*Optical Measurements*
*Paper 14*

# IMPROVEMENTS IN THE APPLICATION OF LASER-TWO-FOCUS VELOCIMETRY TO TRANSONIC ROTOR FLOWS

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# IMPROVEMENTS IN THE APPLICATION OF LASER-TWO-FOCUS VELOCIMETRY TO TRANSONIC ROTOR FLOWS*

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## Abstract

At DLR-Göttingen the Laser-Two-Focus Technique (L2F) is routinely applied to acquire flow field information for cascade and turbomachine flows. An update of the electronic part of the system led to improved performance especially when taking measurements in a rotor.

The measurement procedure was automated and accelerated by controlling the system by a personal computer. The spatial resolution was improved by dividing the blade pitch into 32 segments. The fully two-dimensional histogram is stored i.e. a time-of-flight histogram at every angle. The evaluation program was rewritten.

The storage of the two-dimensional histogram has several advantages: The evaluated data are more accurate, especially the measured turbulence intensities. Not only mean flow vectors and turbulence intensities can be obtained, but also Reynolds shear stress. If bimodal angle or velocity distributions occur, each peak can be evaluated separately. A better discrimination of events caused by stray light is possible, thus allowing measurements nearer to side walls.

Some examples from recent measurements in transonic flows will be shown, where the above mentionned improvements played an important role.

## Nomenclature

| | |
|---|---|
| $l_{ax}$ | axial chord length |
| Ma | Mach number |
| t | pitch |
| u,v | velocity |
| x | axial coordinate |
| $y,\phi$ | circumferential coordinate |
| $p_0$ | total pressure |
| $R_{uv}$ | Reynolds stress |
| Tu | turbulence intensity |
| $\beta$ | angle between flow direction and the cascade plane |

subscripts

| | |
|---|---|
| 1 | inlet |
| u | streamwise |
| v | transverse |
| w | relative system |

## 1 Introduction

Flows in turbomachines display some annoying features as high spatial and temporal inhomogeneity and lack of accessibility which make it difficult to gain information on such flows. As conventional probe measurements give rise to blockage and interference effects, and as probes cannot be used in rotor blade passages, there exists a strong demand for nonintrusive measurement techniques.

Therefore, in the last two decades optical techniques, especially Laser anemometry have been increasingly applied to turbomachinery flows in order to improve our understanding of the flow phenomena and to validate new CFD codes. Whereas Laser Doppler Anemometry (LDA) is superior in flows with good accessibility and moderate spatial

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*Paper presented at the "13th Symposium on Measuring Techniques for Transonic and Supersonic Flows in Cascades and Turbomachines", Zürich, Switzerland, September 5-6, 1996 gradients and in flows with very high turbulence the Laser-2-Focus (L2F) (sometimes also called Laser Transit) - technique is especially useful in measuring flow velocities and turbulence quantities in narrow blade channels or in high speed applications.

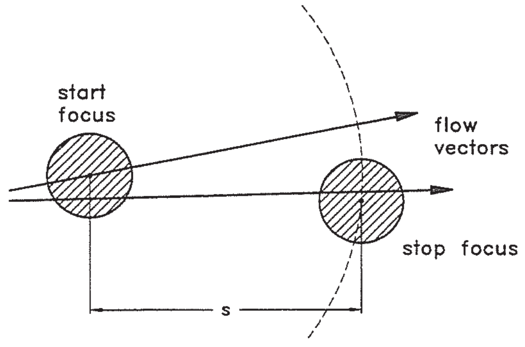

Figure 1: The L2F measurement volume

The measurement principle of L2F, depicted in Figure 1, is rather simple. The L2F-measuring device generates two highly focussed light beams in the probe volume which act as a "light gate" for tiny particles in the flow. The scattered light from the particles provides two successive pulses and from the time interval between the pulses the velocity perpendicular to the Laser beams can be derived. A detailed description may be found in [1] or [2].

## 2 The L2F system of the DLR Göttingen

The two focuses of our L2F device have diameters of 8 μm and their separation, s, is 207 μm. Our system only measures 2D-vectors of the fluid velocity. An advantage of the 2D-system is the slender light cone of 7.5° enclosed angle which provides excellent access to narrow blade channels.

In Figure 2 the system layout is shown. The optical parts are all assembled in a rigid casing, called optical head. It contains the laser, the photomultipliers to detect the scattered light, the optical parts to produce the two focuses and to transfer them to the location of the measurement, and finally a Bragg cell which serves as a light chopper in the case of measurements inside rotating blade channels. Such a light chopper is necessary to protect the multipliers from the intense reflected light which is produced when the metal blade hits the measurement volume.

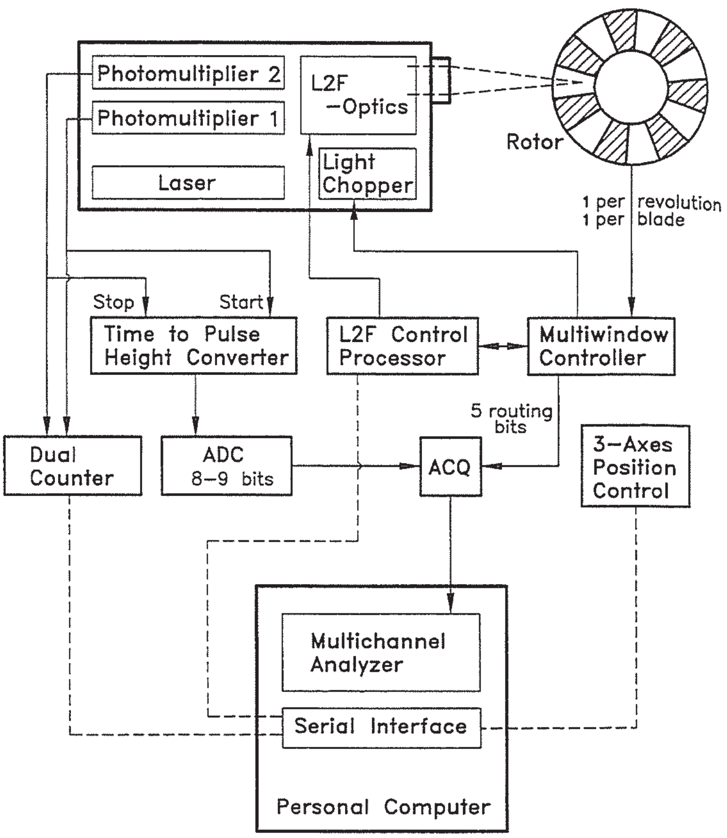

Figure 2: The L2F system of DLR Göttingen

A scattered light pulse from the start focus photomultiplier followed by a scattered light pulse from the stop focus photomultiplier triggers a fast measurement cycle: the 'Time to Pulse Height Converter' converts the transit time into a voltage, a 100 MHz-Analog Digital Converter (ADC) converts the voltage into a 8 to 12 bit number (8 or 9 bits are sufficient for all our investigations), the 'Multiwindow Controller' delivers the actual circumferential position in the rotor with a precision of 1/32 of the blade gap. The 8 or 9 bits from the ADC and the 5 bits from the Multiwindow Controller are tagged together to a 'data word' by a simple electronic device (here called 'ACQ'). Then the data word is stored in the 'Multichannel Analyzer', a board installed in and controlled by a personal computer (PC).

In the Multichannel Analyzer 32 transit time distributions are stored, according to the 5 position bits from the Multiwindow Controller. To determine the actual circumferential position of a blade during a measurement the phase difference between the 1 per blade trigger pulse and the blade nose (y/t=0) has to be determined.

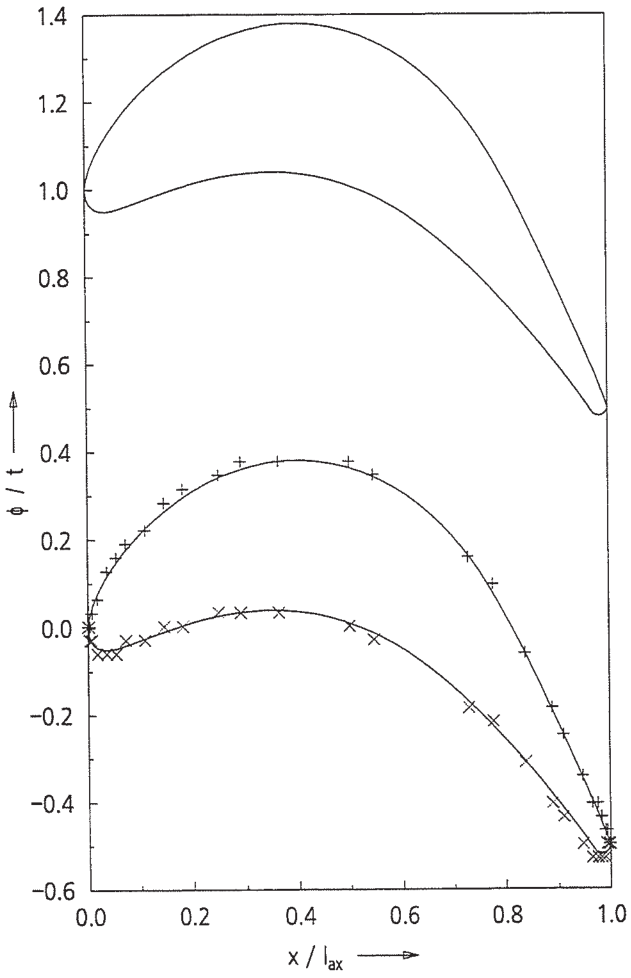

Figure 3: Blade position measurement

This is done with the L2F device, simulating a velocity measurement. The start focus of the L2F is focussed to the blade tip, so the system performs a 'measurement' when the metal blade hits the measurement volume. In the Multichannel Analyzer events are displayed only at those positions in the blade gap where the blade tip is. In Figure 3 the blade contour from such position measurements is indicated by symbols. The line in the figure shows the design blade contour at the tip. By minimizing the difference between the measured and the design blade contour at many axial positions the phase difference between the 1 per blade trigger pulse and the blade nose can be determined better than 1% of a blade pitch, though the circumferential resolution is only 1/32 of the blade pitch.

The position measurement is performed at the design speed of the rotor. This has the advantage that time delays inherent to the electronic part of the L2F system (e.g. the conversion time of the ADC) are the same as during an actual velocity measurement. Axial or circumferential movements of the blade according to the forces exerted by the flow are recognized by the position measurements, too.

The personal computer of the system (Figure 2) also controls a dual counter which counts the total number of particles passing start and stop focus and the 3-axes position control which is used to transfer the measurement volume in axial and radial direction. As the orientation of the L2F focuses has to be aligned to the flow direction, the stop focus can be rotated around the start focus. This rotation is provided by the 'L2F Control Processor' which is also controlled by the PC via a serial interface.

During a velocity measurement the operator of the L2F system is carrying out the following steps: The axial and radial position is given to the position control or taken from a table. When measuring inside a blade row the light chopper has to be set correctly. The particle generator is started. Particles are put into the flow in the settling chamber and by inspecting the particle rate in the measurement volume it can be seen whether the added particles arrive at the measurement location or not. Then the measurement time per L2F angle, the first angle, the angle step and the number of L2F angles have to be given to the PC. These parameters are stored, so they have to be typed in only if they are changed. The number of L2F angles can be changed during the measurement, because the L2F measurement may be stopped at any angle or further angles may be added in the case the flow angle range has been underestimated.

The whole measurement procedure is PC-controlled, automatically changing the L2F angle, measuring the velocity distribution at the specific angle and storing the distribution for each angle. In contrast to the measurements described in [2] not only the integrated distributions were stored. In Figure 4 a two-dimensional distribution, representing one measurement point, is shown where the coordinate axes are particle transit time and L2F-angle.

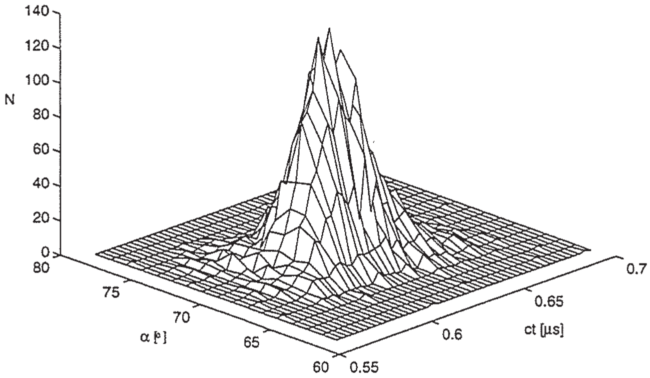

Figure 4: 2D-L2F-event-distribution

The storage of the fully two-dimensional histogram instead of only the two marginal distributions of transit time and angle led to several improvements of which the most important are:

- The evaluated data are more accurate, especially the measured turbulence intensities. This is mainly due to the fact that the background noise in the distributions of particle transit times coming from uncorrelated events can be subtracted at every measured angle. Furthermore some inaccuracies inherent to the statistical evaluation of the marginal distributions are avoided [3].
- Not only mean flow vectors and turbulence intensities can be obtained, but also Reynolds shear stress.

A statistical evaluation procedure is necessary to extract the desired mean flow values $\bar{u}, \bar{v}$, and the mean fluctuating values $\overline{u'^2}, \overline{v'^2}$, and $\overline{u'v'}$ from the stored velocity distributions. To get the turbulence level or the Reynolds stress from the mean fluctuating values those are normalized by the local flow velocity $\bar{u}$.

## 3 Statistical stationarity in the angle range

In order to find the actual flow angle and as the turbulent flow itself has a certain range of flow angles, L2F-measurements of the velocity distribution are performed at a number of angles. The statistical evaluation procedure assumes statistical stationarity in the angle range, i.e. at different angles the statistical properties of the flow and the properties of the L2F system have to be same. Especially this means that the number of particles in the flow, detectable by the L2F system, has to remain constant. Normally this condition is fulfilled by counting the number of particles passing the start focus and by stopping the measurement at each angle at a preset number of counts. This procedure ensures the best results as long as the scattered light has its origin predominantly in the particles, but it may give erroneous results when measuring very near to surfaces where much stray light is produced by the surfaces.

We prefer to measure a constant time per angle. The number of particles per angle passing start and stop focus are simultaneously measured and stored at each angle, therefore we are able to use the particle rate per angle as a weighting factor in order to correct the effect of differing particle numbers.

In Figure 5 the L2F particle rates per angle are shown for two measurements: one measurement far from walls (the upper diagram), the other one very near to the hub. In the case of the measurements far from the wall, where the particle rate per angle was nearly constant, both the above described procedures yielded good results. In the case of the near wall measurements both would fail. In this case (the diagram in the middle) there occured some huge spikes in the 'particle rate' which cannot be due to particles, because they occured only in the rate of the start focus or only in the rate of the stop focus. These spikes had their origin in stray light scattered from the hub.

Nevertheless valid results could be achieved by evaluating these measurements without any weighting, just by assuming that the rate of real particles remains constant in time as in the case of the mid section measurements.

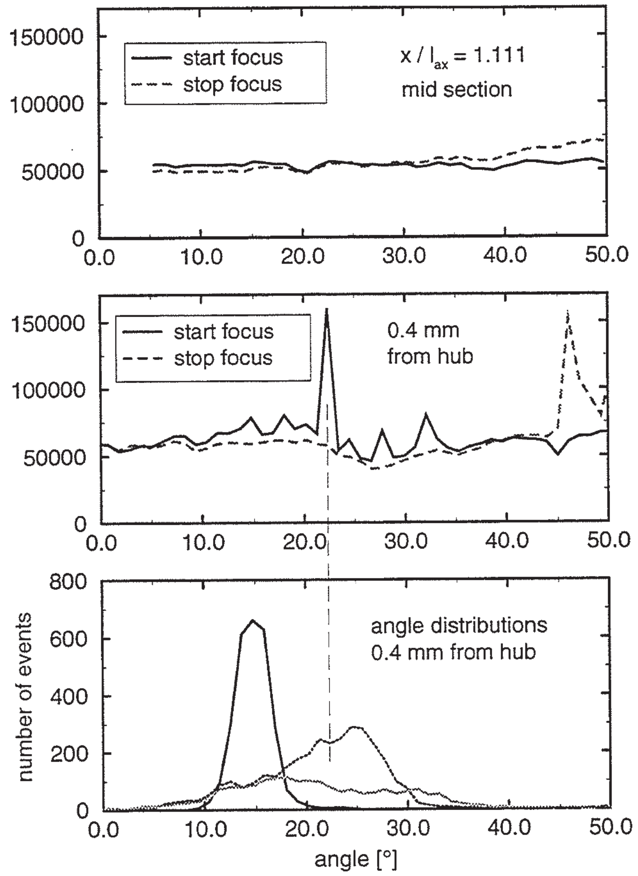

Figure 5: L2F particle and event rates at mid section and near hub

In the lowest diagram of Figure 5 three angle distributions from the near wall measurements are presented. The narrow distribution is an angle distribution from a circumferential position outside the wake. The distribution of next lower height was taken in a region of severe secondary flow and it can be seen that it is partly affected by a spike in the 'start focus rate'. The spike of stray light obviously prevented the detection of some 'useful particles' by the photomultiplier. Nevertheless enough particles were detected to get an event rate at this angle which is comparable to the neighbouring angles. If we would use the 'start focus rate' as a weighting factor or as a stop condition, we would get a deep depression in this angle distribution at the angle where the spike occurs. The angle distribution of lowest height in the diagram was measured inside the wake and it is shown as an example to demonstrate the enormous width of the flow angle range in the wake.

## 4 Example of transonic flow downstream of a rotor

With the L2F system we recently performed investigations of the velocity field in front, inside, and downstream of a transonic turbine rotor. The speed of the rotor was roughly 4000 rpm and the isentropic downstream Mach number in the relative system was 1.1.

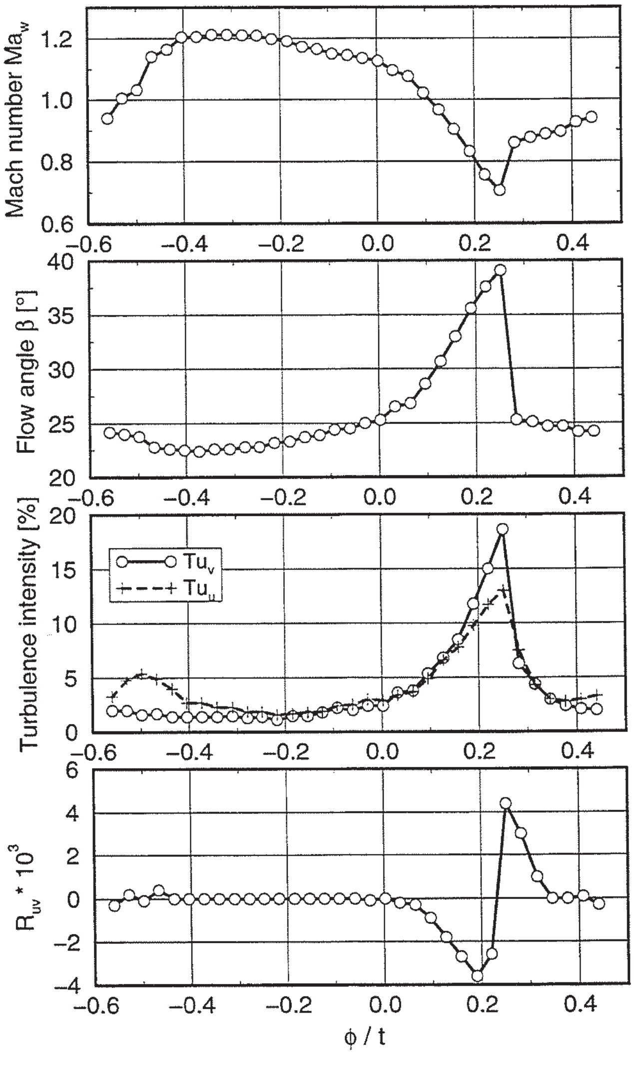

Figure 6: L2F measurement downstream of a rotor, $x/l_{ax}$ = 1.111, mid section

Figure 6 displays the results of a measurement 3 mm downstream of the rotor exit. In the figure the relative flow Mach number, the flow angle and the turbulence quantities are shown for one pitch.

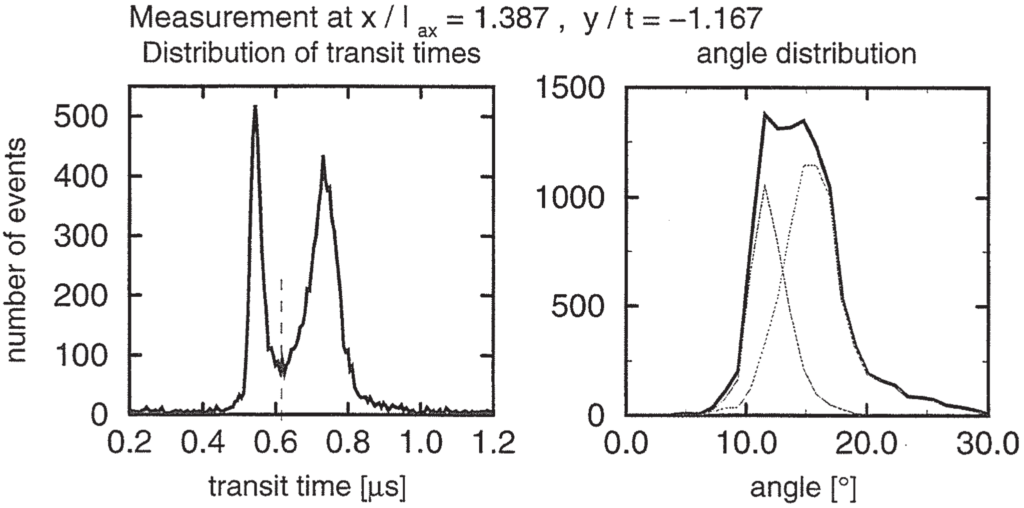

Figure 7: L2F measurement in a straight cascade tunnel downstream of a stator profile in the vicinity of a shock

The wake centre is clearly marked by a peak in the turbulence intensity. A second local peak of higher streamwise turbulence, $\mathrm{Tu}_u$, marks the position of a shock originating at the suction side trailing edge, because a shock always performs slightly oscillating movements and therefore produces an apparently higher turbulence level.

Reynolds stress (lowest diagram) is zero outside of the wake and goes from negative to positive values in the wake (note, that the lower side of the wake is coming from the pressure side of the blade).

## 5 Example of distributions with two peaks

Normally a measured L2F distribution looks like the one displayed in Figure 4. A marginal distribution is produced from the two-dimensional distribution by integrating it along one of the axes. For example to get the marginal particle transit time distribution the two-dimensional distribution is integrated in direction of the angle axis. From a two-dimensional distribution like the one of Figure 4 a regular particle transit time distribution with one peak would be received.

In some cases, however, a distribution exhibiting two peaks is measured. In [4] an angle distribution with two peaks is shown and it could be proved that the two peaks had their origin in a vortex street downstream of the trailing edge.

In Figure 7 a particle transit time distribution, exhibiting two peaks is presented. The distribution was measured by L2F in a straight cascade tunnel downstream of a stator profile. A Schlieren photo revealed that the location of the measurement was in the vicinity of that shock which has its origin at the suction side of the trailing edge and which runs from there into the downstream flow field. The shock obviously performed an oscillating movement and the L2F measured the velocity upstream and downstream of the shock. The velocity difference across the shock was such that the two peaks in the particle transit time distribution could be separated. The angle difference was much smaller, therefore only a broadened angle distribution could be observed. Furthermore the turbulence intensity (not shown here) seemed to be rather high, because this switching of the flow values between two states produces an enormous apparent turbulence level.

As the particle transit time distributions are stored at each angle, it was possible to split up all transit time distributions into two peaks. By this procedure also the individual angle distributions of the two flow states could be reconstructed. The separated angle distributions are shown in Figure 7, too. From the evaluation process using the sep-

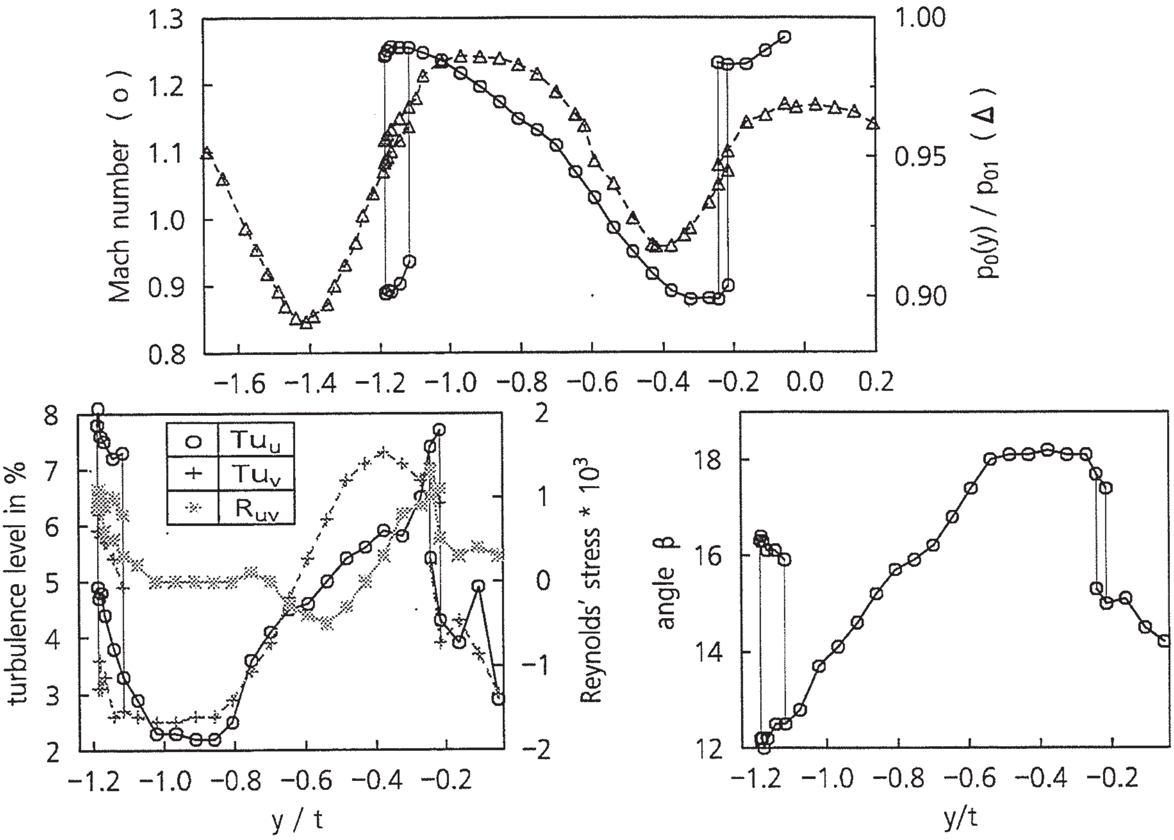

Figure 8: Straight cascade wake measurements by L2F and a pitot probe, downstream of a stator profile. The shocks are oscillating.

aration of the peaks the mean velocities, the mean angles and the mean fluctuating values for the flow in front of and behind the shock were obtained. The mean fluctuating values like turbulence intensity and Reynolds stress now show usual values. From the results in front of and behind the shock, the shock strength could be computed. The evaluation resulted in a shock angle of 74°, i.e. a nearly normal shock.

The whole wake traverse including two of those oscillating shocks is presented in Figure 8. The wake traverse was performed in a plane parallel to the cascade exit. In the same plane also a pitot probe, aligned with the flow direction was used to measure the pitot pressure of the flow. In subsonic flow the pitot pressure is equal to the total pressure. In the supersonic parts of the flow field a straight shock is located in front of the pitot tube inlet. By using the Mach number measured by L2F at the location of the pitot tube, a correction for the straight shock in front of the pitot tube could be made and so the flow total pressure could be received.

The flow Mach number and the total pressure are plotted in the upper diagram of Figure 8. The extent of the shock movement is indicated by vertical lines in the diagram. It can be seen that the left shock movement was roughly 3 mm, whereas the shock on the right moved only 1 mm. The total pressure curve shows two deep wakes. The total pressure loss of the shock is 0.8% according to the known shock strength – it may be realized that in this case the shock loss is only a small contribution to the cascade loss.

In the lower diagrams the turbulence intensities, the Reynolds stress and the flow angle are displayed. The wake minimum coincides with a maximum in the transverse turbulence, $Tu_v$; the maximum of streamwise turbulence, $Tu_u$, is located behind the shock. The Reynolds shear stress is zero outside the wake and away from the shock.

## 6 Conclusions

- The Laser-Two-Focus Technique (L2F) can be routinely applied to acquire flow field information for turbomachine flows.
- There is good access to narrow blade channels.
- The statistical stationarity in the angle range is a problem.
- The storage of the two-dimensional histogram has many advantages:
  - Reynolds' shear stress is acquired
  - a better discrimination of events caused by stray light is possible, thus allowing measurements nearer to side walls
  - the evaluated data are more accurate
  - unusual velocity or angle distributions can be evaluated

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