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Pressure Sensitive Paint measurements at a Transonic Compressor stage

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ABSTRACT

At Darmstadt University of Technology, the department of Gasturbines and Flight-Propulsion operates a single stage transonic compressor test stand. Its main purpose is to present a database for validation of CFD code. In addition it serves as a testbed for new materials and also for the development of new measurement techniques.

In July 2000, a new measurement technique for the regime of transonic compressors was applied to the rig. With Pressure-Sensitive-Paint (PSP) and an image aquisition system developed by the German Aerospace Center (DLR) in Göttingen, the intensity distribution and derived therefrom the pressure distribution on the suction side of the rotorblades could be determined.

Preliminary results of the measurements are shown in this paper and are compared with previous measurements conducted with a 3d-Laser-2-Focus system.

INTRODUCTION

In the early 1990s at Darmstadt University of Technology (TUD) a single transonic compressor stage was brought into operation. The first rotor was manufactured as a titanium blisk.

Rotor No. 1 has been extensively tested with all kinds of measurement techniques. The rotor-blade passage was investigated with 3d Laser-2-Focus (L2F) measurements by Blaha et. al in 1997. Important information on shock structure and its movement at different operating conditions could be obtained.

However, the pressure distribution on the blade-surface was unaccesible for L2F and rotational speeds of up to 400 m/s with profile thicknesses of around 2 mm had proven to be too large an obstacle for the application of sensors.

With promising progress in the development of Pressure Sensitive Paint by the DLR in Göttingen, which was by then successfully applied to the annular cascade of EPFL, MTU Aero Engines initiated a measurement campaign at the Darmstadt Test-Rig.

To be able to compare the PSP results with other experiments, it was decided to run operating conditions, for which L2F measurements had already been taken.

DARMSTADT‘S TRANSONIC COMPRESSOR

This section briefly describes the test rig and conventional instrumentation used to determine the operating point. The following figures show a general sketch of the laboratory (Figure 1) and a cross sectional drawing of the compressor stage (Figure 2).

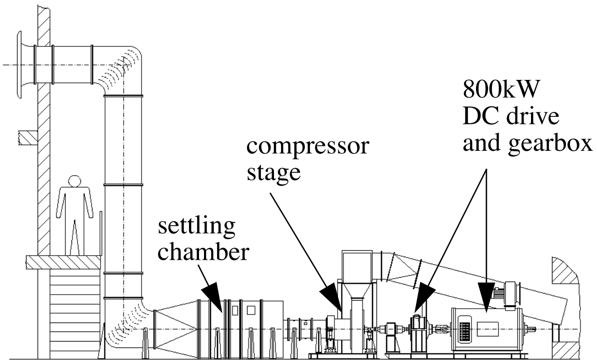

Figure 1. Sketch of the installation

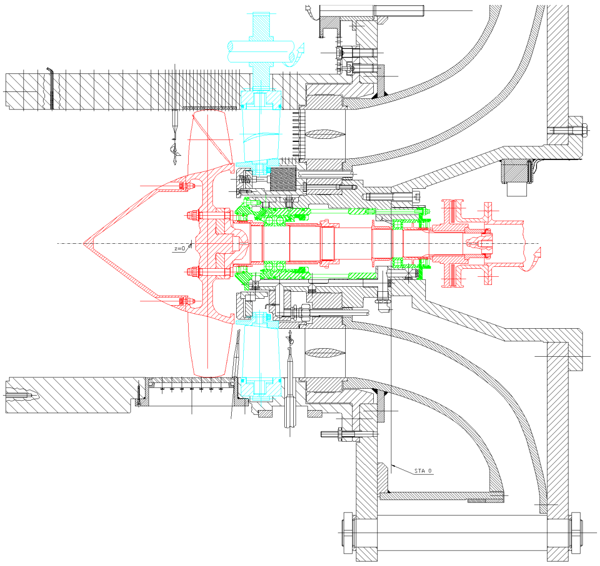

Figure 2. Cross-section of the compressor

Inlet stagnation pressure and temperature are taken in the settling chamber in front of a bellmouth. At the inlet, wall static pressure is measured to determine the mass flow by using a calibrated nozzle. The downstream flow conditions are taken from fixed total pressure and total temperature probe rakes mounted on the bearing support struts behind the stator.

Shaft speed, power and torque are measured by a Torquemeter device between the 800kW DC-drive with gearbox and the compressor.

Aerodynamic characteristics of Rotor No. 1 and an impression of the blisk are given in the table and picture (Figure 3) below.

Characteristics of Rotor No. 1 at design point

shaft-speed	20,000 rpm
shaft-power	638 kW
massflow	16 kg/sec
No. of blades	16
outer diameter	0.38 m
tip speed	400 m/sec
hub to tip ratio	0.51
relative inlet Machnumber - tip	1.35
relative inlet Machnumber - hub	0.7
isentropic efficiency	87,0%
pressure-ratio	1,513

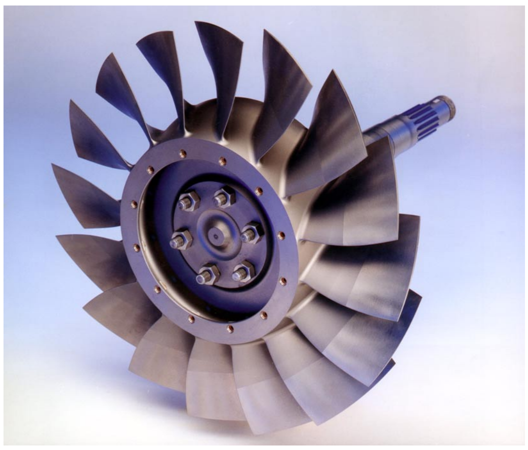

Figure 3. Titanium Blisk Rotor No. 1

The experimental data gathered over the last years has been used for validation of CFD codes and from the experience with Rotor No. 1, new design ideas were incorporated into design of Rotor No. 2, which is an aft-swept blading manufactured of carbonfibre reinforced plastic. For the future, rotor designs with forward swept blades are under consideration to further investigate the influence of Sweep and Lean on the transonic flowfield.

THE PRESSURE SENSITIVE PAINT

The ability to measure 2d pressure distributions on blade surfaces instead of taking discrete pressures from several points is a great progress in assessing the flow in cascades or even rotors. It is a non-intrusive measurement technique, since the coating of the Pressure Sensitive Paint typically has a thickness of around 50 microns and can be considered as smooth.

The PSP measurement technique is based on the deactivation of photochemically excited molecules, i.e. luminophores, by the presence of oxygen molecules. When luminophores absorb light with the correct wavelength, they are promoted from their base energy state to a higher state. These molecules can lose the extra energy either through emission of light (luminescence) or even without radiation. The interaction of excited luminophores with oxygen molecules, i.e. quenching, increases the probability of a radiation-free process, which makes different degrees of luminosity recognizable on the surface of the blade. Such a fluorescent image arising under the flow conditions can be recorded using a CCD camera with optical filter.

The Stern-Volmer expressions relate quantitatively lifetime and luminescence intensity to quencher concentration. For the non-time-resolved measurements, as the were conducted in Darmstadt, the following equation becomes the basis for the so called intensity method:

$$\frac{I_0}{I} = A \cdot p + B$$

Where I_0 is the intensity for ambient conditions and A, B are constants, which are to be determined from calibration experiments.

For use as a luminophore, i.e. molecules with sufficiently long lifetimes for oxygen quenching, platinum (PtOEP) and ruthenium complexes such as tris-2,2‘bipyridil-ruthenium(II) can be employed. For an excitation of ruthenium‘s luminophores, the blue line of an argon ion laser with a wavelength of λ=488nm can be used. Pyrene belongs to a group of aromatic hydrocarbons and is well known as a luminophore in optical sensors. The absorption spectrum of pyrene at a wavelength of λ=337 +/- 10 nm can be used for the excitation of luminophores.

The characteristics of pyrene and ruthenium as luminophores become clear from their calibration curves plotted in Figure 4 according to the Stern-Volmer relation.

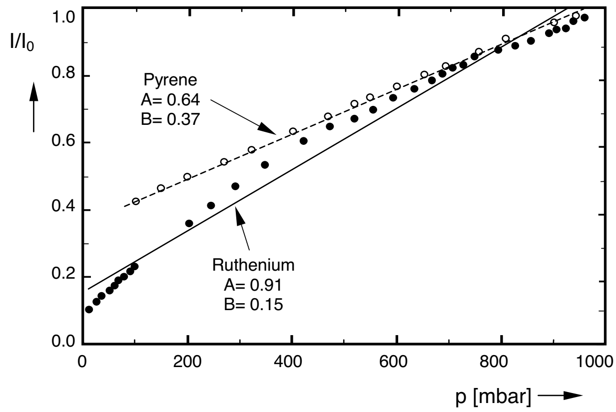

Figure 4. Calibration Curve of pyrene based PSP

While ruthenium shows a greater sensitivity to pressure especially in the low pressure range, pyrene has the advantage of a much more linear behaviour. Also ruthenium‘s sensitivity to temperature, which is of course a source for errors in the measurement, is much larger (5% $°K^{-1}$) than the temperature sensitivity of pyrene (0.2% $°K^{-1}$).

Calibration of the optical pressure sensor is necessary for reconstructing a quantitative pressure image from the initial qualitative image of the flow phenomenon on the surface of the blade. The first approach is to paint a test specimen parallel to the blade itself and then to expose it to known pressures and temperatures in an external calibration chamber. This method was used in the present investigation. An even greater degree of accuracy can be achieved by calibrating the coated blade in the test section itself. This would presume the possibilty to seal the test section airtight and to adjust pressure and temperature in the range of interest. This may be employed in future measurement campaigns.

EXPERIMENTAL SETUP

The goal of the measurement campaign was to obtain steady-state pressure distributions on the rotor‘s suction-side blade-surface. An optical access was installed at the inlet wall upstream of the rotor. The viewing angle was chosen in a way, that a large area of one blade‘s suction-side would be visible without being shadowed by the subsequent blade‘s leading-edge. On the other hand the angle was not to be to shallow, to keep enough resolution of the picture. The compromise found in the measured pictures results in a shadowed area at the downstream region of the blade, displayed in Figure 5

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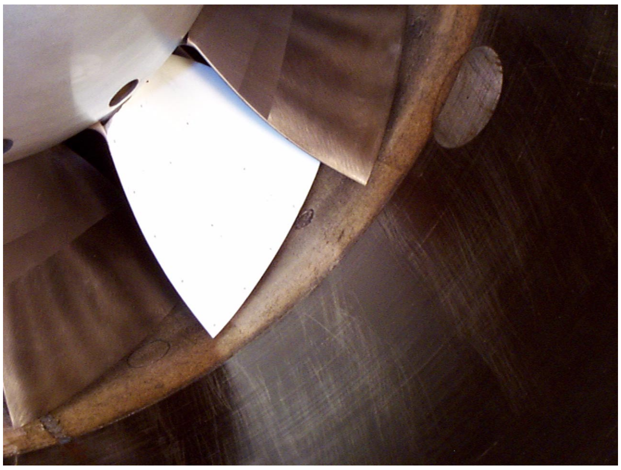

Figure 5.   Blisk with one PSP coated blade

In the rotating frame of reference the flow can be regarded as steady, possible oscillations of the shock position are neglected. However, a possibility had to be found to gather the data from a fixed frame of reference outside the rotor.

The test stand is equipped with a trigger-device, providing a very stable and jitter free TTL pulse once per revolution. It is based on a magnetic field capacitor that detects an intentionally machined tooth in one of the turboflex clutches between the Torquemeter and the shaft. The analog signal of the sensor is evaluated by a special circuit and everytime at the very same angular position of the shaft, the pulse is generated.

The TTL pulse triggers the illumination source, which was in this setup a nitrogen laser with a wavelength of λ=337 nm corresponding to the absorption spectrum of the pyrene sensor. At design speed of 20,000 rpm this happened with a frequency of f_{rotor} = 333 Hz.

To obtain enough exposure of the CCD camera, the shutter was opened for a sufficient amount of single images - in this case 10,000 single laser-pulses were emitted to take one picture. Measurements were repeated for every operating condition to allow further averaging.

To verify the stableness of the trigger-system several marker points were applied to the blade surface by removing the PSP at small points. The accumulation of 10,000 single illumination events showed the markers to be in the exact same position within the resolution of the CCD camera.

Since the measured intensity is subject to imperfections in the illumination - e.g. reflections from hub or casing or shadows from neighboring blades - reference pictures were taken with the rotor halted in the same angular position as the running-condition pictures were taken. For later evaluation the ratio between the intensities was used in combination with calibration data. Another reference picture was taken without illumination. Although the laboratory was dark during the experiment, some ambient light can always make it's way onto the blade and this background-light-image was subtracted from the pictures taken during the experiments.

The whole experimental setup is shown in Figure 6. In this picture the rotor is situated on the left side, with flow coming in from the right. The solid profiles for the camera mount were necessary for vibration-free installation of the CCD-system.

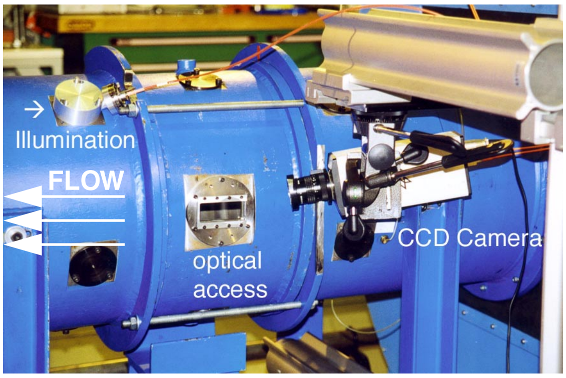

Figure 6.   Experimental Setup of PSP-System

Preliminary Results

Since the measurements were conducted in late July, the process of data evaluation and correction is not yet complete. Especially the sensitivity of PSP to temperature leads to difficulties, since there is no secured temperature information available from the blade-surface.

The presented results show distributions of the intensitiy-ratio, which is inversely proportional to static wall pressure. The color-bars have been adjusted to allow comparison with already available data.

In the two Figure 7 the difference in raw intensity between the still rotor and the running condition is shown in the way the CCD camera looks at the rotor (which is turned by 90°).

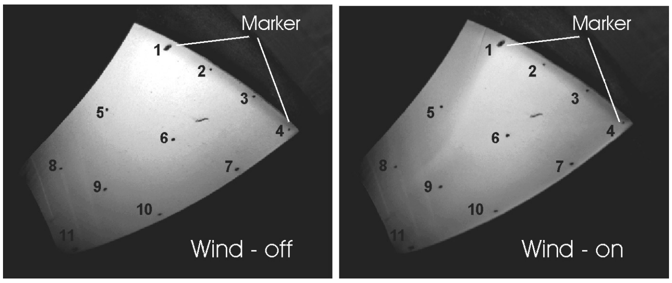

Figure 7.   Raw Data - standing still and running

To transform the raw data into useful information, firstly the background-light-picture is subtracted from both illuminated pictures. Secondly both pictures are brought to a geometric match, using the marker points, which show up as dark spots on the blade. Now the ratio between the intensities is calculated using the calibration of the paint. With averaging over four consecutive measurements at the same operating point and a correction of impurities in the images the following picture can be found:

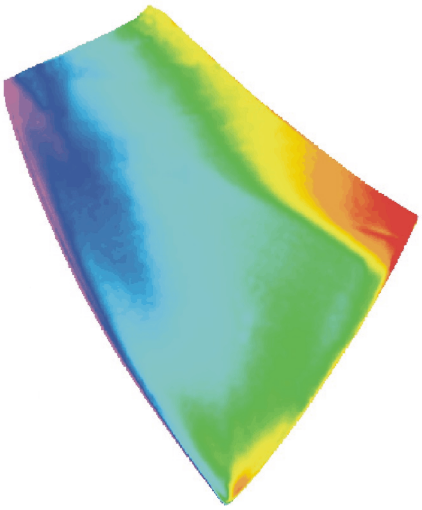

Figure 8. Averaged Intensity Information

The calculation of pressure values was performed with an assumed average surface Temperature of 60 °C, since no secure information on the temperatures at the suction-side surface was available. But even without correction of the paint‘s temperature-sensitivity, pressure values are in good agreement with CFD calculations. However, the emphasis of this early evaluation is on qualitatively interpretations of the flowfield.

The following series of pictures in Figure 9 shows the intensity-distribution on the suction-side surface at design-speed (20,000 rpm) and different massflow rates. From the first picture at near choke condition, the back pressure is increased by closing the throttle gradually up to a near stall condition.

16.25 kg/sec

15.80 kg/sec

15.25 kg/sec

14.80 kg/sec

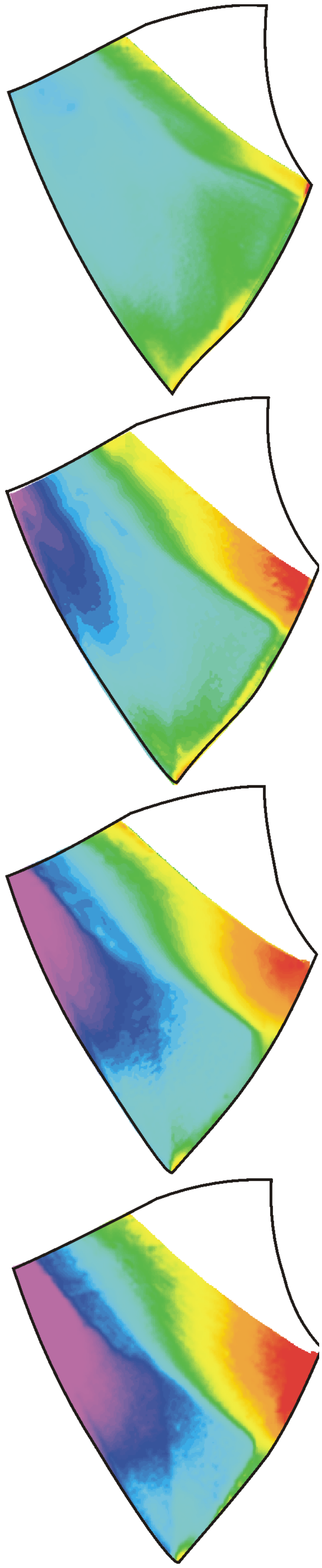

Figure 9. Shock Movement on Suction-Side

The movement of the shock towards leading edge is clearly visible. In the hub region behind leading edge an area of high velocity builds up with increasing incidence. Although the trailing edge is shadowed, a higher pressure-rise can be detected.

These results are in good agreement with Laser-2-Focus measurements taken in the blade-passage. In the Figure 10, for the near stall condition the PSP-picture of the suction-side is compared to the L2F measurement at 80% channel-height at the same operating conditions:

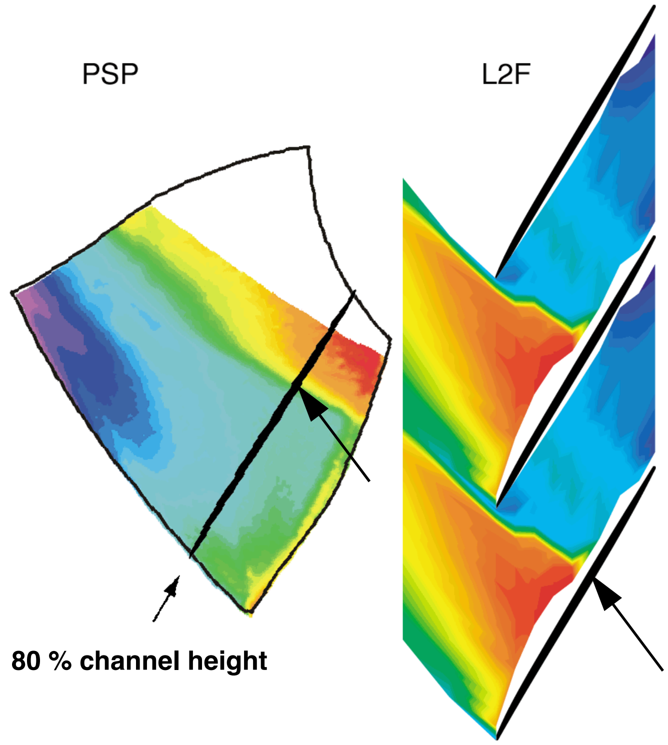

Figure 10. PSP vs. L2F

In both measurements the shock position can be found at around 60% chord (note that the PSP color scheme is adjusted for pressure, while the L2F colors are displaying Machnumbers).

PROBLEMS

One interesting effect that appeared during the experiments was a constantly decreasing signal quality unevenly distributed on the blade-surface. With reference pictures taken before and after the rotor's run, the effect could be quantized and taken into account for the evaluation.

However, remarkably the zone of greatest reduction in signal was towards the tip and downstream of the shock. At the moment it can only be speculated, that the rough transonic flow-conditions seem to affect the paint mechanically. With increasing centrifugal forces of over 80,000 g at the tip, probably the temperature rise of around 20-30 °K behind the shock seems to amplify the process of unhinging molecules from the paint-surface.

CONCLUDING REMARKS

The application of PSP to Darmstadt's Transonic Compressor has proven to be a useful method to determine pressure information from rotating blade-surfaces.

To exploit the potential in PSP for quantitative measurements, the system will be expanded to simultaneously obtain pressure and temperature information of the blade-surface. With introduction of a temperature-correction the accuracy of the measured pressure information should reach the excellent results achieved in previous applications, reported by Engler et. al. 2000.

Therefore the paint used for the experiment will receive temperature-sensitive molecules and with a new CCD camera-system all necessary information can be taken at once. Also the use of molecules that are sensitive only to the intensity of illumination is considered, since this would rule out any error resulting from slight fluctuations in the light-source.

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