PARTICLE CONCENTRATION AND VELOCITY MEASUREMENTS IN A CASCADE WIND TUNNEL BY MEANS OF L2F

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ABSTRACT
The Laser-2-Focus (L2F) measurement system has generally been used for velocimetry. Additionally, the L2F measurement system allows the measurement of particle concentration in flows. For investigations of fouling behavior it is necessary to determine the particle concentration. The present paper deals with L2F measurements in a cascade wind tunnel for boundary layer velocimetry and fouling behavior investigations of riblet structured profiles.

INTRODUCTION
During the last few years, the application of riblets on compressor blades has been investigated in a cascade wind tunnel at the TFD in order to reduce friction losses. In addition to aerodynamic efficiency the contamination behavior of riblet-structured blades was investigated (see e.g. Lietmeyer et al. 2013). For these investigations the cascade wind tunnel test rig (Figure 1) was extended with an exhaust air duct and a particle filter. A seeded flow consisting of air and solid particles was generated with a particle disperser which allows the adjustment of the particle concentration.

The L2F was used in order to investigate the transition behavior of the compressor blades and the particle concentration in the flow. The verification of a defined seeded flow is essential for reproducible investigations of fouling behavior. For this reason the L2F was used in these investigations for velocimetry and concentration measurement. The fundamentals of L2F-measurements are explained in the following sections as well as the details of the velocity and particle concentration measurement of a seeded flow.

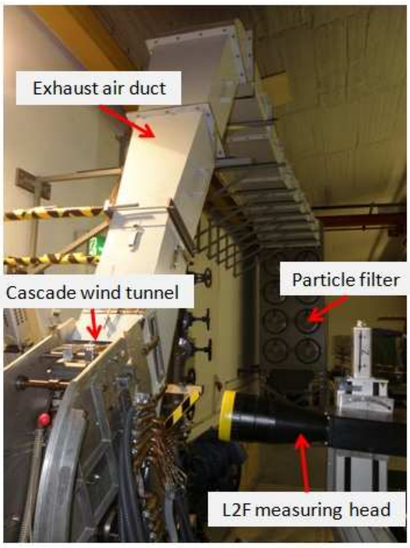

Figure 1. Cascade wind tunnel at the TFD

NOMENCLATURE
Put nomenclature here.

C	1/m³	concentration
c	m	chord length
d	m	diameter
H_{12}	-	form factor
l	m	length
n	-	number
T	s	time period
u	m/s	velocity
x	m	distance to leading edge
δ_1	m	displacement height
δ_2	m	thickness of momentum losses
φ	m²	probe area

LASER-2-FOCUS VELOCIMETRY

In 1968 D.H. Thompson introduced the Laser Two Focus (L2F) – Velocimeter - also known as Laser Transit (LT) - Velocimeter (Schodl 1998). The L2F-Velocimetry measures the time-of-flight of tracer particles carried by the fluid using two separated, parallel, and highly focused laser beams (Schodl 1998).

Thompson emphasized the advantages of the L2F-method in comparison to the LT-method. L2F-velocimeters have a simpler optical setup and simpler data processing compared to the laser Doppler anemometer (LDA) method. Furthermore L2F allows the usage of low-power lasers to detect the scattered light of small tracer particles (Schodl 1998).

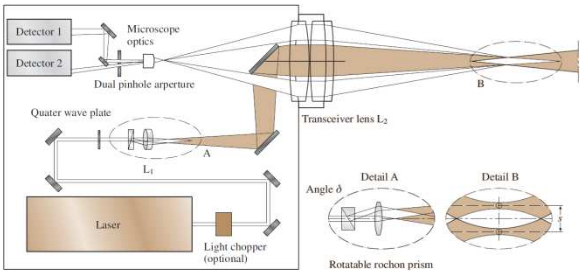

Figure 2. Layout of typical L2F-velocimeter (Tropea et al. 2007)

OPTICS

The optics of the L2F measurement system displayed in Figure 2 contain a rotatable Rochon prism which splits the laser beam in two beams of equal intensity but of different linear polarization. The split laser beams are parallelized and focused using two lenses. The measuring volume of the L2F has to be placed in the defined measuring position of a flow field. Any particle which crosses the measuring volume of one of those both laser beams causes scattered light. The reflected scattered light pulse is transmitted by the lens L2 to the photomultiplier passing a spatial filtering device. The system contains two photomultipliers and each of them is assigned to one of the beams in the measuring volume. The microscopic optics that is located between the lens L2 and the photomultiplier enlarges the reflected scattered beams so that they can be adjusted exactly to the two holes of the aperture. The optical configuration of L2F measuring equipment has barely changed since its inception.

ELECTRONICS

The scattered light pulses induced by particles crossing the measurement volume of the laser beam are detected by the photomultiplier and thus voltage output pulses are generated. The amplitude of the scattered light pulses depends on the velocity and size of the particles, and on the position where the particles pass through the laser beam. The higher the velocity of the crossing particle, the lower the number of transmitted photons detected by the photomultipliers. The voltage pulses of the photomultiplier are used as start and stop signals for the time of flight measurements.

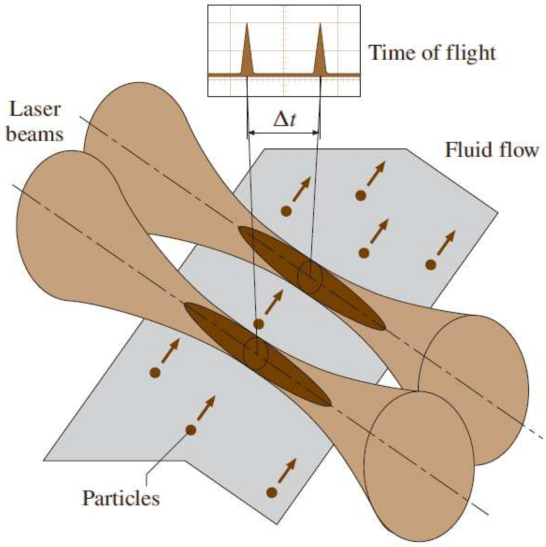

Figure 3. Time-of-flight velocimeter probe volume (Tropea et al. 2007)

TIME-OF-FLIGHT MEASUREMENTS

The two different laser beams of the L2F with a beam waist diameter of 10 µm inside the probe volume are used as a photoelectric barrier with a determined distance which Schodl (1998) states to be 0.2-0.4 mm. While knowing that fixed distance the particle velocity is calculated by using the time-of-flight between the two laser beams. In order to obtain correct time-of-flight measurements the plane which contains the two laser beams has to be aligned parallel to the main flow direction (Figure 3). This is that important because a particle which passes the first laser beam and triggers the start impulse has to pass the second laser beam as well to induce the stop impulse. Otherwise the probability increases that the start and stop impulse is not caused by the same particle (Tropea et al. 2007). The laser distance divided by the duration between the start and stop impulse calculates the current particle velocity, assuming that the particle is well carried by the flow with the result that the particle velocity and flow velocity are the same.

$$\bar{u} = \frac{s}{\overline{\Delta t}} = \frac{separation\ of\ beams}{mean\ value\ for\ time\ of\ flight}$$

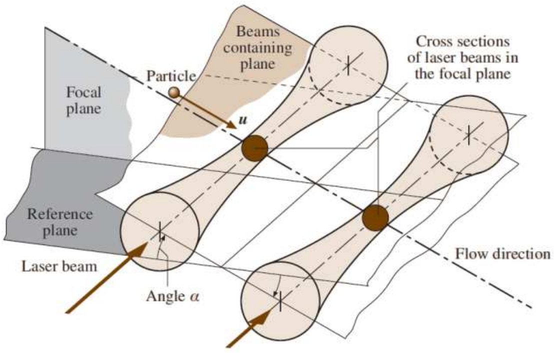

Figure 4. Measuring plane of L2F-method (Tropea et al. 2007)

A large number of measurements in the plane of the laser beams (Figure 4) are required to distinguish between correct and incorrect time-of-flight measurements. Probability histograms are used to detect the correct time-of-flight measurements (Figure 5). The number of measurements includes randomly distributed incorrect measurements which are represented in the histogram by the baseline of nearly constant frequency level (briefly called noise band *NB*) and the Gaussian curve represents the correct time-of-flight measurements.

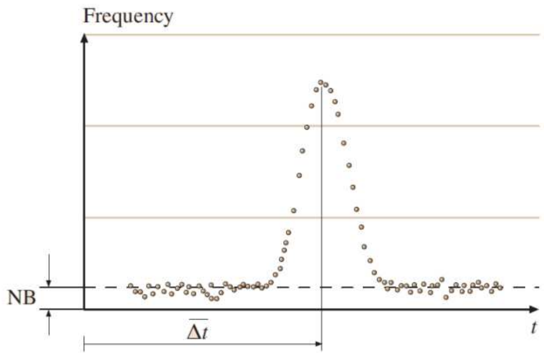

Figure 5. Time-of-flight data histogram at one single angle (Tropea et al. 2007)

A histogram analysis is used with a weighted calculation to take those measurements more into account which corresponds with the expected flow velocity. Two-dimensional probability histograms can be generated by collecting data histograms for slightly different angles of the plane which contains the beams. Therefore this plane has to be rotated (Figure 6).

A complex evaluation procedure uses the data of these histograms to compute typical outputs such as mean values of the velocity components and turbulence intensities. The computation of Reynolds shear stresses and higher-order-moments is also possible (Tropea et al. 2007).

For low turbulence intensities (<5%) a higher accuracy of velocity measurement (measurement error <1%) and angle determination (measurement error <0.2°) is achievable than by LDA (Tropea et al. 2007). The accuracy is greatly dependent on the quantity of collected data, and the background noise caused by reflections of the laser light on surfaces inside the probe volume. At turbulence intensities of more than 30% LT or L2F is not applicable because it becomes difficult to distinguish between correct and incorrect measurements.

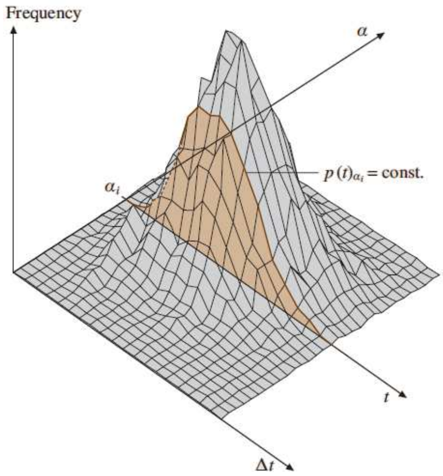

Figure 6. Two-dimensional histogram at different angles of the measuring plane (Tropea et al. 2007)

APPLICATION OF L2F AT THE TFD

The cascade wind tunnel at the TFD which is shown in Figure 7 was used to investigate the application of riblets on compressor blades (Lietmeyer et al. 2013). In addition to the effects on the pressure losses and the transition from laminar to turbulent flow, the fouling behavior was investigated. Therefore it was necessary to use an optical measuring system that allows velocimetry close to airfoil surfaces and measurements of the particle concentration inside the main flow.

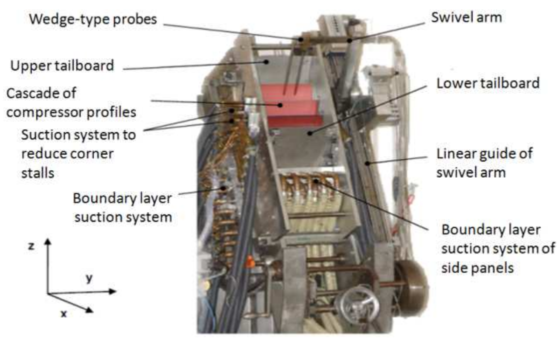

Figure 7. Cascade wind tunnel at the TFD

Three screw compressors provide the flow for the cascade wind tunnel. These compressors can produce air mass flows up to 9 kg/s. The air passes through a settling chamber and a turbulence grid before entering the cascade wind tunnel to ensure homogeneous flow conditions. The homogenous flow conditions at the inlet of the cascade wind tunnel are disturbed by corner stalls at the transition between blades, and side walls and by arising boundary layers downstream the walls of the wind tunnel. These undesired effects can be minimized with a boundary layer suction system.

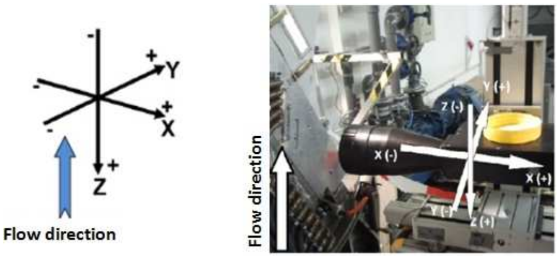

Figure 8. Coordinate system of L2F-traverse system

Appropriate optical accesses on the cascade wind tunnel allow the usage of the Laser-2-Focus measuring system. The probe head of the L2F which contains the optics can be moved in all spatial directions (Figure 8). The cascade wind tunnel was extended by an exhaust air duct and a particle filter to allow the investigation of the fouling behavior.

Within the preliminary investigations velocity measurements close to the surface were performed before examining the fouling behavior of riblet-structured surfaces. The velocity profiles of the boundary layer were recorded by traversing the probe volume of the L2F from the leading edge to the trailing edge, as an average value of at least 5000 suitable measurements was required to ensure appropriate accuracy for the velocimetry at every measurement point. Velocity measurements in the boundary layer close to surfaces are useful when determining the transition area. The velocity measurements were applied to calculate characteristic values of turbulent boundary layers like Reynolds stresses, displacement height δ_1, thickness of momentum losses δ_2, and form factor H_{12}. The transition area on the surface must be known to avoid a disadvantageous placement of the riblets. An undesired accelerated boundary layer transition caused by incorrectly placed riblets can lead to an increase of the integral frictional resistance. Besides the determination of the position where the flow transits from laminar to turbulent it was also important to investigate the influence of riblets on the transition.

Another objective during the investigations of riblet structured surfaces of compressor blades was to examine the fouling behavior. For this kind of investigation it is required to generate a defined seeded flow in order to ensure repeatability and comparability simultaneously, hence a particle disperser was used. Cartridges filled with a defined amount of dust powder were inserted into the particle disperser. The particles are dispersed by means of a rotating brush and compressed air. The functional principle of the particle disperser is displayed in Figure 9.

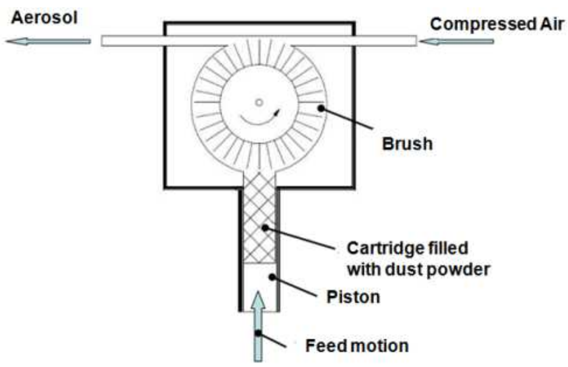

Figure 9. Functional principle of particle disperser

A defined amount of particles are dispersed by adjusting the feed rate of the feed piston. The particle flow is guided through a short tube and enters the cascade wind tunnel approx. 1300 mm upstream blade row to ensure a homogeneous particle distribution within the main flow. The usage of the particle powder at the test rig requires appropriate handling. For that reason it is necessary to install a particle filter system which protects the measuring devices, the test rig itself and the environment from contamination even if the test powder is not toxic. Thus, an exhaust air channel and particle filter housing were mounted so that a seeded turbomachinery-like flow can be experimentally used without particle emission.

Analogous to the aerodynamic experiments the boundary conditions during the deposition behavior experiments are the same. The inlet flow shows a velocity of Ma=0.5 and a Reynolds-Number of $Re=10^6$. For a period of 90 min the particle concentration of the flow is $C=3.07\cdot10^9\,m^{-3}$ to ensure significant particle deposition occurs on the airfoil surface.

The particle concentration in the main flow was determined by counting the scattered light pulses induced by particles crossing the probe volume of one single laser beam. The concentration C inside the probe volume can thus be calculated using the counted number of particles n which cross the probe volume of the laser beam within a defined period of time *T*.

$$C = \frac{n}{V} = \frac{n}{T \cdot \dot{V}} = \frac{n}{T \cdot u \cdot d_0 \cdot l}$$

Only one laser beam and its related photomultiplier are required to count the amount of crossing particles to determine the concentration measurement by means of L2F. Besides the number of counted particles the flow velocity u and the beam waist diameter d_0 can be determined easily however the length l of the probe volume cannot be determined exactly. For this reason Lietmeyer (2008) introduced the coefficient φ which is the product of beam waist diameter d_0 and the length l. By substituting the coefficient and transforming the equation the following equation can be obtained:

$$\varphi = \frac{n}{C \cdot T \cdot u}$$

This coefficient is a measure of the size of the control area. In addition to the measured quantity of particles n within a defined period of time T, it is required to determine the velocity u and the particle concentration C of the flow. A location where all the unknown quantities can be assumed as known is the outlet of the particle disperser. The coefficient φ is calibrated at the disperser outlet. The time period T and the flow velocity u are well known at the outlet and the particle concentration can be easily determined by using the specific properties of the dust powder (Lietmeyer 2008). Depending on the feed rate of the disperser piston the amount of the escaping particles can be determined if the specific properties of the dust powder are known.

The measurements were carried out always on an airfoil with a smooth surface and an airfoil with a riblet structured surface simultaneously to ensure the same flow conditions for both probe blades. The riblet structured airfoils were built using a metal surface and also with a plastic surface realized by glued foils. This procedure allows comparability of particle deposition at smooth and structured surfaces. To determine the particle deposition the probe airfoils are dismantled and subsequently weighed with a high precision scale.

RESULTS OF THE NEAR WALL VELOCIMETRY

The experimental investigations used a L2F system which was extended within the scope of an additional DFG project. The L2F allows the examination of the boundary layer near the surface due to its laser focus diameter of $d \approx 30$ µm and the distance between the two focal points of $d \approx 280$ µm.

The measurement locations start at the leading edge of the airfoil and follow the pressure and suction side down to the trailing edge.

The surface of the smooth metal airfoil was covered with black paint to reduce the undesired back scatter of the laser beam. Unfortunately the riblet surface of the laser structured metal airfoil could not be painted because of the deposition behavior of the paint inside the riblet structure. Therefore, the closest approach for the measurement apparatus was >200 µm at the suction side and >500 µm at the pressure side.

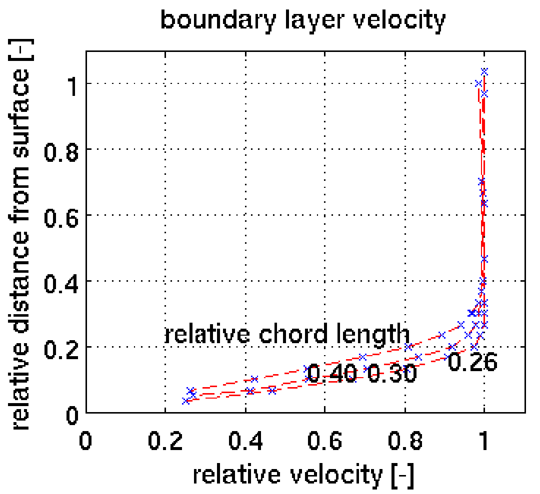

Figure 10. Velocity profile close to the surface

The velocity near the airfoil surface decreases significantly because of the wall shear stress. The constant flow velocity of the outer main flow begins to decrease at the beginning of the boundary layer. The three example velocity plots in Figure 10 show the increase of the boundary layer for growing relative chord length.

$$c_{rel} = \frac{x}{chord\ length}$$

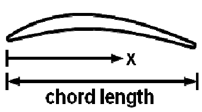

Figure 11. Relative chord length

The run of the curve shows the expected tendency to reach no velocity at the wall because of the no-slip conditions at the wall. A clear statement on the influence of riblet structured surfaces on the transition is not possible because of the increased back scattering of riblet structured surfaces. However along the riblet structured surface a tendency was detected that the displacement height δ_1 and thickness of momentum losses δ_2

inside the turbulent boundary layer was reduced (Figure 12). Reduced Reynolds stresses were also measured at the riblet structured suction side as well as the pressure side when compared to the smooth profile. This effect is probably caused by an attenuation of turbulent cross flow near the wall, induced by the riblets. The fact that these results confirm the results Boese and Fottner (2002) obtained affirms that Laser-2-Focus velocimetry is suitable for measurements close to the wall.

Figure 12. Course of integral boundary layer quantities on the suction side (Lietmeyer et al. 2013)

Figure 13. Course of form factor H_{12} on the suction side (Lietmeyer et al. 2013)

RESULTS OF PARTICLE CONCENTRATION MEASUREMENTS

Previous investigations of the fouling behavior of riblet-structured compressor blades were performed in the open wind tunnel of the TFD (inlet conditions: Ma=0.11 and Re=$2.1 \cdot 10^5$). During these studies different feed rates were used to generate different particle concentrations in order to investigate the correlation between particle concentration and particle deposition on riblet-structured and smooth compressor blades. The particle concentration inside the main flow was measured by means of L2F at the varying feed rates of the disperser piston.

Figure 14. Linear coherence between particle concentration and feed rate (Schwerdt, 2012)

These investigations showed a linear coherence between the piston feed rate and the measured particle number respectively concentration (Figure 14).

For the investigations in the cascade wind tunnel a higher particle concentration by a factor of 3.4 was expected due to the different volume flow compared to the previous investigations and a higher feed rate of the disperser piston. The measurements during the investigations in the cascade wind tunnel showed a concentration of $C=3.07 \cdot 10^9$ m^{-3} which is only 1.5 times higher than expected.

One possible source of error is uncertainties which can occur during the calibration of laser and optics. These uncertainties cause some of the observed deviation. Another reason is different distance between the position where the particle flow enters the main flow and the leading edge of the blade row respectively to the location where the particle concentration was measured by means of L2F (10 mm upstream the leading edge). While the distance for the previous investigations was only 300 mm the distance at the cascade wind tunnel was 1300 mm. Due to the longer distance the particles are distributed more evenly over the entire flow cross section and the particles deposit partly on the walls of the cascade wind tunnel.

CONCLUSION

In addition to the conventional velocimetry inside the main flow, L2F can also measure velocity close to walls and allows the investigation of boundary layers. Due to its small probe volume it can be applied when measuring close to the wall.

Hence it is possible to determine the boundary layer thickness.

By rotating the plane which contains the two laser beams, the velocity components in the focal plane (compare Fig. 4) can be determined. The results of the investigations show that the velocimetry up to 0.3 mm to the wall is precise enough to detect the influence of riblets on the boundary layer or the transition.

The concentration measurement using L2F-method is precise enough to detect the expected linear correlation between feed rate of the disperser piston and the particle concentration. Attention should be paid to the fact that a reliable quantitative analysis of the particle concentration inside the main flow is only possible if the size of the probe volume is precisely known. Otherwise L2F allows only a qualitative analysis of the correlation between the amount of the released dust powder and the measured particle number. The assumed number of particles which leaves the particle disperser is an estimate based upon the properties of the test powder and may lead to an error at the determination of the coefficient φ.

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