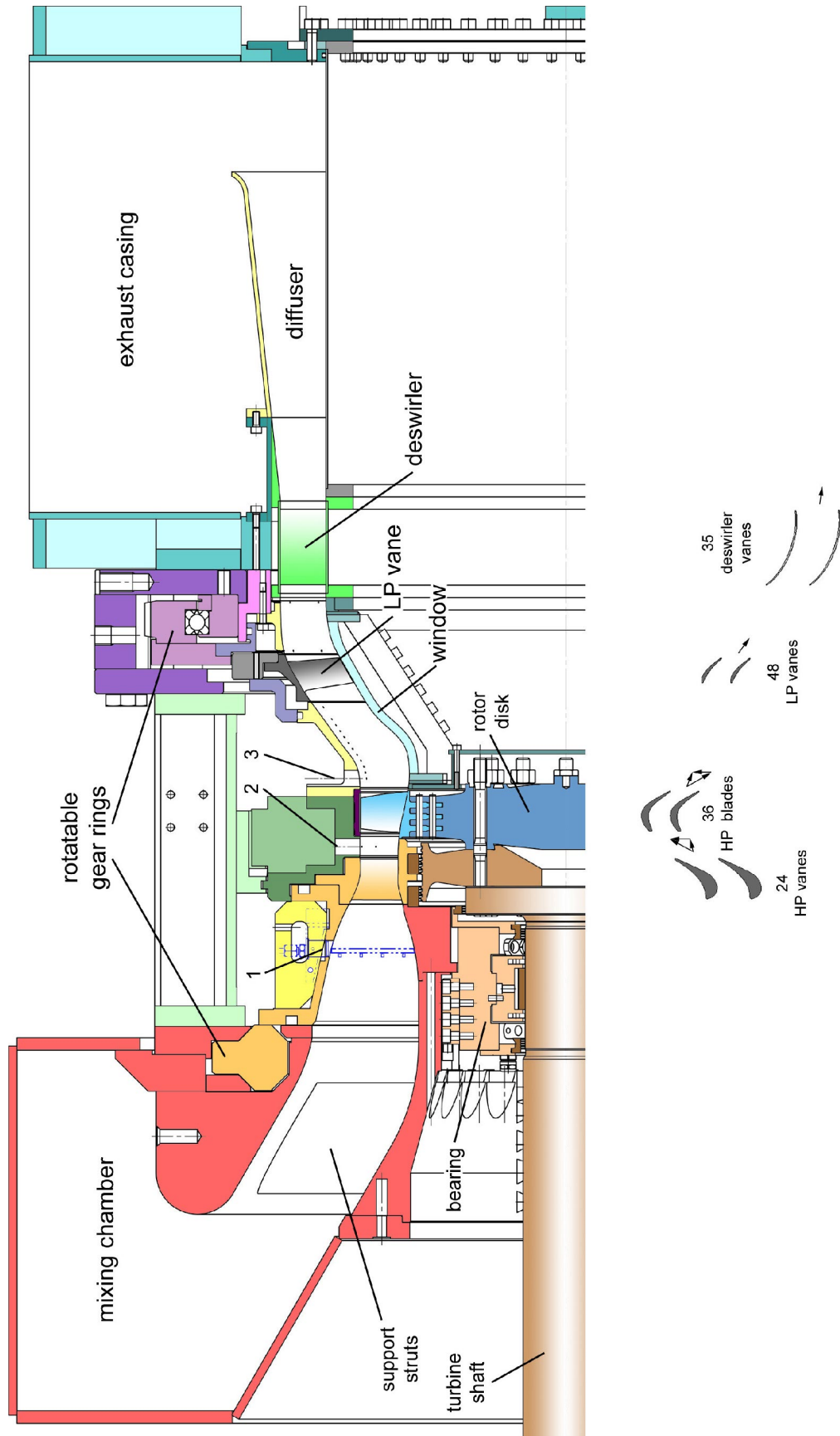


Fig. 6: AIDA test rig assembled in transonic test turbine facility (TTTF)

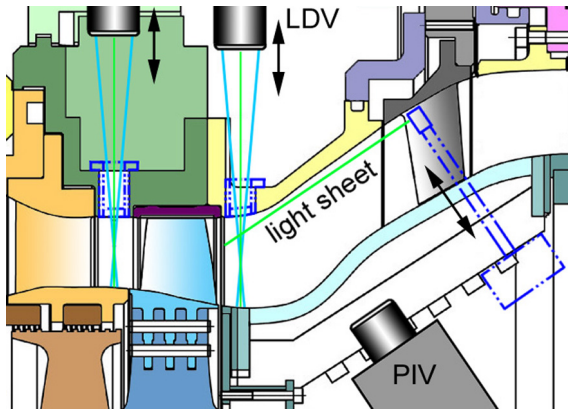


Fig. 7: Setup with optical measurement techniques

Calibration was performed by means of a calibration oven and a standardized Pt 100 sensor.

The TTF is equipped with a Bently Nevada System 3300 shaft monitoring system which provides also the reference signal or the trigger input for the unsteady time-resolved flow measurement techniques.

OPTICAL MEASUREMENT TECHNIQUES

Optical access to the flow path is essential for the application of optical measurement techniques like two-component Laser-Doppler-Velocimetry, 3D-

LDV, and three-component stereoscopic Particle-Image-Velocimeter, 3C-PIV. A DANTEC FiberFlow two-component LDV system (with two BSA processors) fed by a 6W argon-ion laser (COHERENT) will be used for the measurement of the axial and circumferential velocity components in radial axis-perpendicular planes upstream (measurement position “2”) and downstream (measurement position “3”) of the HPT rotor. The optical access is realized with small glass windows in the interfaces at position “2” and “3” (see Fig. 7). The system allows the point-wise detection of time-resolved velocity and turbulence data of a defined measurement grid. The LDV probe head has to be traversed only in radial direction; the position in circumferential direction can be adjusted by turning the stationary blade rows by the rotatable gear rings. Droplets of DEHS oil (Di-Ethyl-Hexyl-Sebacin-Esther) with a nominal diameter 0.7 μm were added by a PALLAS AGF 5.0D seeding generator 30 cm upstream of the stator blades as seeding material for the optical measurements. These particles guarantee sufficiently high particle response at transonic flow conditions.

The optical access to the intermediate turbine duct is realized with large acrylic glass window inserts in the inner contour. The whole area from the ITD inlet to the LPT exit is fully transparent over a width of 150 mm at two different circumferential positions in the upper half of the inner duct.

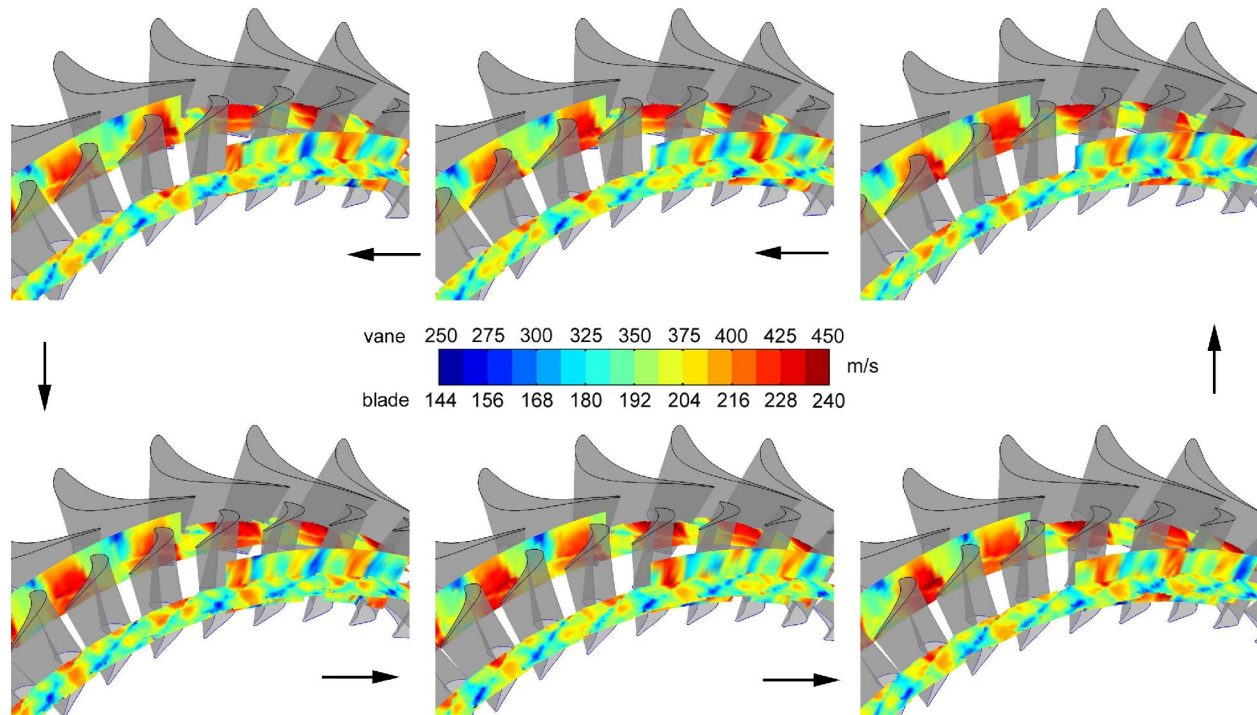


Fig. 8: Examples of time-resolved velocity distributions at six different vane-blade positions gained by 2D-LDV (radial planes) and 3C-PIV (tangential planes), all measured in the TTF together with the “TTM test stage” [11]

These window inserts allow the setup of the stereoscopic Particle-Image-Velocimeter inside the inner liner of the IDT. A triggered DANTEC Flow-Map 1500 System together with two DANTEC 80C60 HiSense cameras (1280×1024 pixel) and a NEW WAVE Gemini double cavity Nd:YAG laser (120 mJ/pulse) will be used to measure the time resolved 3D-velocity distribution of the whole flow field in tangential planes simultaneously enabling the determination of vortex structures and flow separations. The arrangement of the laser light sheet optics and the CCD-cameras can also be seen in Fig. 7. The measurement planes were realized by rotating the vanes and/or adjusting a trigger-delay in the acquisition software of the PIV system, while the positions of the cameras and the light sheet optics were fixed in the laboratory frame.

Figure 8 shows some examples of time-resolved velocity distributions at six different vane-blade positions gained by 2D-LDV (radial planes) and 3C-PIV (tangential planes), all measured in the TTTF together with the so called "TTM test stage" already investigated in [3], [7] and [11].

CONCLUSIONS

The design of a new test rig for the TTTF at Graz University of Technology and the adaptation of the facility were shown. Now it is possible to perform detailed measurements in a one and a half stage turbine setup together with intermediate turbine ducts under engine representative flow conditions.

The rig is designed for the application of the most common conventional and optical measurement techniques to provide a unique database of aggressive intermediate turbine duct flows. A detailed investigation of the aerodynamic performance of more aggressive diffusive systems is needed and the results will be very valuable for the gas turbine community.

The main future perspective is to realize much shorter engines without increased losses in order to save weight and to reduce the fuel consumption.

ACKNOWLEDGMENTS

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