Experimental Turbine Research at DLR Goettingen

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ABSTRACT

At DLR Goettingen (Germany) two windtunnels especially adapted to turbine research in the transonic flow regime are available. These are the “Windtunnel for Straight Cascades” and the “Windtunnel for Rotating Cascades”. The Straight Cascade windtunnel is of blow-down type, operating in the Mach number range of 0.2 to 1.6. The Rotating Cascade Tunnel is a facility with closed flow path enabling the independent variation of Mach and Reynolds number. In the Rotating Cascade Tunnel the investigated objects range from isolated vanes to 1½ stages. In the following the features of the windtunnels will be described and some experimental results shown.

INTRODUCTION

DLR (German Aerospace Center) is a company mainly funded by the government which carries out applied research in the aerospace field. One of its institutes, the “Institute of Propulsion Technology” is dedicated to research in the field of Turbomachinery. The institute provides at its location in Goettingen several facilities especially adapted to turbine research and mainly active in the transonic flow regime. The two main windtunnels used in the Turbine Technology group are described in the following chapters.

THE WINDTUNNEL FOR STRAIGHT CASCADES

The Straight Cascade Windtunnel at DLR Goettingen (EGG: Windkanal fuer Ebene Gitter Goettingen) is of the blow-down type with atmospheric inlet. Ambient air first passes a silica gel dryer, subsequently the inlet line equipped with a butterfly valve, two screens and a honeycomb flow straightener and enters the cascade downstream of the contraction. The test section is installed in a spacious walkable plenum chamber.

Downstream of the cascade the flow passes an adjustable diffuser and the main butterfly valve and at last enters a large vacuum vessel (10,000 m^3). This vessel is evacuated by two sets of 250 kW water-ring vacuum pumps, enabling intermittent measurements with run times from 7 to 10 minutes in case of transonic flow. At Mach numbers below 0.8 continuous operation of the wind tunnel is possible, whereas the run time decreases to 30 s at an exit Mach number of 1.6.

The inlet total pressure of the cascade is, not regarding the small pressure loss in the dryer and the inlet line, always equal to the ambient pressure. This assures a high stability of the inlet pressure without any control equipment. On the other hand the Reynolds number cannot be varied independently, but is a function of the Mach number. In the downstream flow field of the cascade Reynolds numbers occur from 160,000 to 900,000 when a standard blade chord length of 60mm is considered, corresponding to a Mach number operating range of 0.2 to 1.6 (cascade exit Mach number).

The diffuser is composed of an axisymmetrical housing and a centered body movable in axial direction. Its main purpose is to provide an adjustable throat in order to keep the pressure downstream of the cascade constant independent of the pressure in the vacuum vessel. Additionally a certain pressure recovery is expected depending on the cascade outlet angle and downstream Mach number.

The valve in the line upstream of the wind tunnel is closed only when regenerating (dewatering) the silica gel dryer or for pressure calibration purposes. The valve downstream of the cascade is the main operating valve of the windtunnel. By rapidly opening of this fast acting O-ring flap the flow is started.

The wind tunnel is equipped with an industrial electronic control system (*Simatic*) and all electric components except the data acquisition system are part of this central system. The locking of all safety-relevant doors and openings is controlled by this system.

For the development of high-pressure turbines the investigation and optimization of cooled blades is of particular interest. Therefore the Straight Cascade Wind-

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tunnel (EGG) is equipped with three independent supply lines for the simulation of coolant ejection using air or carbon dioxide as coolant.

Test Section

The EGG can be used for investigations of a large variety of turbine profiles, ranging from the flat-plate-like tip sections of steam turbines to the high turning profiles of gas turbine rotor hub sections. Different cascade geometries are easily installed and flow conditions adapted. The cascade is mounted with fixed geometrical parameters (stagger angle, pitch-chord ratio) in a support frame, which is inserted into the test section, between two circular discs establishing the side walls of the flow channel. The inlet angle is adjusted by turning this assembly. The test section dimensions are (380x125) mm², which allow a straight cascade to consist of up to 15 blades.

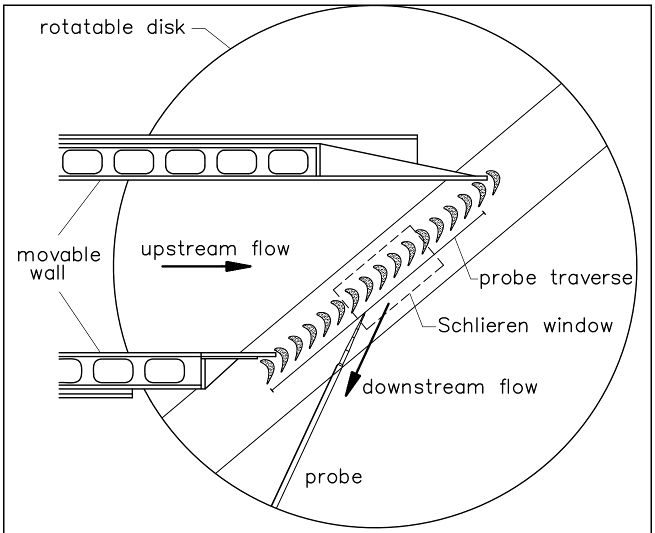

Figure 1: Test section of the EGG

Of great importance is a homogeneous flow field at the inlet of the cascade. This is provided by a long upstream extension of the side walls up to the contraction and by movable upper and lower nozzle walls. These can be adjusted in vertical and horizontal direction up to the desired location relative to the most upper and most lower blade, while the test section width is fixed. The optimum location of the upper and lower nozzle walls has to be found empirically based on the static pressure distribution in a plane parallel to the cascade inlet.

Near the center line of the flow channel the cascade support is equipped with exchangeable panes in which typically four to five blades (depending on the pitch-chord ratio) are fixed. While for Schlieren observations mineral glass panes are installed here, for special purposes (e.g. measurements of the pressure distribution at the blade surface) steel panes are used. A window with high infrared transmission (e.g. zinc sulfide) is used in case of the measurement of heat transfer and cooling effectiveness with the aid of an infrared camera.

Guided carriages driven by stepping motors via jacks are installed on both sides of the flow channel downstream of the cascade. They are utilized for mounting the probes and adjusting them parallel to the cascade outlet plane. The flow downstream of the cascade is not guided. Flow angle and Mach number are only adjusted in mutual dependency by the plenum pressure (i.e. setting of the diffuser).

Blades are typically manufactured from brass or steel by DLR using an eroding-by-wire machine. The outline of some blades is controlled by measurements with a 3-coordinates-measuring-device. An exactness of 0.02 mm is achieved. For surface pressure measurements one blade is instrumented with drilled pressure taps at mid-span. All pressures are measured by means of a *PSI 8400* high speed pressure scanner, including tunnel or probe pressures.

Measurement Techniques and Data Evaluation

At the Straight Cascade Windtunnel (EGG) the most frequently used measurement techniques are wake traverses by a probe downstream of the cascade, pressure distribution measurements on blade surfaces and side walls, and Schlieren-optical recordings. Other measurement techniques used recently are heat transfer measurements, application of hot films, Laser velocimetry including L2F and PIV, determination of blade boundary layer characteristics or cooling effectiveness, concentration measurements, and oil flow visualization.

In the upstream flow field total pressure, total temperature and humidity of the air are measured in the settling chamber, where flow velocities are low - about 15 m/s - using a Pitot probe, a thermocouple and a sensor for moisture, respectively. The inlet wall static pressure, p_1, is determined from measurements with many tappings, distributed in a line upstream of the cascade inlet. Only one side is instrumented because it is assumed that the flow behaviour is symmetric about the mid-span plane. From these pressure readings the average value of the static pressure is computed.

For evaluating flow quantities downstream of the blades a wedge-type probe is used. Figure 2 shows a drawing of the probe. A detailed description together with the calibration curves are given by Tiedemann [1]. From the probe readings the local values of total pressure, static pressure and flow angle are determined.

In order to determine the performance of the cascade, wake flow measurements are made by traversing the probe behind the cascade in a plane parallel to the cascade exit plane. The probe is traversed at a fixed angle to avoid time consuming adjustments at each local position.

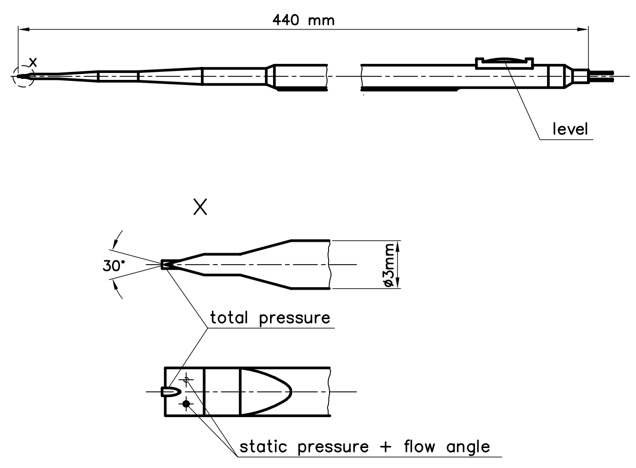

Fig. 2: Wedge probe used for cascade wake traverses

The probe samples data for the local downstream parameters such as local Mach number, local total pressure, and the local outlet flow angle. For investigations of three-dimensional flow fields (e.g. near the cascade end walls) a pyramid-type probe is available. From the data of the local inhomogeneous flow in the traverse plane, the properties of the equivalent homogeneous (mixed out) outlet flow are obtained by applying the equations of conservation of mass, momentum and energy (Amecke and Safarik [2]). As a result the quantities of the homogeneous flow field are delivered as the outlet Mach number, Ma_2, the total pressure, p_{02}, and the outlet flow angle, α_2. From these homogeneous flow values blade loss and other characteristic data can be derived.

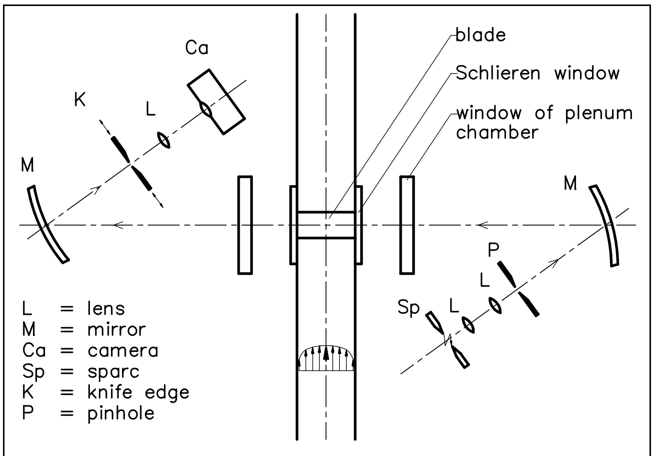

Figure 3: Schlieren optical arrangement at EGG

Valuable additions to all other measurement techniques are Schlieren pictures taken to assist the interpretation of the data. The qualitative density gradient information of these photos provides an excellent overview on the flow field and indicates the existence or absence of certain flow features such as shocks and separated flow regions. The Schlieren optical system is arranged conventionally, as shown in Figure 3. As light source a flash is used triggered by a light pulse generator for high-speed investigations (pulse width 20 ns).

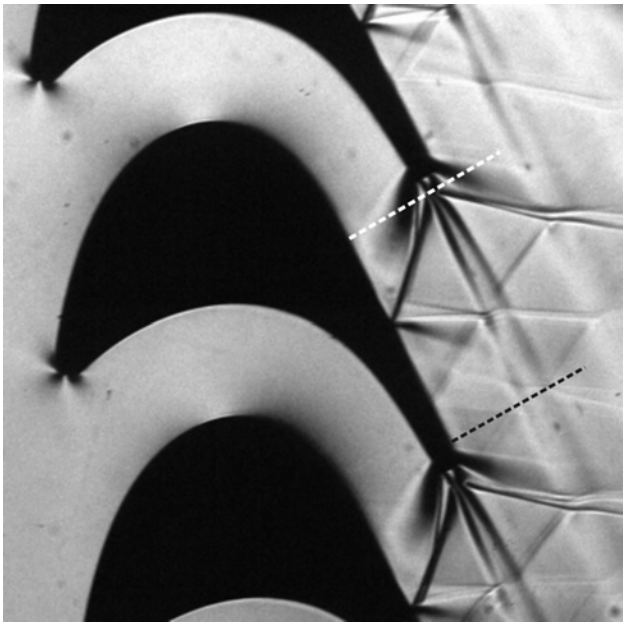

Figure 4: Schlieren photo of cascade HL at $Ma_{2is} = 1.2$

For a better physical understanding of the flow on the blade surface, oil flow visualization pictures are sometimes taken. A mixture of titan dioxide and a mineral oil is spread almost uniformly on a black colored blade to give better contrast. This blade is inserted instead of the instrumented blade for surface pressure distribution measurements. After each test the blade has to be removed from the cascade in order to take photos of the flow pattern.

The Laser-2-Focus (L2F) system is an optical system especially useful for turbomachinery flows. A description is given in the chapter on the Rotating Cascade Tunnel below. The used L2F system measures 2D velocities and turbulence quantities. As the L2F system additionally delivers the particle flow rate, concentration values may be determined, e.g. coolant concentration in film cooling investigations (Kost and Nicklas [3])

Some Experimental Results

A recent experimental investigation dealt with blading development for a high-pressure turbine at supersonic exit Mach numbers. Figure 4 shows the flow field at an isentropic exit Mach number of 1.2. The two dashed lines drawn into the Schlieren picture mark the position of Pitot probe and L2F-measurements undertaken to clarify the loss development due to the suction side boundary layer and to shocks which have their origin at the trailing edge of the blade above. Figure 5 displays results gained at the position of the white dashed line in Figure 4.

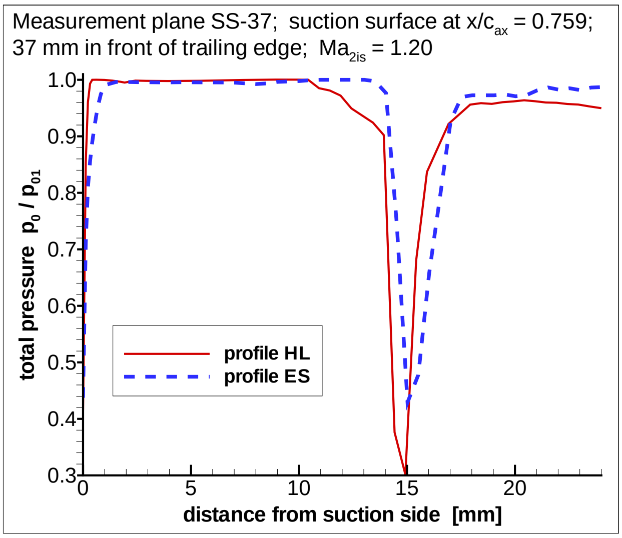

Figure 5: Boundary-layer- and L2F-measurements

With a flattened Pitot probe especially adapted to thin boundary layers the Pitot pressure was measured at the indicated line perpendicular to the suction surface. The determination of Mach number by L2F measurements outside the suction side boundary layer was additionally necessary as in supersonic flow probe Pitot pressure has to be corrected to get the real total pressure.

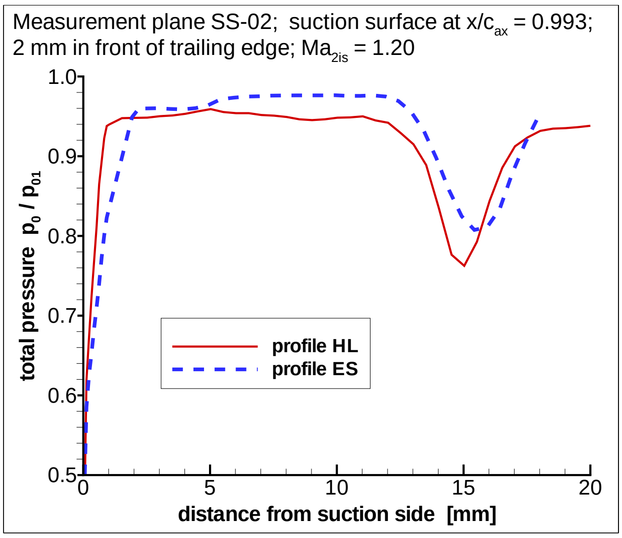

Figure 6: Boundary-layer- and L2F-measurements

Figure 6 shows the result of a similar measurement at a position 2 mm in front of the trailing edge (black dashed line in Figure 4). From the measurements at these two positions the boundary layer development and the loss production by shocks could be compared for different blades and thus the progress in the computational design of blades checked. More information on this project is available from Sonoda et al. [4].

The design of a film-cooling configuration is especially difficult for the three-dimensional flow regime near hub and casing. Together with German gas turbine industry a platform cooling configuration was investigated. A stator cascade endwall served as model platform which could be cooled by slot and hole ejection. The cascade endwall was electrically heated, the 'coolant air' could be cooled or heated from zero to 90°C, and an infrared camera was used to determine the wall temperature. From these data heat transfer and film cooling effectiveness could be derived.

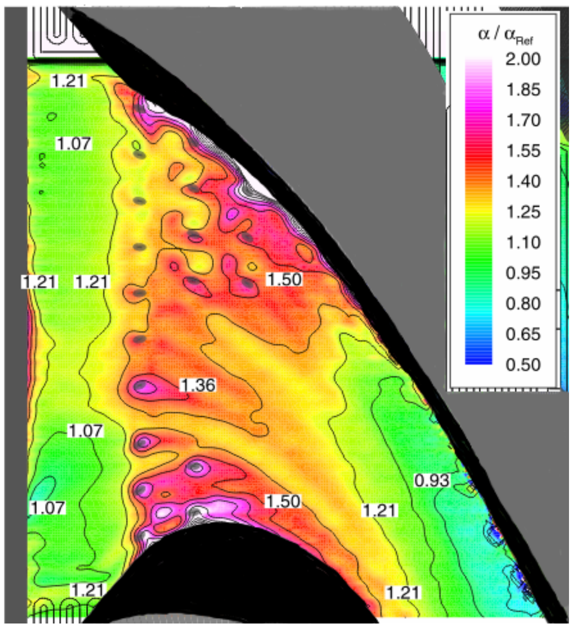

Figure 7: Heat transfer at film-cooled stator platform

Figure 7 shows heat transfer aroused by air ejection from the coolant holes (the reference values are those without coolant ejection; Nicklas [5]).

A wide variety of investigations have been carried out in the Straight Cascade Tunnel. In addition to many performance tests for industrial customers, several aerodynamic research projects were conducted. Among these are AG-TURBO (Germany) and BRITE/EURAM (Europe) projects (Kost and Giess [6]; Kapteijn et al. [7]). Typical tasks for the EGG cover performance tests, secondary flow research, as well as heat transfer and cooling aspects.

THE WINDTUNNEL FOR ROTATING CASCADES

The Windtunnel for Rotating Cascades (RGG) is a closed circuit, continuously running facility (Figures 8, 9). A four stage radial compressor (maximum pressure ratio 6.1, inlet volume flow rate of up to 15.5 m^3/s) driven by a speed-controlled 1 MW dc-motor enables transonic Mach numbers in the test section.

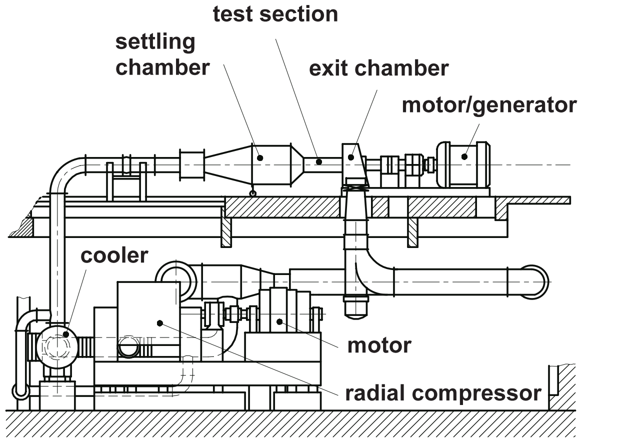

Figure 8: Schematic of the RGG

The RGG was originally designed for the investigation of the flow through rotating annular cascades. Annular cascades provide an improved periodicity of the flow field compared to plane cascades. These annular cascades have to be rotated in order to achieve incidence angles deviating from zero. Nowadays, typical projects range from investigations in annular stationary and rotating cascades to full stages and so-called 1½ stage set-ups, where the stator of the next stage is mounted downstream of the actual stage. Even though compressor tests are feasible, the facility has so far exclusively been used for turbine tests.

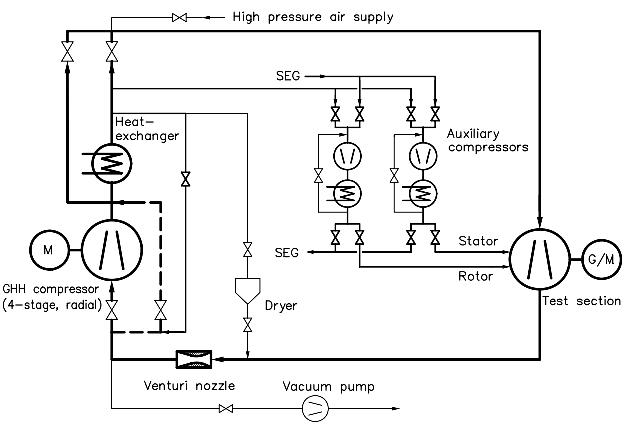

Figure 9: Windtunnel circuit diagram

Mach and Reynolds number are the most important similarity parameters which must be identical in the windtunnel set-up and the real engine in order to enable tests under conditions as realistic (and thus relevant) as possible. The RGG enables the independent adjustment of these two similarity parameters which makes it a facility with an extremely versatile application profile. For the different set-ups a large range of Reynolds numbers and pressure ratios can be investigated, covering significant portions of the aircraft engine, stationary gas turbine, and steam turbine markets.

Settling chamber pressure	10 – 150 kPa
Settling chamber temperature	295 – 450 K
NGV exit Reynolds number range	3×10^4 – 10^6
NGV exit Mach number range	0.2 – 1.7
Maximum tip diameter	700 mm
Minimum hub diameter	360 mm
Maximum stage total pressure ratio	5

All components of the facility are accurately controlled by means of a *Simatic S5* industrial control system. The pressure in the windtunnel is set by a combination of a vacuum pump and a high pressure air feed. The settling chamber temperature can be increased up to 450 K by bypassing the heat exchanger downstream of the main compressor with a variable bypass ratio. The turbine rotor is coupled to a speed-controlled 1200 kW dc-motor/generator which can drive or brake the rotor in either direction and enables rotor speeds of up to 14,500 RPM in both directions. Humidity of air in the tunnel is removed by a bypass dryer. During the actual tests, the conditions in the test section are adiabatic. In order to enable the simulation of internal and/or film cooling of the vanes and blades two auxiliary compressors provide air for the simulation of stator and rotor coolant ejection.

The auxiliary compressors can furthermore be utilized for driving air through a special test section dedicated to probe calibration purposes (Giess et al. [8]).

Measurement Techniques

In order to exploit the full potential of a sophisticated facility such as the RGG, state-of-the-art instrumentation is required. The RGG data acquisition system is divided into two parts, a standard system and a set of special purpose systems.

The standard data acquisition system is used to gather the data needed to determine the so-called boundary conditions of a test. These conditions are then utilized to determine the exact operating conditions of the turbine. This standard system is assembled around a PC that controls and evaluates all connected devices by

means of a software package based on *LabView*.
Thermocouples and a high accuracy pressure transducer are utilized for the determination of the stagnation properties in the settling chamber. Static pressure taps in the side walls are used to measure the static pressures up and downstream of the cascade or the stage. These pressures are measured by means of a *PSI 8400* high speed pressure scanner. Steady pressures and temperatures on stationary blades (e.g. stator surfaces), as well as from stationary probes are measured by the standard acquisition system, too. A shaft encoder and a torque meter provide information on the rotor speed as well as on the turbine's torque and power balance, respectively. The mass flow is determined with a calibrated Venturi nozzle which is part of the windtunnel circuit.
Special purpose data acquisition systems which are particularly tailored to specific measurement tasks are utilized for new or complex measurement techniques.
Among the measurement techniques which are connected to special purpose data acquisition systems at the RGG are L2F (see below), Kulite sensors for measuring unsteady pressures, heat transfer sensors, hotfilm sensors, as well as rotating pressure transducers which are connected to static pressure taps on the rotor surfaces. Where no optical access to the measurement region is possible, hotfilm probes are used to provide turbulence information. Surface pressures are utilized to determine the pressure distribution on turbine blades, whereas some characteristics of blade boundary layers can be determined by surfacebound hotfilm sensors.
A measurement technique used at the Straight Cascade Tunnel (EGG) as well as at the RGG is the Laser-2-Focus velocimeter (L2F). In the following paragraph some more information is given on this special optical technique:
The measurement principle of L2F, is rather simple. The L2F-measuring device generates two highly focused light beams in the probe volume which act as a 'light gate' for tiny particles in the flow. The scattered light from the particles provides two successive pulses and from the time interval between the pulses the velocity perpendicular to the laser beams can be derived (Schodl [9]).The two foci of our L2F device have diameters of 8 μm and their separation is 210 μm. In order to apply the technique the flow has to be seeded. The necessary particles are oil droplets of 0.3 μm diameter which are produced by a special seeding generator and injected into the flow in the settling chamber. At DLR Goettingen the Laser-2-Focus technique is routinely applied to acquire flow field information for cascade and turbomachine flows (Kost and Kapteijn [10]). The system measures 2D-vectors of the fluid velocity. As a result the mean velocity as well as the turbulence values are obtained. Using the upstream total temperature the velocity can be converted to a Mach number.

Some Experimental Results

Funded by AG-TURBO (Germany) investigations at an annular stator and a rotor were carried out to gain experimental data for comparison with Navier-Stokes codes.

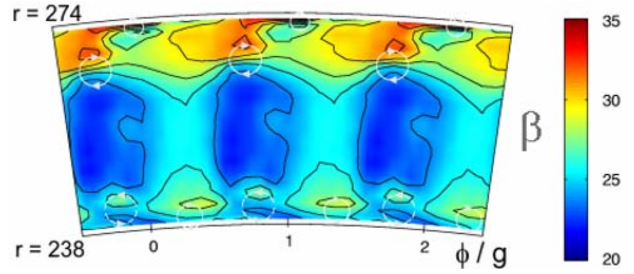

Figure 10: Flow angle downstream of rotor

Figure 10 shows as a result the downstream flow field of a rotor, measured by L2F (Giess and Kost [11]). Some typical secondary flow vortices are indicated and it can be seen that secondary flow is affecting much larger parts of the region near the tip than near the hub.

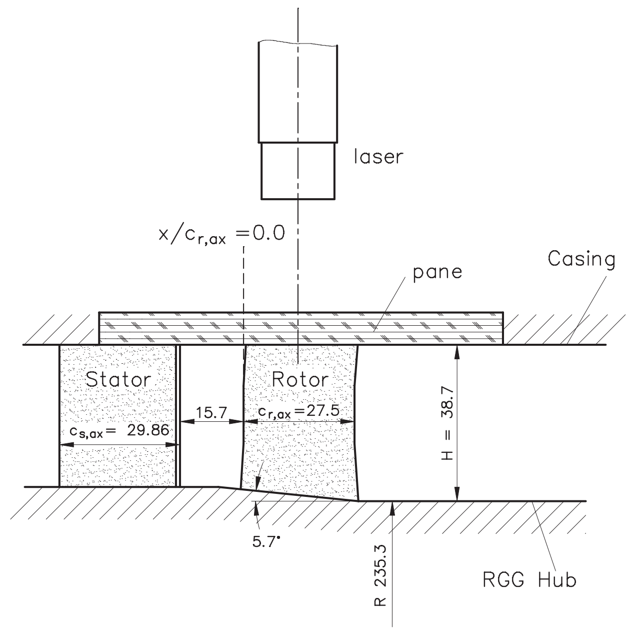

Figure 11: Meridional flow path of the BE-stage

Within a European project, called "Brite Euram: BE", a high-pressure turbine stage was investigated. It comprised a state-of-the-art, full size, transonic, aero-engine HPT (flow path of the stage see Figure 11).

Surface hotfilm gauges at rotor mid section were used to determine the location and the extent of laminar-to-turbulent transition in the boundary layer of the turbine rotor (Tiedemann [12]). L2F measurements at mid section, Kulite sensors on rotor blades and probes equipped with steady and unsteady (Kulite) pressure sensors served to resolve the periodic-unsteady rotor flow (Tiedemann and Kost [13], Kost et al. [14]).

The Laser-2-Focus device served as a velocimeter measuring 2D-velocity vectors and turbulence quantities and as a tool to determine the concentration of coolant ejected at the trailing edge of the stator blades. The measurement of coolant concentration downstream of the stator and inside the rotor provided a detailed picture of the stator wake development and its interaction with the moving rotor. Axial measurement locations reached from the stator exit through the rotor to that downstream measurement plane where probes were installed measuring steady and unsteady total pressure of the rotor exit flow. In Figure 12 an instantaneous picture of the unsteady flow field is displayed [14]. The vectors show the unsteady relative (rotorfixed) velocity where the mean relative velocity is subtracted, the turbulence level is coded by the size of the green spots and the measured coolant concentration is shaded blue.

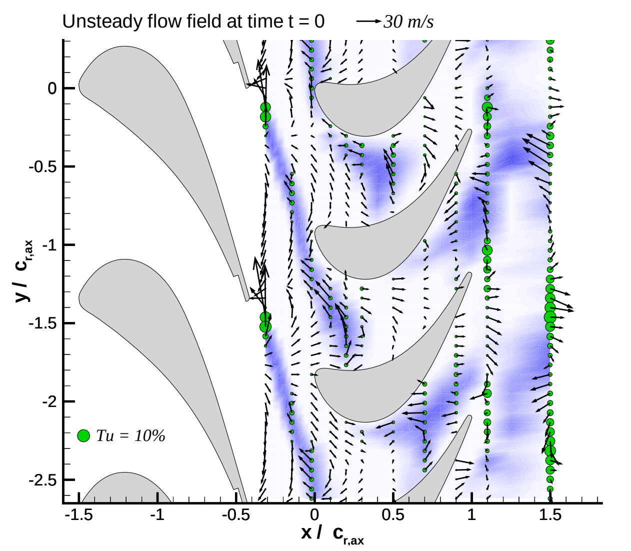

Figure 12: L2F-measurements in a turbine stage

Using the same stage later on a new European project was initiated aiming at the investigation of forced response of the rotor blades by the action of the upstream stator blades. Within this project mainly measurements of unsteady forces and pressures were carried out, but additionally the axial and radial development of steady pressures, steady and unsteady velocity vectors were determined (Joecker et al. [15]).

A follow-up project deals with 'Low Engine Order Excitation'. In the aerodynamic part of this project the flow field downstream of a stator with periodically changing blade gap was determined by L2F and probes. The varying stator gap is producing a 5th order rotor excitation.

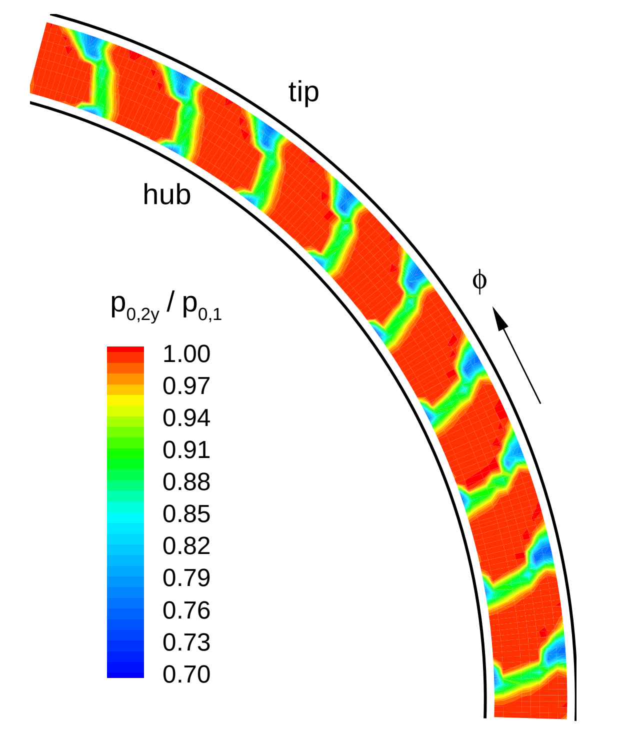

Figure 13: Total-pressure field downstream of stator

In Figure 13 the total pressure field of stator downstream flow is shown. Nine pitches of the stator comprise one period of Low Engine Order. The small differences between the pitches are only observable by a close inspection of the data (Joecker et al. [16]).

SUMMARY

The Turbine Technology group of DLR, located in Goettingen, but part of the Institute of Propulsion Technology, is responsible for research in transonic turbine flow. To investigate the phenomena of transonic turbine flows, high quality numerical tools are needed as well as experimental facilities adapted to turbine research. Information on the experimental facilities, the "Windtunnel for Straight Cascades" and the "Windtunnel for Rotating Cascades" and on some results in turbine research are assembled in this article. Some more information is available on the Web site of the institute: http://www.dlr.de/at.

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