

PIV APPLICATION TO TRANSONIC AXIAL AND RADIAL COMPRESSORS

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ABSTRACT

This paper summarizes latest DLR activities in turbomachinery research, involving the laser-based planar particle image velocimetry technique (PIV, see Raffel et al., 2007). In the first part of this contribution the experimental investigation of a single-stage transonic axial compressor equipped with casing treatment (CT) will be described. The measurements focused on the investigation of the blade tip interaction with the CT and flow phenomena occurring at the compressor's surge line. A new approach regarding light sheet introduction via periscope probe as well as a smoke-based type of seeding particles have been approved. The results obtained were subsequently used for comparison and validation of numerical calculations of the same compressor geometry performed in parallel to the experiments. The second part of this paper gives an overview on PIV measurements performed in the diffuser passage of a transonic high pressure ratio centrifugal compressor. PIV was used to analyze and further improve the understanding of the complex flow phenomena inside the vaned diffuser given the capability of capturing spatial structures.

INTRODUCTION

Regarding turbomachinery, the fields of application for conventional and laser-based measurement techniques are both diverse and challenging. For these the prime emphasis is on improving the understanding of the complex flow phenomena present inside turbines, compressors or entire stages and combustion chambers for jet engines as well as stationary gas turbines.

The first part of this contribution describes the PIV investigation of a single-stage transonic axial compressor equipped with a casing treatment (CT), consisting of 3.5 axial slots per rotor pitch. The nearly rectangular geometry of the CT cavities shown in Fig. 1 allowed one dividing bridge between two slots to be made of quartz glass with curvatures matching the casing. Thus the flow phenomena could be observed with essentially no disturbance caused by the optical access. Contrary to most other studies (e.g. Hathaway 2002, Lu et al. 2005 and 2006), the CT was designed especially accounting for an optimized optical access in the immediate vicinity of the CT, rather than giving maximum benefit in terms of stall margin extension. Details on the compressor facility can be found in Müller et al. (2007). Two periscope light sheet probes were specifically designed for this application to allow for precise alignment of the laser light sheet at three different radial positions in the rotor passage (see right part of Fig. 1, at 87.5%, 95% and 99% blade height). For the outermost radial position the light sheet probe was placed behind the stator and aligned to pass the light sheet through one stator passage into the blade tip clearance. For the two remaining light sheet positions in the tip region of the blade passage another special periscope probe was placed upstream of the rotor in a clearance groove of the casing with a considerable circumferential and axial distance to the blades, hiding the end cap of the probe. This measure allowed minimizing the effect of the probe to the main inlet flow field. It was demonstrated that the PIV technique is capable of providing velocity information of high quality even in the tip clearance region of the rotor blades. Phase-constant measurements were carried out with a resolution of 8 phase angles per blade pitch in relation to the CT slots visible in the camera's field of view. The chosen type of smoke-based seeding with very small particles (about 0.5 μm in diameter) supported data evaluation with high spatial resolution, resulting in a final grid spacing of 0.5 x 0.5 mm.

The PIV results were compared with numerical simulations of the same compressor stage including the CT geometry, carried out using the DLR TRACE code following a new approach to efficiently perform time-accurate casing-treatment simulations (see Yang et al. 2003, 2006). The PIV data base established in this project will also be used for validation of the new implementations of DLR TRACE code.

In the second part of this paper a PIV application in the diffuser passage of a highly loaded transonic centrifugal compressor is presented. Based on previous, primarily, point-wise laser-optical measurements the compressor was re-designed resulting in an improved impeller as well as an advanced diffuser geometry with a single-stage pressure ratio of 6:1 at 50,000 rpm. Due to the conical shape of the diffuser geometry (Fig. 2, upper

right part) as well as high pressure and temperature, it was not possible to use standard, off-the-shelf light sheet probes with a common 90° deflection of the light sheet at the exit. Again, a periscope light sheet probe needed to be designed specifically for this application. The periscope probe shown in Fig. 2 (left part) allowed for adjustment of the light sheet in rotational and axial position and angle relative to the chord of the vane profile. The probe was purged with dry and clean air for cooling purposes during compressor operation and to avoid seeding contamination of the optical parts at the tip of the probe. This study also included phase-resolved measurements of the diffuser vane passage flow with respect to the impeller blade position (16 phase angles related to one complete main-splitter-main passage). Velocity fields have been acquired for three light sheet planes in the diffuser passage, adjusted at the different span-wise positions chosen for investigation (total passage height approximately 8 mm). In addition, the potential of stereo PIV for this type of turbomachinery application could be successfully demonstrated.

As in the previously mentioned research project the flow field results obtained by PIV are to be used for validation of related CFD calculations, which in turn are expected to lead to further improvements in compressor performance. Based on the combined results of PIV measurements and CFD calculations of the same compressor geometry a better understanding of the complex flow characteristics can be achieved.

RESULTS AND DISCUSSION

In Fig. 3 the combined flow field results of the PIV measurements in the axial compressor are shown for all three light sheet planes and for one phase relation ($\Phi = 0^\circ$) between the rotor and the CT. The left part of the figure represents the phase-averaged absolute velocity distribution at peak efficiency of the aerodynamic design point (PE-ADP) at 100% rpm. A clear bow shock can be detected upstream of the rotor blade's leading edge. An additional passage shock develops on the blade pressure side at approximately 10% chord length. While for the lowest light sheet position the homogeneous inlet flow dominates the flow field, the two upper light sheet planes show evidence of the CT interacting with the rotor flow. Driving the compressor to near stall conditions by increasing the back pressure of the stage (see right part of Fig. 3), the leading edge bow shock moves upstream and is now much more detached. The pressure side passage shock also moved upstream merging with the detached bow shock. At near stall conditions the influence of the CT is also more pronounced for the lowest light sheet plane, which is indicated by the non-homogeneous inlet flow approaching the rotor. For the measurement planes at 95% and 99% blade height the effect of the CT to the main flow is visible in terms of smaller structures of higher and lower velocity, scaling with the dimension of the slot width. Those structures are due to mass flow recirculation between the main passage flow and the CT: a portion of the fluid is driven into the CT slots from the blade pressure side and injected to the main flow again on the suction side of the blade. Therefore regions of very low in-plane velocity can be interpreted to have a very strong out-of-plane component, which unfortunately could not be quantified during the PIV measurements presented herein. In the accompanying CFD calculations of the same compressor stage the mass flow recirculation could be detected clearly and the velocity maps are in very good agreement with the PIV results (see Voges et al. 2008, Schnell et al. 2008). In an additional part of the research program stereoscopic PIV measurements are planned to validate the interpretation of the third velocity component from the PIV data of the first measurement campaign.

Regarding the phase-resolved PIV measurements performed in the highly loaded diffuser of the circumferential compressor stage, the instantaneous velocity fields given in Fig. 4 are dominated by small structures and strong gradients, indicating the unsteady and highly turbulent character of the diffuser flow. In contrast to that the flow direction is strongly aligned with the chord line of the diffuser vanes. The only variation of flow direction can be observed for the interaction with impeller blade wake flow or with the leading edge of the diffuser vane. Following the development of the transient diffuser passage flow obtained from different phase angles, the flow structures of the passing impeller can be observed. Downstream in the diffuser inlet area the fast mixing process of blade passage flow and the wake smoothes out the turbulent structures. Although the passage height in the diffuser is only about 8 mm, the flow field shows a strong 3-dimensional behavior, which was predicted by the accompanying CFD calculations and successfully validated by means of the point-based Laser-2-Focus technique as well as stereoscopic PIV measurements.

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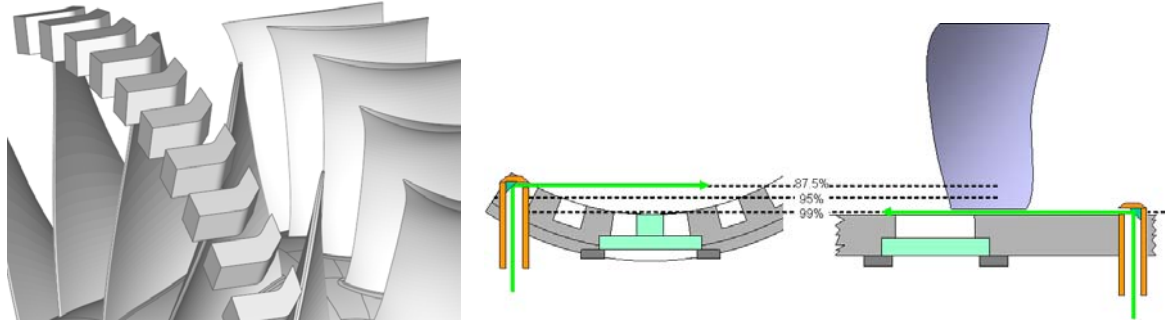


Fig. 1 Transonic axial compressor stage with the investigated casing treatment geometry (left part); light sheet positions in the blade tip region (87.5% and 95%) and in the tip clearance (99%) of the rotor (right part)

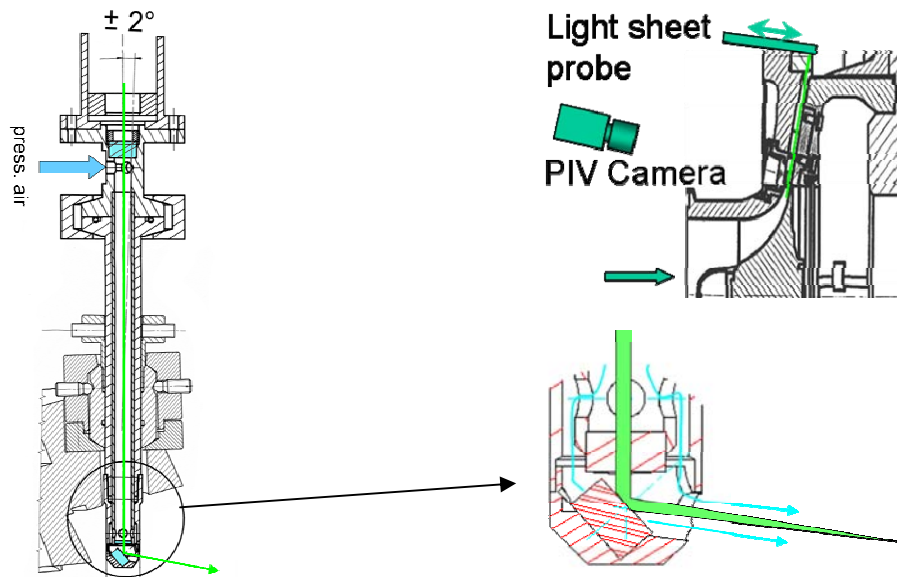


Fig. 2 Schematic of the periscope light sheet probe (left and lower right part) and PIV setup at the centrifugal compressor stage (upper right part)

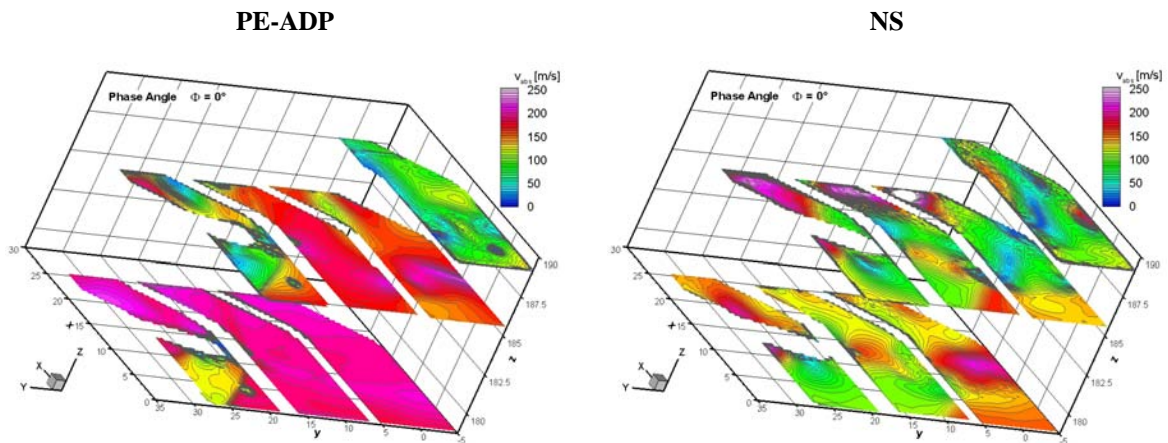


Fig. 3 Measured velocity fields with treated casing at 100% RPM comparing peak efficiency (PE-ADP, left part) and near stall (NS, right part) conditions, illustrated for a rotor phase angle of $\Phi = 0^\circ$

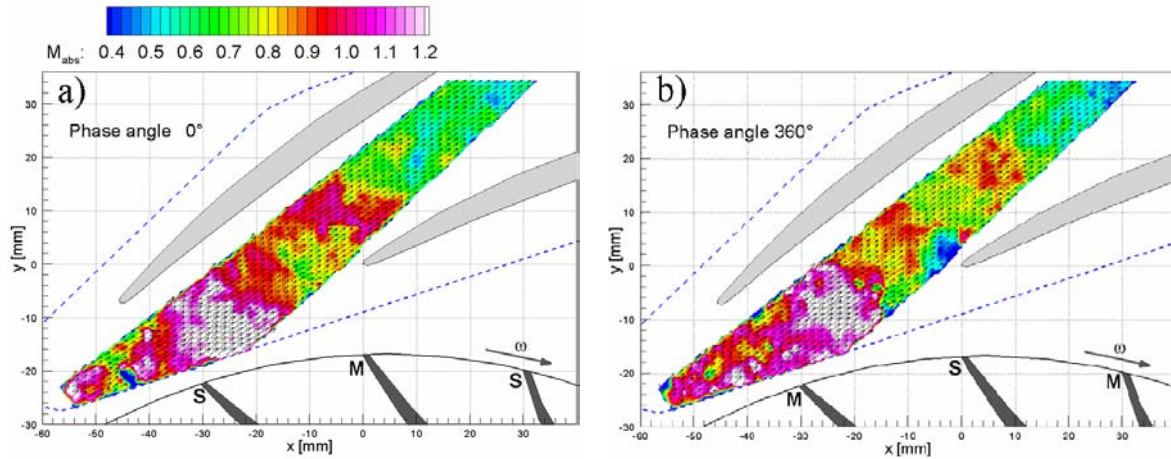


Fig. 4 Instantaneous Mach number distribution in the diffuser passage at 50% span comparing two opposite phase angle relations of the impeller at a rotational speed of 50,000 RPM (number of shown vectors reduced for better overview)

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