PIV Measurements in a Compressor Test Rig with Distorted Inflow

Sonja Schulze[*], Rainer Hain[†]
Christian Cierpka[‡] and Christian J. Kähler[§]
Institute of Fluid Mechanics and Aerodynamics
Universität der Bundeswehr München, 85577, Neubiberg, Germany

Abstract

At high angles of attack and under gusty conditions the engine of an aircraft is typically exposed to distorted inlet conditions. The disturbed inlet flow may alter the efficiency of the engine or even may lead to an increased loading of the blades. Thus, Particle Image Velocimetry measurements were performed in the transonic compressor test rig at TU Darmstadt. A distortion generator was applied for generating a total pressure loss as well as strong vortices. The stereoscopic PIV investigations in front of the transonic rotor allowed the identification of counter-rotating vortex pairs behind the distortion generator. The acceleration of the flow in the duct between spinner and housing led to a strong decrease of the disturbances and thus to a moderate influence of the flow in front of the rotor.

1 Introduction

The presented paper deals with inlet distortions caused either by wakes from the aircraft or high angles of attack resulting in local flow separations on the inner contour of the nacelle, see [2]. Such separations may also be caused by flight maneuvers and ground crosswind operation, see [5]. In order to allow for a save operation of the aircraft, the engine must be insensitive to these inlet distortions. The level of distortion needs to be specified/quantified and an engine will be designed and tested to show stable operability within the specified distortion limits. For the engine manufacture it is therefore important to use appropriate distortion descriptors and a strategy to test the engine which is accurate and cost efficient. Once the engine is certified and flight testing of the aircraft started the aircraft/engine configuration will be certified.

In the 1960s Rolls-Royce performed a lot of testing of compressors and suggested circumferential critical values, see [4]. Distortions concentrated within a circumferential section of 60° were found to cause the most severe stability issues and the so called DC60 value was established

[*]Research scientist
[†]Research scientist
[‡]Research scientist
[§]Professor

and worked well in combination with the parallel compressor theory for many years. DC60 is the ratio of difference in total pressures averaged over the worst 60° segment and the complete fan face to the dynamic head at the fan face. Using simplified circumferential distortion descriptors assumes a response based on the rotation of the rotor through a fixed distortion area and neglects radial redistribution of distortion. For improved modelling of the time response of the compressor the shape of the distortion is important. In addition to the circumferential shape which is steady in the absolute frame of reference dynamic parts are present, which can add up to one-third to the steady state pressure. If the compressor tends to stall in the near tip region and tip flow becomes important the parallel compressor theories will not be accurate enough and a better understanding of the tip flow is necessary. Therefore numerical investigations by means of state-of-the-art CFD as well as state-of-the-art experimental methods are required. The experimental results serve as a data base for the validation of the numerical results as these will be more and more be applied for compressor design.

According to [1] different kinds of distortions were observed which are:

- Large scale vortices behind the fuselage causing swirl and unsteady inflow
- Longitudinal vortices build up on the fuselage (similar to ground vortices)
- Intake shock induced lip separation causing separation bubbles

In the literature several papers can be found discussing those kinds of distortions. The majority of them are dealing with swirl and longitudinal vortices. In this paper the characterisation and the effect of separation bubbles in the intake and unsteadiness caused by the fuselage wakes (small scale vortex shedding), on the performance is the main focus. On the rig a vortex generator is used to simulate the vortex shedding. The experiments were performed in the well established compressor rig at TU Darmstadt by using standard compressor instrumentation along with unsteady pressure measurement equipment as well as optical measurement techniques such as stereoscopic Particle Image Velocimetry (PIV). In the present paper, the results of the stereoscopic PIV measurements will be discussed. Further information is given in [1].

2 Test facility and experimental setup

All compressor investigations were conducted in the transonic compressor test facility of the TU Darmstadt. The open circuit designed facility sucks ambient air into the compressor via a settling chamber and a flow meter before entering the test section, see Fig. 1. To be able to investigate generic inlet distortions the known research compressor Darmstadt-Rotor-1/Darmstadt-Stator-1 (see [3]) was equipped with a modified casing to hold the distortion generator. The casing section with the distortion generator could automatically be rotated to different circumferential positions. This was important to obtain the full flow information behind the distortion generator without traversing the PIV measurement plane and the Kulite and to keep the relative position to the stator. The test section depicted in Fig. 2 shows the axial position of the distortion generator and the large PIV window. The positions MP1 to MP3 show the measurement planes for the Kulite total pressure sensor. The upstream position MP1 is 75 mm downstream of the distortion generator. The distortion generator is connected to a ring inside the casing which can be freely positioned by an external actuator. Downstream of the stator five equally distributed rakes in circumferential direction measure total temperature and total pressure at eleven radial positions.

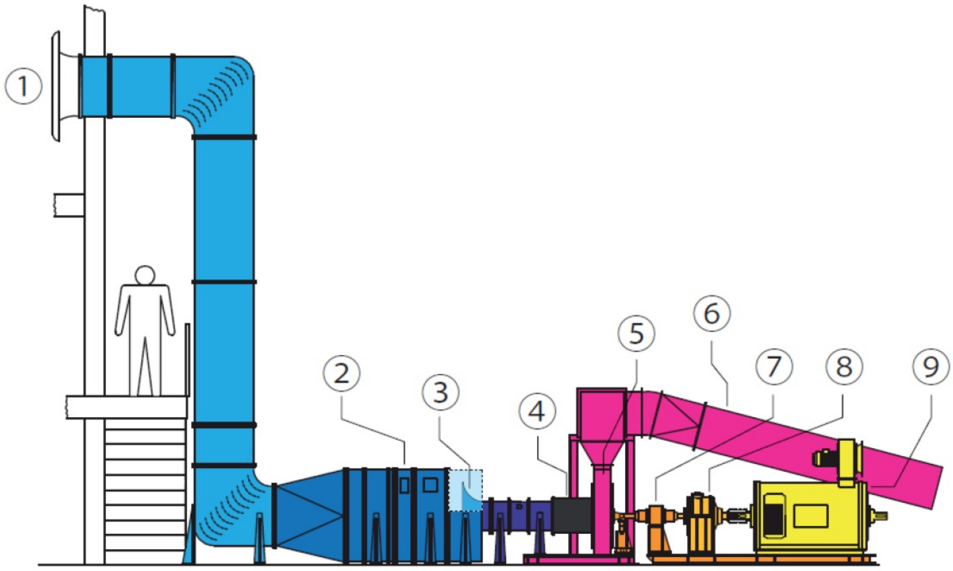

Figure 1: Schematic drawing of the transonic compressor test facility at TU Darmstadt. 1) Inlet, 2) Settling chamber, 3) Nozzle, 4) Test section, 5) Radial diffusor, 6) Outlet ducting, 7) Torque meter, 8) Gearbox, 9) D/C Drive. From http://www.glr.tu-darmstadt.de/media/glr/tsv/pruefstand.png

In order to gain more insight into the flow structure behind the distortion generator stereoscopic Particle Image Velocimetry (PIV) measurements were conducted with the measurement setups described. Fig. 3 on the left hand side shows the positions of the five investigated measurement planes relative to the distortion generator for the measurements in the $x - y$-plane. As already mentioned, the distortion generator was rotated while the PIV setup and the lightsheet were not moved. In addition, measurements in the $y - z$-plane at location $x = 84\,\text{mm}$ were performed. A sketch of the setup is given in Fig. 3 on the right hand side.

3 Results

Special emphasis was put on the near stall and peak efficiency operating points for the 65 % and 100 % characteristics. But also other massflow rates between near stall and peak efficiency were analyzed. In Fig. 4 averaged vector fields are shown for the five different positions behind the distortion generator. The flow first approaches the distortion generator plotted on the left hand side of each figure and continues afterwards towards the rotor plane on the right hand side. The operating point is peak efficiency of the 100 % characteristic at a true massflow rate of 12.14 kg/s. The background color depicts the value of the velocity component in the axial direction. Blue regions thus represent areas of reversed flow. In general it can be seen that the flow is accelerated towards the rotor plane since the spinner causes a reduction of the test rig crosssection. The area of reversed flow is largest in the middle of the distortion generator ($\delta = 90°$, about 62 mm length) and decreases towards the side edges of the generator. Note that the measurement planes $\delta = 70°$ and $\delta = 110°$ are shifted equally from the middle of the distortion generator to both sides. The areas of reversed flow however differ slightly to the symmetrical geometry. The reason for this deviation is the influence of the rotating spinner and the rotor blades. The area of reversed flow for $\delta = 70°$ is always a little smaller than the according area for $\delta = 110°$.

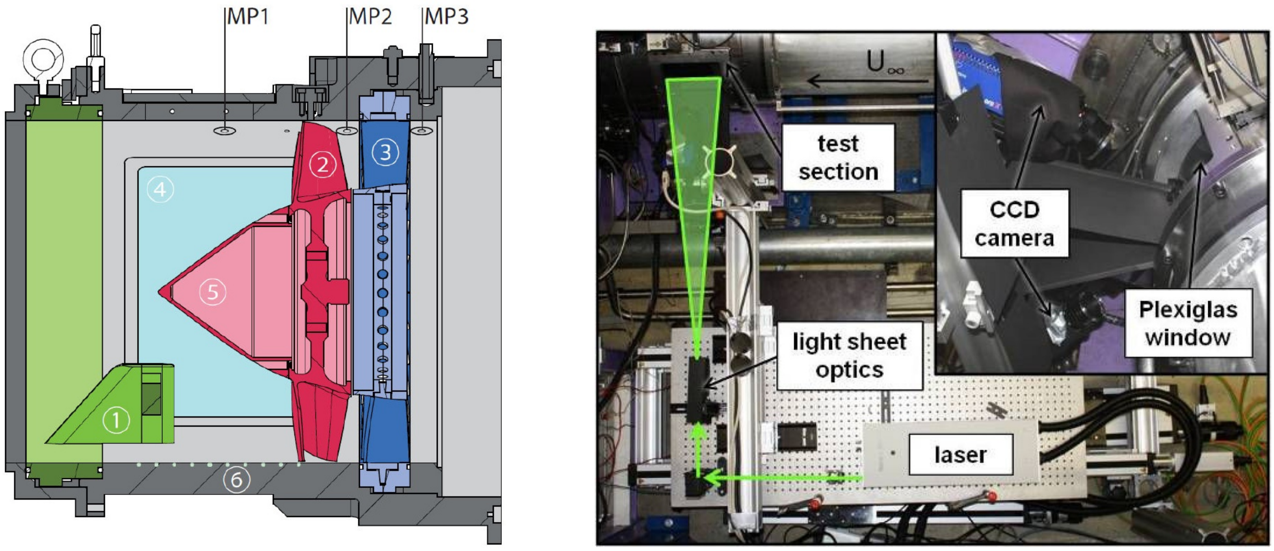

Figure 2: Left hand side: Drawing of the test section: 1) Distortion generator, 2) Darmstadt-Rotor-1, 3) Darmstadt-Stator-1, 4) Plexiglas window, 5) Spinner, 6) Static wall pressure taps. From [1]. Right hand side: Experimental setup of the PIV measurements in the $x - y$-plane.

Within a characteristic the size of the area of reversed flow is also dependent on the true mass flow rate in the test rig. The higher the true mass flow rate is the bigger the region of reversed flow becomes (not shown here). The effect of the rotational movement of the spinner and rotor blades can also be observed in Fig. 5 where the turbulent kinetic energy is displayed for all investigated positions behind the distortion generator. The exemplary operation point again is peak efficiency of the 100 % characteristic at a true mass flow rate of 12.14 kg/s. The utmost measurement planes outside of the distortion generator ($\delta = 55°$, $\delta = 125°$) are still affected by the generator body, and the influence of rotating spinner and blades can also be observed. The values of turbulent kinetic energy for all investigated operation points are in general higher for the outer measurement planes in the direction of rotation ($\delta = 55°$) than for the planes in the opposite direction ($\delta = 125°$). Also the vortices are carried further downstream close to the spinner than close to the Plexiglas window at $\delta = 70°$ and $\delta = 110°$. The authors hope for a more comprehensive insight into this 3D flow problem from numerical simulations for this setup. Furthermore Figs. 4 and 5 show discontinuities close to the test rig wall where the Plexiglas window is situated at approximately $x = 31$ mm and $x = 84$ mm. These discontinuities are due to the transonic operating point of the compressor. Here shocks form at every single rotor blade and proceed upstream. The abnormality of the flow field around $x = 105$ mm and $y = 100$ mm is a consequence of reflections at the spinner's surface which in the future can be avoided by applying special fluorescent paint on all surfaces and using suitable filters in front of the cameras. The turbulent kinetic energy in the $y - z$-plane at $x = 84$ mm is given in Fig. 6. The results correspond well with these given in Fig. 5. It is observed that the flow is strongly altered by the distortion generator.

The distortion generator was analytically designed to show a vortex shedding with a frequency of ≈ 440 Hz, and pre-experiments in a blow-down wind tunnel at the Universität der Bundeswehr in Munich with a simplified distortion generator and a time-resolved PIV system yielded a characteristic frequency in the order of magnitude of ≈ 450 Hz up to $x = 100$ mm and ≈ 900 Hz behind, see Fig. 7. The increasing frequency at higher x-locations results from the vortices which are shed at the lower and upper side of the distortion generator and which

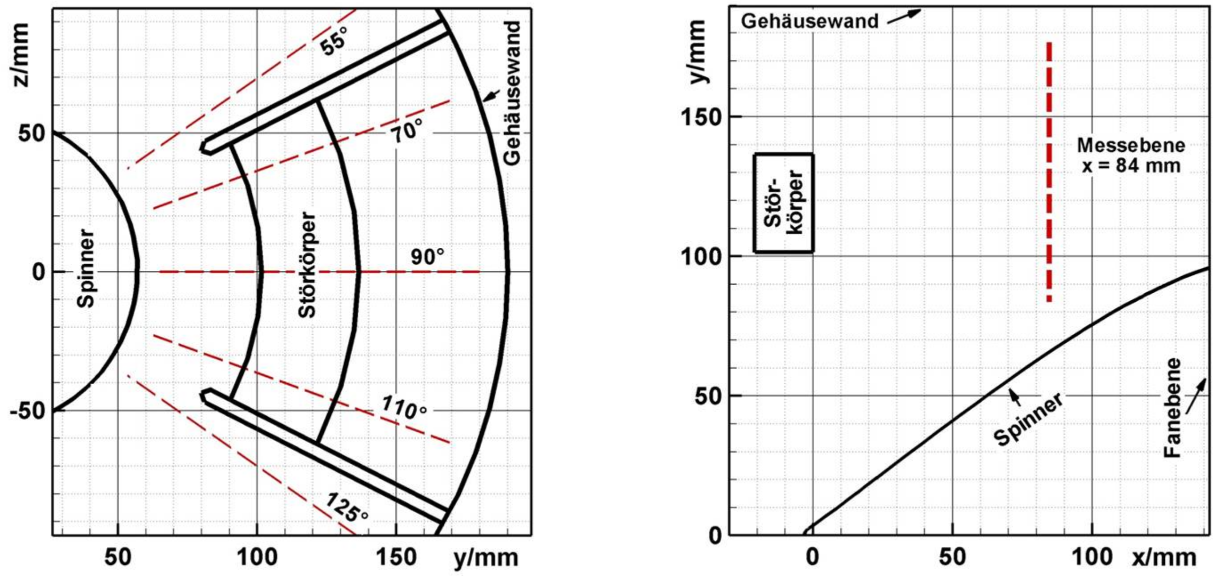

Figure 3: Left hand side: Measurement plane positions behind the distortion generator for the $x-y$-plane measurements (view upstream). Right hand side: Light-sheet orientation and position for the $y-z$-plane measurements.

periodically influence the flow in this region. In the experiments at TU Darmstadt no time-resolved PIV system was applied. Therefore the characteristic frequency of the vortex shedding was estimated by determining the distance d between two counter-rotating vortices and their convection velocity U_w. Thus the frequency of the vortex street is calculated from Eq. 1:

$$f = \frac{U_w}{d} \tag{1}$$

Fig. 8 shows vortex pairs from instantaneous vector fields which are typical for the distortion generator's vortex street. From a variety of instantaneous vector fields a characteristic frequency between 390 Hz and 500 Hz was found by this means for equally rotating vortices. A comparison with the intended 440 Hz proofs that the design of the vortex generator in this aspect was successful. In Fig. 8 an entire instantaneous flow field is shown for peak efficiency of the 100 % characteristic. The coloring depicts the absolute value of the velocity vectors, and it can be stated that the large scale coherent vortices decay before they even reach the rotor plane. This can also be assumed by looking at the size of the area of reversed flow which hardly expands over half the distance between distortion generator and rotor plane, see Fig. 4. However, the interference of the distorted flow with the compressor's stage is still significantly in agreement with pressure measurements, see [1] for more information. The results obtained from the stereoscopic PIV measurements give detailed insight into the 3D topology of the flow field, induced by the distortion generator, the distribution and intensity of the turbulence and the frequency of the coherent vortices. This information is valuable for the validation of numerical flow simulation techniques but also for designing distortion generators with other properties.

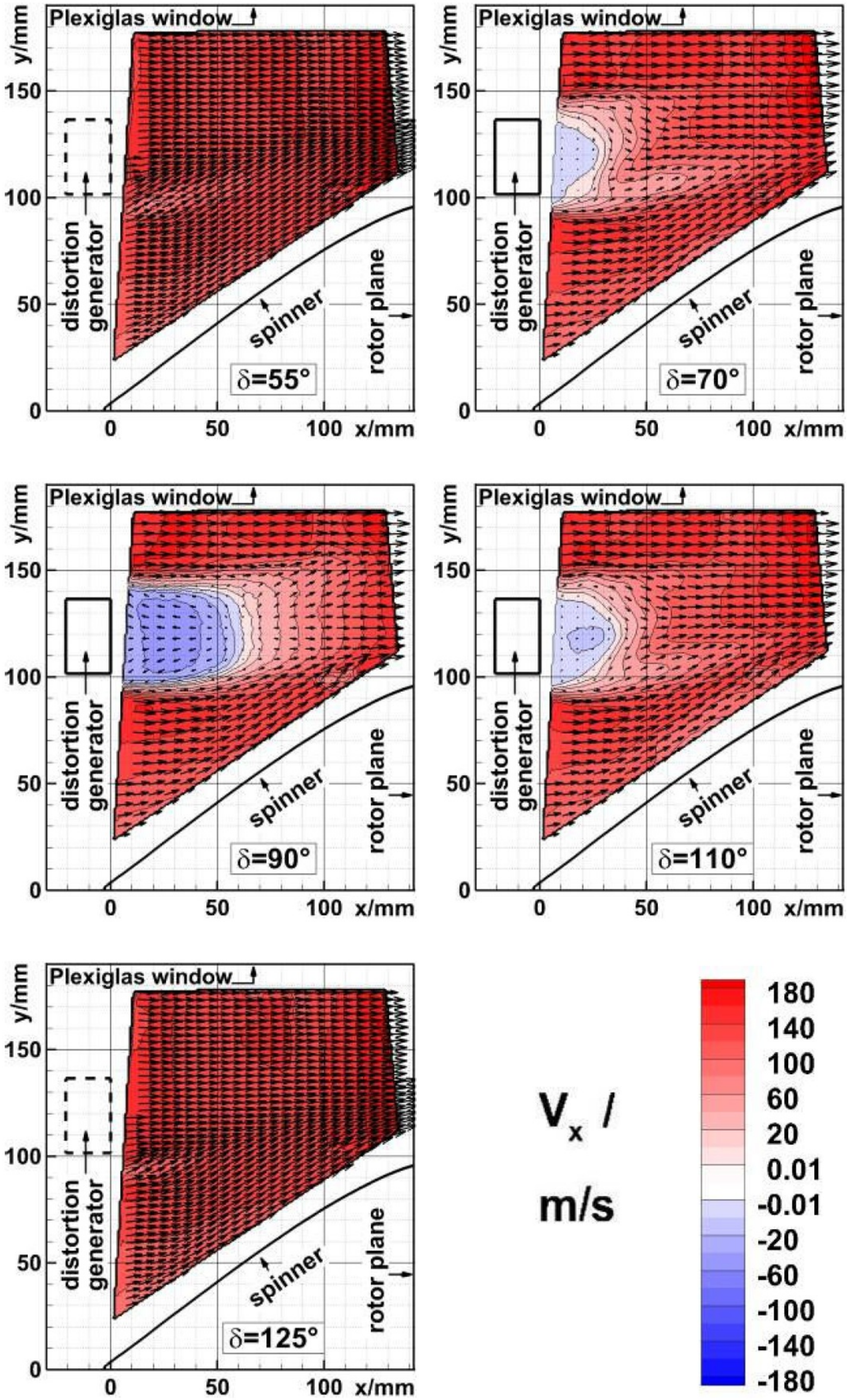

Figure 4: Regions of reversed flow for different positions behind the distortion generator, peak efficiency, 100 %, $m_{\text{true}} = 12.14\,\text{kg/s}$.

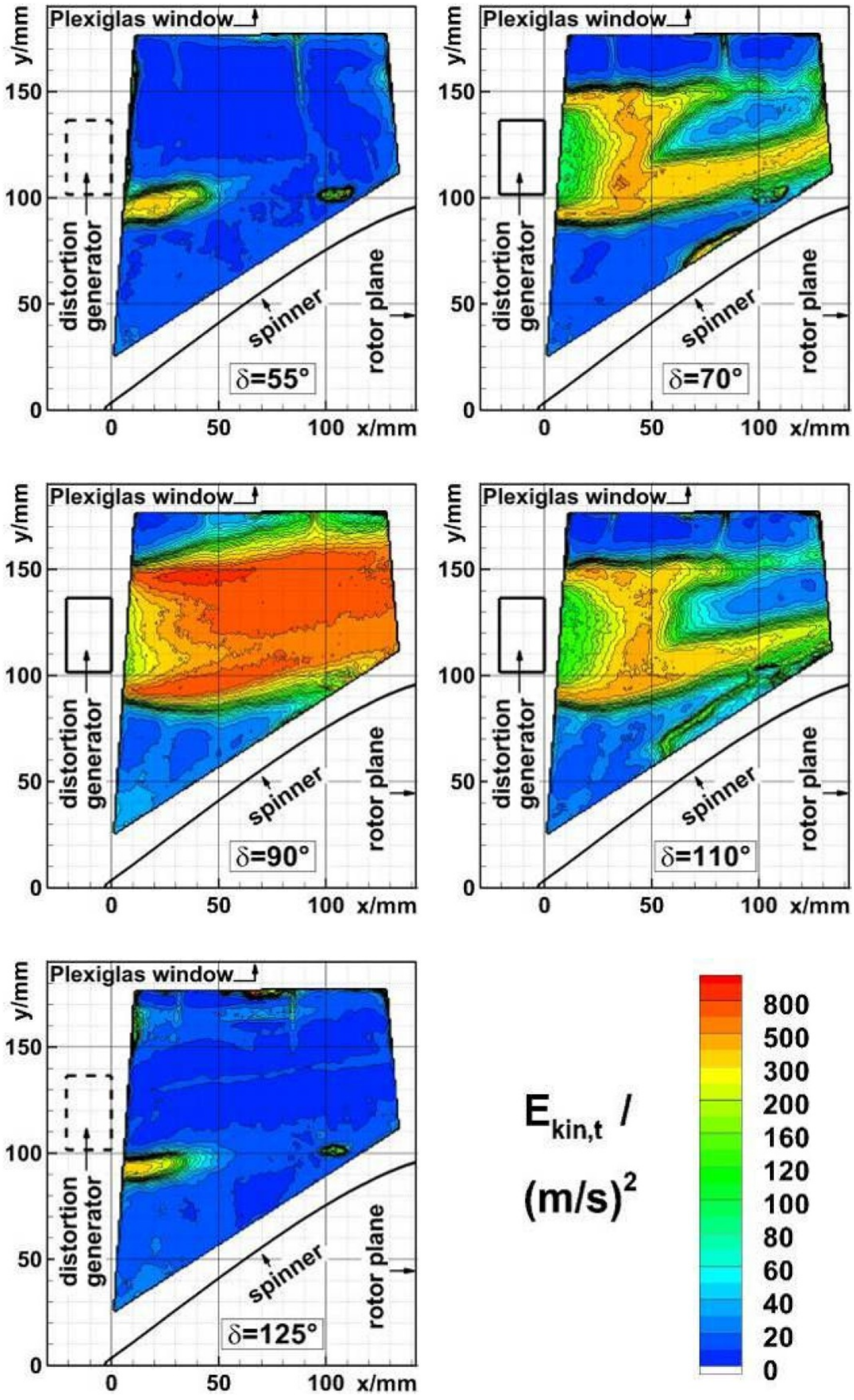

Figure 5: Turbulent kinetic energy for different positions behind the distortion generator, peak efficiency, 100 %, $m_{\mathrm{true}} = 12.14\,\mathrm{kg/s}$.

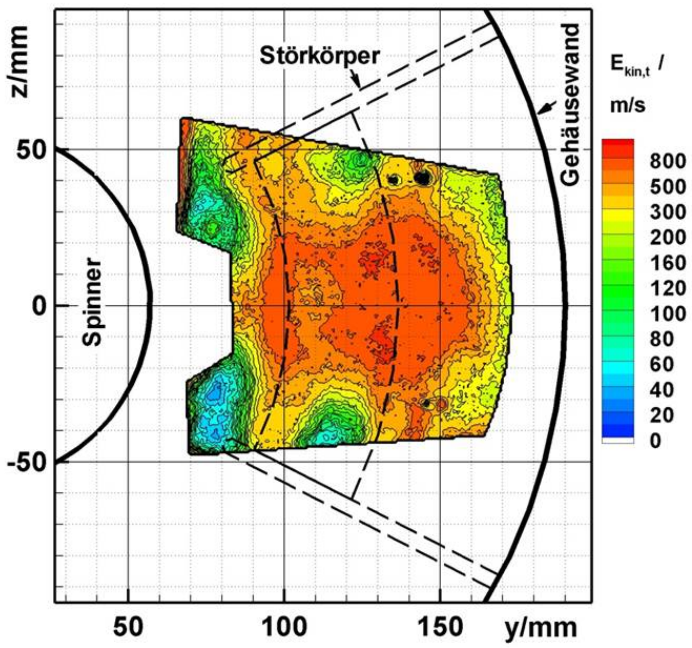

Figure 6: Turbulent kinetic energy behind the distortion generator in the $y - z$-plane at $x = 84\,\text{mm}$, peak efficiency, $100\,\%$, $m_{\text{true}} = 12.14\,\text{kg/s}$.

4 Conclusion

The paper presents the results of stereoscopic PIV measurements of a generic rig test to simulate unsteady inlet distortions and their influence on a transonic compressor stage. One of several possible kinds of distortions was chosen to show the feasibility of the rig and measurement techniques to gather all important information for better understanding of the fan distortion interaction and validation of numerical methods. The test was supposed to focus on aerodynamic phenomena and blade vibrations were avoided, which was monitored by the rigs tip timing system. The TU Darmstadt compressor rig was successfully modified for generation and detailed measurements of the distorted inflow. The mechanical design and traverse control in the facility allows reproducible measurements. The window for the PIV measurements was sufficiently large and small vibrations did not lower the measurement accuracy.

As shown by the PIV measurements, the distortion is locally focused on a 60° segment and

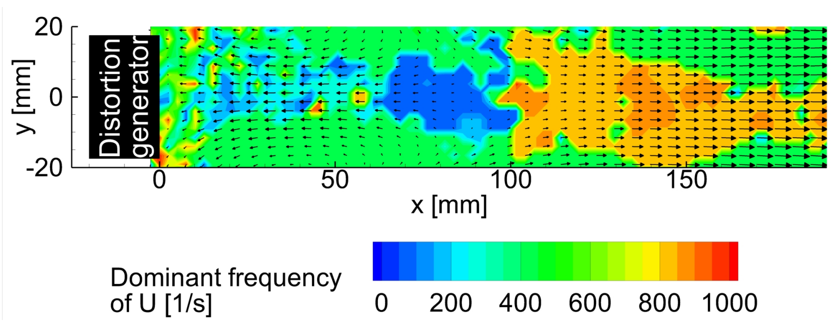

Figure 7: Results from pre-experiments at Bundeswehr University Munich. 2D distortion generator, Ma = 0.4.

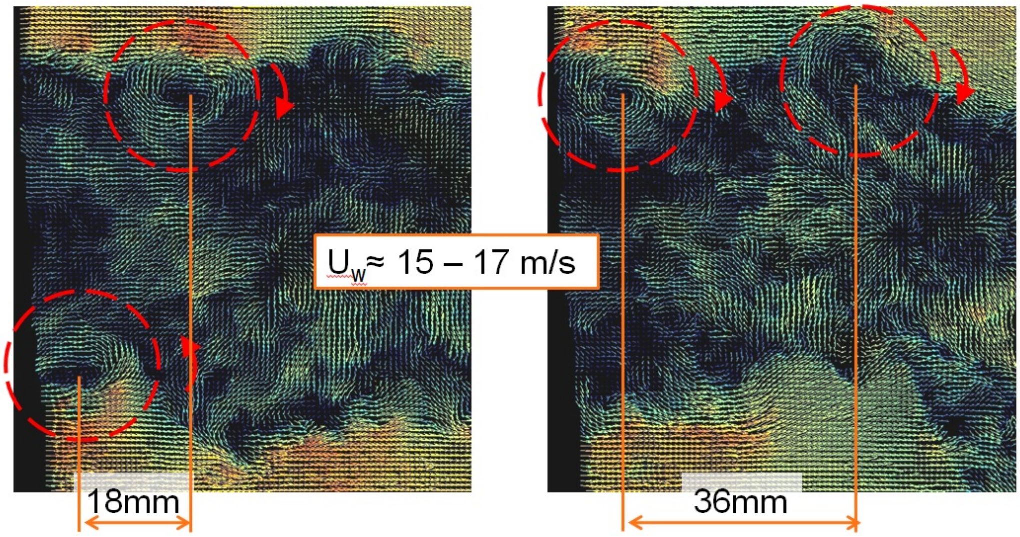

Figure 8: Instantaneous vector fields, peak efficiency, 100 %, $m_{\mathrm{true}} = 12.14\,\mathrm{kg/s}$.

midspan of the rotor. The axial development in front of the rotor shows a decay of vortices shed by the distortion generator before they reach the rotor face. In the tests of the distortion generator in a wind tunnel without a rotor/spinner and constant mean flow speed the decay moved further downstream. Characteristic frequencies derived from the PIV measurements correspond to the design of the distortion generator and isolated measurements.

However, the effect of the distortion generator on the overall perfomance is quite limited. In the proposed follow-on program the distortion will therefore be increased by moving the generator closer to the rotor and the distortion will focus on the blade tip. The used rotor 1 of the TU Darmstadt rig is sensitive to tip flow disturbance and in the next campaign the aim is to significantly drop stability margins by affecting the tip vortex.

Acknowledgments

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