Tip clearance flow field measurements at a turbine rotor with squealers

Andreas Fischer¹*, Jörg König¹, Lars Büttner¹, Jürgen Czarske¹,
Clemens Rakenius²*, Heinz-Peter Schiffer²

¹: Laboratory for Measuring and Testing techniques, Technische Universität Dresden,
Helmholtzstr. 18, 01062 Dresden, Germany
²: Department of Gas Turbines and Aerospace Propulsion, Technische Universität Darmstadt,
Petersenstraße 30, 64287 Darmstadt, Germany
*correspondent authors: andreas.fischer2@tu-dresden.de, rakenius@glr.tu-darmstadt.de

Abstract  Understanding and designing the tip clearance flow (TCF) in turbine rotors is one key aspect for improving the efficiency of turbines. Especially for rotor blade tips equipped with squealer, the TCF behavior is not fully understood. For this reason, optical measurements and numerical flow simulations of the mean velocity in the TCF are presented. Optical field measurements of all three velocity components were accomplished in the rotor TCF at a turbine test rig using frequency modulated Doppler global velocimetry. This measurement technique provides a high temporal resolution of 10 $\mu$s for resolving the TCF during rotation of the rotor at a blade passing frequency of 930 Hz. The rotor blades were equipped with squealer tips and the TCF above the squealer cavity in the tip gap was successfully measured. The measurement agrees well with flow simulations showing gradients in the tip gap above the squealer cavity. Furthermore, the tip clearance vortex was resolved downstream at the suction side of the rotor blades. Considering the presented characterization and perspectives of the experiment, the capabilities of the applied measurement technique for non-invasive field measurements of the TCF in turbine rotors are promising. This greatly supports the development of new turbines with improved efficiency by designing the TCF.

1. Introduction

Improving the efficiency of aircraft engines for reducing noise, fuel consumption and pollutant emissions is an ongoing challenging task [1]. For this purpose, the understanding of the flow behavior in turbo machines is of utmost importance, which always requires flow measurements, either for validating flow simulations or to identify new flow phenomena. Regarding the improvement of the efficiency of the turbine, the understanding and proper design of the tip clearance flow (TCF) is one key aspect of the research [2]. The TCF between the tip of the rotor blades and the casing causes a flow leakage and introduces turbulence affecting the performance of the machine [3]. In order to reduce the flow leakage, rotor blades with so-called squealer tips are investigated [4,5]. However, the potential of squealer tips is not fully understood, because flow field measurements of the TCF in the tip gap of rotating turbine rotor blades with squealers are missing. The three main challenges are

a) to obtain a high temporal resolution of typical $\leq 10 \mu$s for resolving the blade motion,
b) to achieve a field measurement of all three velocity components to image the entire TCF,
c) to use a non-intrusive optical technique and to illuminate the TCF in the tip gap (usually only about 1 mm wide in the experiment) and thereby avoiding strong reflections from the casing or the moving blades, which can preclude the measurements.

Recently, particle image velocimetry (PIV) was used for instance for measuring the TCF above the squealer cavity in a linear cascade [6]. However, the TCF in rotating devices is finally of interest, where, contrary to a linear cascade, the measurement technique has to cope with a curved casing and machine vibrations. For instance, Kegalj et al. [7,8] presented PIV measurements in a turbine test rig. However, measurements in the tip gap were not achieved due to reflections. Voges et al. [9] presented PIV measurement results from a transonic compressor with casing treatment resolving the TCF beside the tip gap. However, measurements directly above the blade tip were also precluded by
reflections. Hence, the common planar illumination when using PIV seems to be not appropriate for measurements in rotating machines with a curved housing.

In order to minimize disturbing reflections in a round-shaped environment, the novel idea is to use a narrow axial laser beam through the center of the tip gap. The complete velocity field can be resolved by measurements at different rotor and stator positions. The velocity is measured with a frequency modulated Doppler global velocimeter (FM-DGV) [10], whose capabilities for near-wall measurements down to 100 µm wall distance was recently shown [11]. Using FM-DGV, the Doppler frequency shift of light scattered at seeding particles is evaluated and, thus, the particles do not have to be optically resolved. This allows robust light detection. Furthermore, it provides multi-point, multiple component measurements, a sufficiently high temporal resolution of 10 µs and it was already successfully tested in a cascade with plane tips resolving the TCF [12,13]. As a result, FM-DGV meets the requirements a) and b). Concerning c), measurements at a turbine test rig have to be performed to prove the capabilities of FM-DGV in rotating machines for investigating the TCF of a rotor with squealer tips having a small tip gap of only 900 µm.

This paper reports on the successful FM-DGV flow measurement in the tip gap above the rotor squealer cavity performed in a rotating turbine test rig. First, the FM-DGV measurement principle is briefly summarized in section 2. Subsequently, the test rig and the applied measurement setup are described in section 3. The measurement results are presented and compared with simulations in section 4. The paper closes with an outlook and final conclusions, which are given in section 5 and 6, respectively.

2. The FM-DGV measurement principle

The schematic of an FM-DGV system is illustrated in Fig. 1a for a one component measurement. The beam of a narrow band laser with the sinusoidally modulated frequency is illuminating the measurement region in the flow. The laser center frequency is stabilized at a molecular resonance. Due to the flow velocity $\vec{v}$ and the occurring Doppler effect, the scattering on seeding particles causes a shift in frequency

$$ f_D = f_c \frac{\vec{v}(\vec{o} - \vec{i})}{c} \quad (1) $$

of the scattered light with $c$ as light velocity and $f_c$ as laser center frequency. This Doppler frequency shift $f_D$ is caused by a velocity component along the direction $(\vec{o} - \vec{i})$ while $\vec{o}$ and $\vec{i}$ are the observation and laser incident direction, respectively. For three component measurements, two additional observation directions are applied for instance [13,14].

In order to determine the Doppler frequency, the illuminated measurement region is imaged through a molecular absorption cell onto a fiber array coupled with a detector array. Since the laser center frequency is stabilized at the molecular resonance frequency, the laser frequency modulation and the non-linear spectral transmission behavior of the absorbing gas in the absorption cell lead to a modulation of the transmitted light intensity as shown in Fig. 1b. The ratio

$$ q = A_1 / A_2 \quad (2) $$

of the first and second order harmonic amplitudes $A_1$, $A_2$ of the sampled detector output signals serve as a measure of the laser center frequency. Hence, the Doppler shift of the laser center frequency (corresponding to the flow velocity) is measured as a change of the amplitude ratio $q$. 
The first and second order harmonic amplitudes are estimated by calculating the corresponding Fourier coefficients:

\[ A_k = \frac{2}{N} \sum_{n=0}^{N-1} s(n/f_a) \cdot \cos(2\pi knf_m / f_a) , \quad k = 1,2, \quad (3) \]

with \( s(t) \) as detector output signal, \( f_a \) as sampling rate and \( N \) as number of samples. As a result of evaluating only integer multiples of modulation periods, no leakage effects occur and no additional peak detection algorithm is required. Further details about the measurement principle can be found in [10-14]. The calibration curve (ratio \( q \) versus velocity \( v \)) measured with the applied FM-DGV system is shown in Fig. 2. The velocity axis holds for the perpendicular arrangement of the laser incidence and the observation direction (\( \vec{\vartheta} \perp \vec{\varphi} \)).

High measurement rates up to the modulation frequency are possible with FM-DGV [15,16]. Since a modulation frequency of 100 kHz is used in the present FM-DGV setup, the maximum achievable measurement rate is 100 kHz. As a consequence, the temporal resolution is 10 \( \mu \)s, which is sufficiently high for the application in the rotating turbine.
3. The measurement setup

3.1 Turbine test rig

The measurements were performed at the 1.5 stage turbine test rig at the Technische Universität Darmstadt. The rig is set up vertically as shown in Fig. 3a. It consists of two stators and one rotor in between. Each stator has 30 vanes. The rotor consists of 45 blades. The turbine casing diameter is equal to 881 mm. The turbine is operated at the design point. The rotational speed is 1240 rpm and the actual flow velocity at the intake amounts to 19.3 m/s. The air mass flow rate at the design point amounts to 6.2 kg/s. The flow temperature at the intake was 308 K.

The rotor blades have a span of about 101 mm and the tip gap is only 900 μm wide. The rotor blade tips are equipped with a squealer cavity, which is shown in Fig. 4a. The rotor is about 50 mm high (dimension along z-direction) and the circumferential blade pitch is 123 mm. This gives the required size of the measurement area: 50 x 123 mm².

For applying an optical measurement technique, the test rig has optical accesses for illumination and light detection as shown in Fig. 3a. Regarding illumination, a hole was prepared in the casing for light supply by an endoscope. For observing the measurement region, a curved glass plate made of fused silica is mounted in the casing at the rotor. The window is 100 mm wide, 70 mm high and 15 mm thick. Its inner radius is equal to the casing radius.

In order to obtain the rotor position simultaneously with the FM-DGV measurement, a trigger signal from the turbine was recorded. It provides one pulse per rotation.

Fig. 3 a) Side view and b) top view of the 1.5 stage turbine test rig with the applied FM-DGV measurement system for measuring the flow fields in the tip gap.

Fig. 4 a) Rotor blade tip with squealer cavity and b) alignment of the array measurement channels in the TCF.
3.2 Application of the FM-DGV system

Laser light illumination
As laser source, a master oscillator power amplifier laser system from the Co. Toptica Photonics was used. The master laser emits at 895 nm, which coincides with the atomic resonance frequency of cesium gas (cesium D\textsubscript{1} line) [14,15]. Furthermore, its bandwidth (< 1 MHz) is sufficiently narrow for resolving the Doppler-broadened absorption line (full width at half maximum about 590 MHz) and a fast frequency modulation with 100 kHz is possible by modulating the laser diode current. The power amplifier provides a high laser power. The light is coupled into a single-mode fiber by the fiber dock of the laser system. The fiber is plugged into the fiber connector of the endoscope yielding a flexible and robust light supply. The diameter (1/e\textsuperscript{2} width) of the laser beam in the tip gap was about 500 μm and, thus, was narrower than the tip gap. It was adjusted to pass in the tip gap at the gap center. The available power was about 0.5 W.

Receiving of scattered light
The detection of the scattered light is performed through the optical window from the side as shown in Fig. 3b. In order to obtain three velocity components, three different observation directions were applied subsequently. While the first observation direction was aligned radially (\(y\)-direction), the additional observation directions were turned by ±35 °. Since the velocity components along the bisecting lines of the light incidence and observation directions are measured according to Eq. (1), a coordinate transform is applied to finally obtain the orthogonal velocity components \(v_x\), \(v_y\), and \(v_z\). In rotor coordinates, \(v_t\), \(v_r\), \(v_a\) correspond to the tangential, radial and axial velocity.

The fiber-coupled detector array consists of 25 avalanche photo diodes, but only 23 array elements were used here due to the limited number of channels of the data acquisition system and the additional recording of the trigger and the modulation signal. The avalanche photo diodes have a high sensitivity and a sufficiently large bandwidth of 450 kHz for resolving the first and second harmonics according to the FM-DGV measurement principle. Their minimum noise equivalent power is 39 fW/Hz\textsuperscript{1/2}. The imaged measurement points of the fibers are linearly aligned along the laser beam illumination as shown in Fig. 4b. Since the spot of the measurement points is about 1.2 mm in diameter, two measurements at different axial positions were subsequently accomplished for acquiring the entire axial blade extent (see depicted measurement regions in Fig. 4b). The complete TCF field over the entire blade pitch is obtained by using the high measurement rate of the FM-DGV system and the rotation of the rotor. At 1240 rpm, 45 rotor blades and 100 kHz measurement rate, 108 points were resolved in circumferential direction per blade pitch. To summarize, images of 43 x 108 pixels were obtained.

As an example, a sampled detector signal over one rotation cycle is shown in Fig. 5a with seeding generation switched on and off (at 70 % of the axial blade extent, measurement region 1, channel 11 from bottom,). From the signals in case of no seeding, only reflections at the turbine are measured. Obviously, each blade caused reflections saturating the detector. However, four blades were anodized and the reflections at these blades were reduced. When zooming in at one anodized blade as shown in Fig. 5b, the reflections above the squealer cavity between the blade tip edges are found to be negligibly small. When seeding was switched on, higher signals were detected obviously originating from the scattering on seeding particles. Since the laser modulation was running, the signals are modulated as shown in Fig. 5b. Hence, FM-DGV measurements of the TCF were possible above the squealer cavity and also in between the blades.

Signal processing and measurement uncertainty
Since two subsequent measurements each over 2 s have been performed, an averaging over 82 rotor cycles is possible. Averaging the results of the two anodized blades 26 and 27 in addition, the cumulative averaging time amounts to \(T = 1.64\) ms for each pixel. The mean scattered light powers
\( P_{s,i}, i=1,2,3 \), for the three observation directions are 0.5 nW, 0.6 nW, 0.2 nW, respectively. As a result, the standard uncertainties of the originally measured velocity components originating from shot noise and thermal noise of the detectors can be estimated according to [9,12] by

\[
\sigma_{v_i} = \frac{1}{\sqrt{T/s}} \sqrt{\left(\frac{(0.0084 \text{ m/s})^2}{P_{s,i}/nW}\right) + \left(\frac{(0.0051 \text{ m/s})^2}{P_{s,i}/nW}\right)}
\]

yielding 0.45 m/s, 0.38 m/s and 1.07 m/s, respectively. Using an error propagation calculation and assuming uncorrelated errors, the expected standard uncertainties of the orthogonal velocity components \( v_r, v_t, v_a \) are obtained: 1.4 m/s, 5.7 m/s and 5.3 m/s. These theoretically predicted uncertainties are in very good agreement with the measured values, which amount to about 1 m/s, 5.6 m/s and 5 m/s. Estimated and measured values agree, although the measured velocity standard deviations contain noise as well as flow turbulence effects. Consequently, the measurement uncertainty dominates the velocity standard deviations. Hence, the velocity standard deviations can be reduced by reducing the measurement uncertainty, which can be achieved by increasing the scattered light powers and by using longer averaging times.

Fig. 5 | Photo detector signal (one channel as an example) a) over one rotation cycle and b) at the tip gap above an anodized blade (blade number 26) with and without seeding. The reflections are lower at anodized blades. Negligible reflections occur above the squealer cavity in between the blade tip edges, which allows measurements.

4. Measurement and simulation results

Numerical computations were conducted throughout the investigation of the TCF in order to support the experiment. The commercial solver FINE/TURBO by NUMECA was used to simulate the flow in the 1.5 stage turbine. A transient calculation (TRS) was performed to obtain high quality results. Several blade passages were included in the model to achieve an ensemble pitch ratio of unity for all blade rows. The model includes the two stator and three rotor passages. One rotor pitch is resolved by 30 time steps. Hence, 90 time steps are used for one period. The total number of nodes of this mesh is about 10^7. The baseline mesh has 101 layers of nodes in each row. To model the squealer cavity, the mesh blocks in the tip gap were replaced by new blocks with a resolution of 45 layers in the gap at the rotor tip and 75 nodes in the squealer cavity. The cells at the rotor tip are connected with those in the outer passage by a non-matching interface.

The fluid was modeled as perfect air, with constant values of specific heat capacity and isentropic exponent. The one-equation model of Spalart-Almaras was used for turbulence modeling. A radial distribution of axial velocity in combination with the mass flow was defined at the inlet boundary. The profile was obtained by circumferentially averaged pressure measurements. At the outlet, a radial distribution of static pressure was specified. All walls, i.e. vanes, blades and end-walls, were specified as adiabatic. Circumferential boundaries of each passage were matching periodic. Subsequently, the measurement and simulation results are discussed for each velocity component.
Tangential velocity $v_t$

The measured and simulated tangential velocities are shown in Fig. 6a and Fig. 6b, respectively. For a better comparison between the measurement and the simulation results, the measured TCF field over one complete blade pitch was periodically continued. As explained in section 3.2, the TCF regions above the squealer cavity and outside the rotor blade are resolved successfully. At the blade edges, reflections disturb the measurement. These velocity values are rejected by evaluating the scattered light power and applying a threshold. In addition to the values from the clearly visible blade tip contour some further values were rejected. Because no rotor blade is present at these measurement points, the reason of it is assumed to be multiple reflected light. Similar holds also for the measurements of the radial and axial velocity component.

Maximum tangential velocity occurs at the pressure side of the tip gap near the blade leading edge. Hence, the flow is accelerated toward the squealer. In the measurement however, the velocity gradient is smaller than in the simulation. Furthermore, the increase in circumferential direction has a lower slope. Above the squealer cavity, the measured and the calculated tangential component of the TCF decrease toward the center of the cavity region and are more or less homogeneous in the center squealer region. At the suction side corner of the squealer tip, the TCF is accelerated again, followed by deceleration inside the passage. Starting from mid chord of the blade, the tip clearance vortex occurs shedding from the blade suction side [13]. The development of the tip clearance vortex is shown to be in very good agreement between measurement and numerical results. Finally, the turning of the direction of the tangential flow velocity between the blades is correctly resolved. The tangential velocity is positive at the leading edge and becomes negative at the trailing edge.

![Figure 6](image_url)

**Fig. 6** a) Measured and b) calculated tangential velocity $v_t$ of the TCF.
Radial velocity \( v_r \)
Comparing the measured (see Fig. 7a) and calculated (see Fig. 7b) radial velocity component, the measurements contain several line-like artifacts due to reflections. The reason of these additional artifacts in comparison with the result of the measured tangential component is as follows: For the tangential component the laser incidence direction has no influence, because of the symmetric detection. According to the coordinate transformation and by applying Eq. (1) for the second and the third observation direction, the relation

\[
v_r \propto v_3 - v_2 \propto (\hat{\alpha}_3 - \hat{\alpha}_2) \cdot \vec{v}
\]

applies with \( v_3 \) and \( v_2 \) as originally measured velocity components with the third and the second observation direction. To prove this relation, the difference of both observation vectors is obviously found to yield a vector along the tangential direction. As a consequence, the incident light direction is irrelevant for the measurement of the tangential component. Since the artifacts occur in the radial (and also the axial) component, but not in the tangential component, a non-intended laser incidence direction is assumed to be the reason of these artifacts. Most likely light reflections occur in the machine for instance at the housing or at the stator below the rotor.

Furthermore, the measurement result of the radial velocity is more noisy than the result of the tangential velocity. This is due to the uncertainty propagation when using the coordinate transformation for calculating the radial velocity. It is in excellent agreement with the measurement uncertainty investigations described in section 3.2.

\[\text{Fig. 7 a) Measured and b) calculated radial velocity } v_r \text{ of the TCF.}\]

Despite of these artifacts, measurement and simulation agrees well. For instance, the structures of the tip clearance vortex behind the blade at the suction side are consistent. Furthermore, the radial
velocity is more or less zero between the blades as expected. In addition, it is in general positive at the pressure side and negative at the suction side at the blade tip edges (upper measurement region 1). This is also true for the edges of the squealer cavity. While this is always the case in the numerical results, it is not in the second measurement region (cf. Fig. 4b). Here, the radial flow tends to be negative at the pressure side edges. The reason for this is not fully understood. Maybe the radial position of this measurement was different from the desired position. Apart from that, the agreement between the measured and simulated radial velocity is obvious.

**Axial velocity \( v_a \)**

The discussion of the disturbances for the radial velocity measurement can also be applied for the axial velocity measurement. The measurement results shown in Fig. 8a also contain similar line-like artifacts and the spatial fluctuations are also higher than in the measurement results of the tangential velocity (cf. Fig. 6a). Except for these issues, the measured (Fig. 8a) and calculated (Fig. 8b) axial velocity field of the TCF are in very good agreement. For instance, the shedding tip clearance vortex was correctly resolved yielding regions of maximum and minimum velocity behind the blade at the suction side. The axial velocity of the TCF is reaching its maximum in the tip gap region without squealer cavity and has a local minimum above the squealer cavity. This indicates a reduction of the leakage flow for squealer tips. Above the squealer cavity, a velocity gradient is visible. The axial velocity decreases toward the blade suction side. Furthermore, the velocity has a maximum at the front part of the suction side edge. Although dimensions of these flow phenomena are slightly different in measurement and simulation, the qualitatively good agreement between both is apparent.

![Image of axial velocity](image)

**Fig. 8** a) Measured and b) calculated axial velocity \( v_a \) of the TCF.
5. Outlook

The measurement of the TCF in the tip gap of a rotating turbine rotor equipped with squealer tips was successful. The measurement uncertainty can be reduced further in order to improve the measurement capabilities for validating flow simulations and flow models. According to the uncertainty estimation with Eq. (4), which was shown to be applicable here by comparing predicted and measured uncertainties, the uncertainty can be decreased for instance by temporal averaging. Hence, more measurement data has to be acquired. In the present experiment, the detector signals were acquired continuously, then stored at a hard disc and processed later rejecting the signals from the non-anodized blades. Only 2 blades out of 45 total blades were evaluated. As a result, implementing a triggered acquisition and data segmentation will significantly reduce the amount of data to be processed. This will allow longer measurements yielding a lower uncertainty. In addition, a higher scattered light power is important, which can be achieved by increasing the effective numerical aperture of the receiving unit for instance by using absorption cells with larger aperture. In order to reduce disturbances due to light reflections in addition, the laser beam radius can be reduced further. Furthermore, the light reflections can be measured and corrected by developing a model for describing the systematic disturbances [11]. These improvements might offer to resolve also the third (radial) flow dimension and to obtain results of the TCF above the blade tip edges. Finally, simultaneous three componential measurements are easily achievable by using three observation directions simultaneously. This would also reduce the duration of the experiment and would offer investigations of unsteady flow effects in the TCF.

6. Conclusion

It is of utmost importance to understand the behavior of the tip leakage flow in turbines, which cause significant losses and degrade the turbine's efficiency. A current concept for reducing the flow leakage is to use rotor blade tips with a squealer cavity. However, the potential of this technique is unclear. This requires non-intrusive measurements of the tip clearance flow (TCF) in a rotating turbine rotor, which is challenging due to the small tip gap height of usually about 1 mm and the resulting light reflections when the tip gap has to be illuminated. For this reason, a novel measurement approach was presented. The approach is based on a narrow beam illumination instead of a planar illumination for minimizing light reflections near the tip gap. The velocity measurements along this laser beam were performed by the FM-DGV technique, which achieves a high measurement rate of 100 kHz. This allowed temporal resolution of the rotor movement at 930 Hz blade passing frequency. The proposed technique was successfully applied at a 1.5 stage turbine test rig with 900 μm tip gap finally yielding velocity images of all three velocity components of the TCF of a rotor with squealer tips with 43 x 108 pixels per blade pitch.

Although no measurement was possible near the tip edges due to reflections, the TCF was successfully measured in the tip gap above the squealer cavity as well as in between the blades. The three measured velocity components were compared with flow simulations and a very good qualitative and quantitative agreement between both was found. By analyzing the TCF, the development of the tip clearance vortex at the suction side behind the blade tip and the increase of the axial velocity in the tip gap above the squealer cavity were studied for instance. The achieved measurement results together with the identified improvement capabilities offers promising prospects for investigations of TCF phenomena using FM-DGV in order to develop turbines with increased efficiency.
Acknowledgement

The financial support of the Deutsche Forschungsgemeinschaft (DFG project Cz55/22-1) is gratefully acknowledged. The investigations were conducted as part of the research program AG Turbo COORETEC. The work was supported by the Bundesministerium für Wirtschaft und Technologie (BMWi) according to a decision of the German Federal Parliament under grant number 0327716V. The authors gratefully acknowledge Rolls-Royce Deutschland and Alstom for their support and permission to publish this paper. The responsibility for the content lies solely with its authors.

References

