3-Component-Doppler-Laser-Two-Focus Velocimetry Applied to a Transonic Centrifugal Compressor

by

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ABSTRACT

The conventional Laser-Two-Focus (L2F) method also known as Laser Transit Anemometry (LTA) measures two components of the flow vector in the plane normal to the optical axis by measuring the time of flight of particles crossing the two laser beams in the probe volume. Recently a new three component system was developed, named 3C-Doppler-L2F, which operates with the same confocal optical set-up as the two component L2F system, thus enabling three component measurements even under the extremely difficult conditions of limited optical accessibility as they appear for example in centrifugal compressors. The new hybrid system combines the principle of the L2F technique with the basic idea of the Doppler Global Velocimetry (DGV). The two velocity components in the plane perpendicular to the optical axis are measured by the L2F time of flight technique, the third velocity component in the direction of the optical axis is determined by analyzing the Doppler frequency shift of the scattered light. The system was developed with respect to an application in a transonic centrifugal compressor and designed in the shape of an optical probe shown in Fig. 1. The set-up and all important components of the 3C-Doppler-L2F system are described in detail as well as the way of operation and calibration of the system. Tests on a free jet demonstrate the measurement accuracy of the hybrid technique. With its successful application to a transonic centrifugal compressor it was the first time that three component velocity data could be collected from a high loaded high speed centrifugal impeller. The data are presented and discussed.

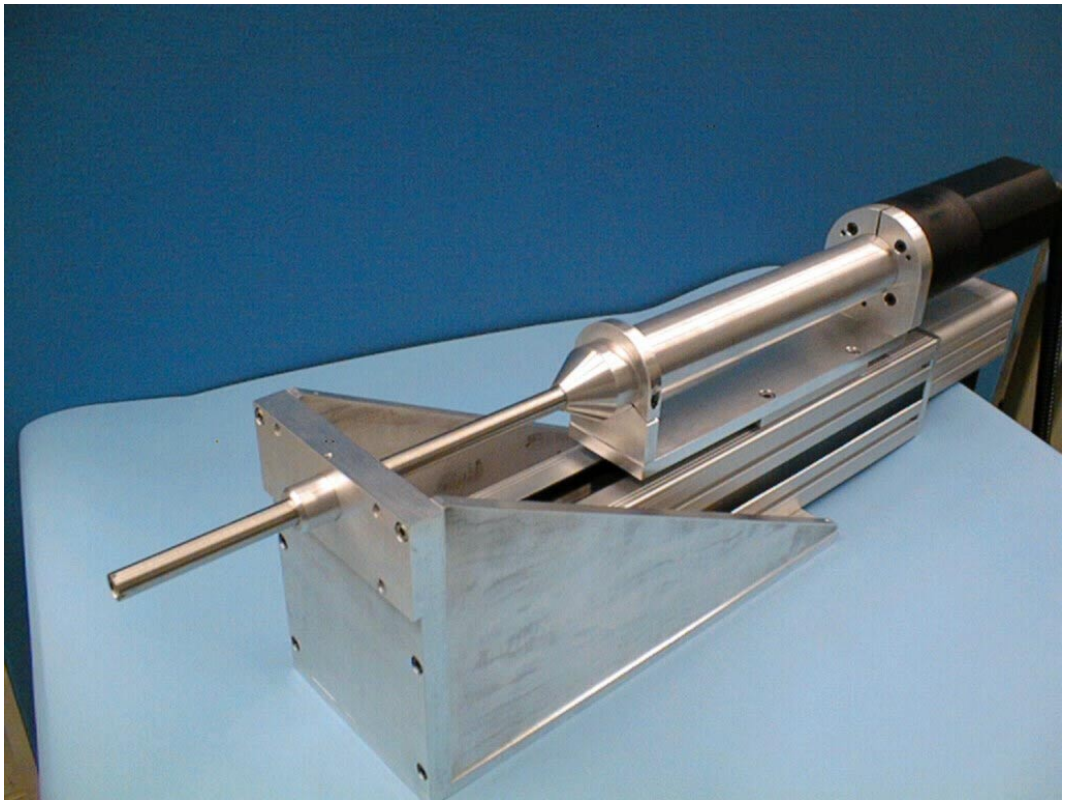

Fig: 1 3C-Doppler-L2F-probe

1. INTRODUCTION

Advances on the aero-thermodynamic design of gas turbine engines can be achieved most efficiently by co-operative efforts aimed at the improvement of both the numerical simulation methods and the experimental data which are needed to improve the understanding of the physical flow processes and to validate the theoretical results. In this context significant instrumentation research efforts are being conducted to develop the needed measurement technologies. The enhancement of modern compressor and turbine technology requires accurate, reliable and detailed experimental velocity data from the flow inside the turbomachinery components. State-of-the-art non-intrusive techniques for this purpose are Laser-2-Focus-Velocimetry (L2F), Laser-Doppler-Anemometry (LDA) and Particle-Image-Velocimetry (PIV). Often, the most severe problem in applying these techniques is the limited optical access to the flow. This is especially true when 3-component flow velocity data are required.

To date, the 2-Component-Laser-Two-Focus technique (L2F) has been suited best in overcoming serious access problems, since it is a back-scattering technique with a confocal optical beam path (see Schodl, 1980). Furthermore it is capable of measuring very close to walls and windows (down to 0.3 mm). At the same time it is capable of detecting very small particles (typ. 0.2 µm diameter) which can follow very strong accelerations.

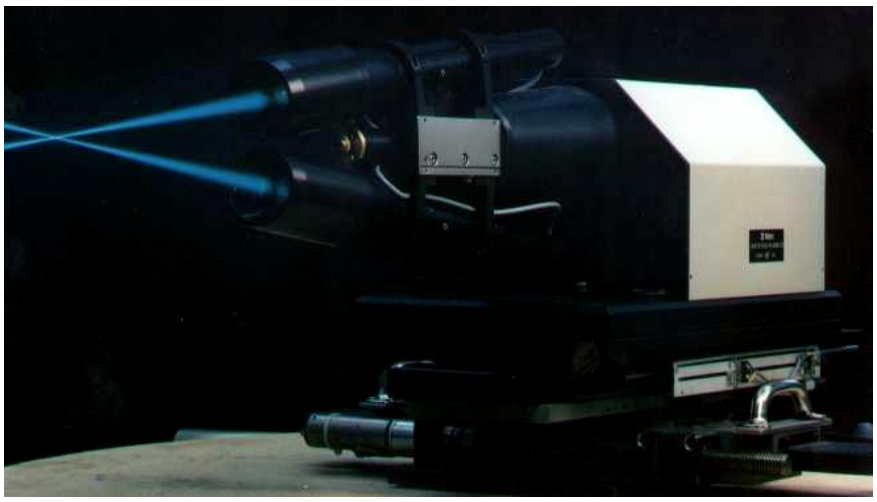

Fig 2. 3C-L2F optical head

Due to it's specific properties the L2F technique is well established in the experimental flow analysis of turbomachines. This is especially true when high speed turbomachines, e.g. centrifugal compressors and turbines, are considered. In these cases optical access problems are most severe and standard 3-component velocimeter arrangements which need a solid angle of 30 to 40 degrees for optical access can not be applied. A specially designed 3-component L2F system, see Schodl (1998), is on the market today and in use at different European institutions. This system (Fig. 2) is set up from two independent 2-component L2F systems with a tube type optical head construction. The two tubes are mounted to a mechanical rotation unit inclined to the rotational axis at an angle of 7.5°. The location where the laser beams intersect each other is on the rotational axis and determines the probe volume. From the two component data of the two independent L2F systems the three velocity components can be deduced. Since the system is designed to automatically adjust to the maximum sensitivity of the radial component measurement the solid angle required for optical access is only 20 – 25 degrees, remarkably smaller than that needed for a standard three component arrangement.

Even though the 3C-L2F is well suited for turbomachinery measurements in general there are extreme applications where either this small solid angle for optical access is still too large or where not enough space to place and operate the optical head is available. In these cases only 2-component systems can be used because they need only 11 degree solid angle for optical access.

Recently a new 3-component system was developed, named 3C-Doppler-L2F, which operates with the same confocal optical set up as the 2-component L2F system, thus enabling 3-component measurements even under difficult conditions, e.g. in centrifugal compressors. This technique combines the principle of the L2F method with the principle of the Doppler Global velocimetry (see Roehle and Schodl, 1995, and Roehle, 1996). From the time-of-flight data the standard two-component measurements deliver the velocity vector component in the plane perpendicular to the optical axis. An additional frequency analysis of the scattered light determines the

Doppler frequency shift which represents the velocity component along the optical axis. The Doppler shift is measured by using the frequency depending absorption of iodine.

The system was developed with respect to an application in a transonic centrifugal compressor and designed in the shape of an optical probe with an outer diameter of 25 mm and a probe throw of about 100 mm. The 3C-Doppler-L2F probe is shown in Figure 1.

2. PRINCIPLE of OPERATION

2.1. L2F Velocimetry

The L2F technique is a non-intrusive technique for the measurement of flow velocities in gases and liquids. Here the velocity of extremely small particles is recorded which are usually present in all technical flows or may be added if required. The light scattered by the particles when irradiated by a light source is used in this measurement. The required particles are in the size range of the light wave length (< 1µm) and follow the flow even at high acceleration so that correlation between particles and flow velocity is assured.
In the measuring volume of the L2F device (Fig. 3), two highly focussed parallel beams are projected which function as a time-of-flight gate. Particles which traverse the beams in this area each emit two scattering light pulses which are scattered back are detected by two photodetectors each of which is assigned to a beam in the measuring volume.

Should a particle traverse both beams, then it transmits two scattering signals whose time interval provides a value for the velocity component $V_\perp$ in the plane perpendicular to the beam axis. Two associated double signals are only then obtained when the plane through which the two beams are spread out is nearly parallel to the flow direction. The beam plane is rotatable and its angular position is determined by the angle α. In turbulent flow the magnitude and direction of the momentary velocity vector changes constantly. The flow values are therefore usually given as mean values and measures of fluctuation. For this reason the beam plane for a L2F measurement is adjusted in various positions (angle α) in the range of the mean flow direction and some thousands of time-of-flight measurements are carried out for each position. The measured data may be represented graphically as two-dimensional frequency distribution (Fig. 4). Incorrect measurements are then separated from the correct measurements by means of a statistical method. Incorrect measurements, which arise when two different particles trigger the start and stop signals of the time measurement process, appear in the statistical representation as constant background and can thus be recognized and subtracted. Further evaluation of the data results in the 2-dimensional components of the flow vector, i.e. the magnitude $\overline{V}_\perp$ and the direction $\overline{\alpha}$ of the mean flow vector in the plane perpendicular to the optical axis of the measuring system as well as the degree of turbulence, shearing stress and other high order moments of the fluctuation velocities.

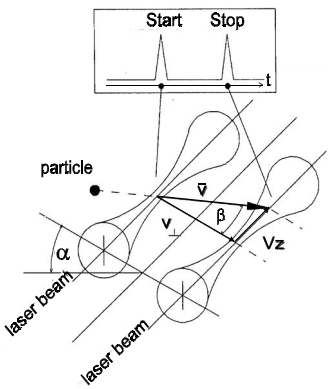

Fig. 3. L2F-probe volume

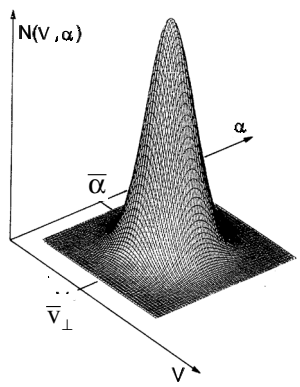

Fig. 4. Two dimensional frequency distribution.

2.2. Measurement of the V_Z Velocity Component

Since the velocity component in the direction of the optical axis, the component V_Z (Fig. 3) causes a frequency shift of the scattered light due to the Doppler effect it can be measured by analyzing the scattered light frequency

ν . Given the laser frequency ν_0 and the vacuum speed of light, C, the Doppler shift $\Delta\nu = \nu - \nu_0$ for the special case of backward scattering is most sensitive against V_Z and results in

$$\Delta\nu = 2\nu_0 \frac{V_Z}{C} \quad .$$

This frequency shift is analyzed by measuring the transmission of the detected scattered light through an iodine cell which serves as a frequency to intensity converter (Fig. 5). An iodine cell is a glass cylinder, evacuated and filled with iodine vapor. Molecular iodine has strong absorption lines which interfere for example with the 514 nm wavelength of an Argon ion laser.

The transmission T is the ratio of the light intensity emerging from the iodine cell (signal) related to the light intensity entering the cell (reference). The transmission function $T(\nu)$ of an iodyne vapour absorption line has a very strong frequency dependency especially in the region of the steep slope of the transmission function. In order to take advantage of this high frequency sensitivity the laser frequency ν_0 should be tuned to a certain position of the transmission slope and stabilised at a desired transmission value T_0. If the scattered light undergoes a frequency shift the transmission value T derived from the photodetector signals changes. With the known transmission function $T(\nu)$, the Doppler shift $\Delta\nu$ and with this transmission value, T, the velocity component V_Z can be determined.

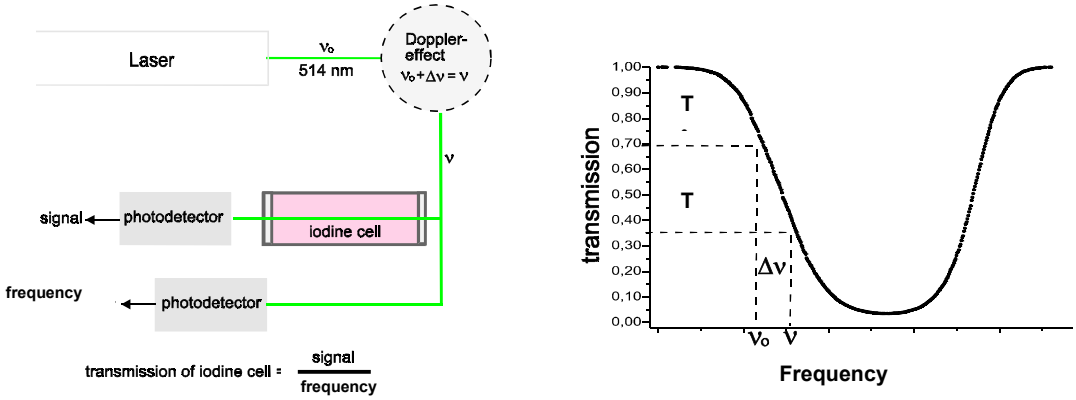

Fig. 5. Principle of the Doppler shift measurement.

3. SET-UP of the 3-COMPONENT-DOPPLER-L2F-VELOCIMETER

The set-up of the 3C-Doppler-L2F device is shown in figure 6: A frequency stabilized argon ion laser with intracavity etalon is used as a light source. While operating in multicolor mode the Ar^+-laser was frequency stabilized using the green line (λ=514 nm). The laser was fibre linked to the probe head. Lens f1 collimates the laser beam emerging from the fibre end and guides the multicolor beam to a dispersion prism where the various colors experience different angular deflections, so that with the aid of lens f2, parallel multicolored beams with differing separations are focused in the probe volume (PV).

The multicolor scattering light scattered by the particles traversing these beams is collected by the outer area of lens f2 and sent through the same dispersion prism where the various colors are again deflected such that the light produced at the various places in the probe volume is projected in a single focal point by lens f3 and thus may be coupled into a multimode receiving fibre which additionally functions as a aperature for spatial filtering. The receiving fibre guides the multicolor scattered light to a color-separation unit where the various colors of the detected light are separated and launched into the three assigned fibres.

The scattering light pulses from the 488 nm and 496 nm laser beams in the probe volume (beam diameter 13 µm, beam separation 75 µm) are guided to a L2F processing unit where the start and stop signals for the time-of-flight measurements are generated. The signals are processed by standard, commercially available L2F signal processors (see Schodl , 1980 and Schodl, 1998), and deliver the two velocity component $V_\perp$ and angle α in the plane perpendicular to the optical axis.

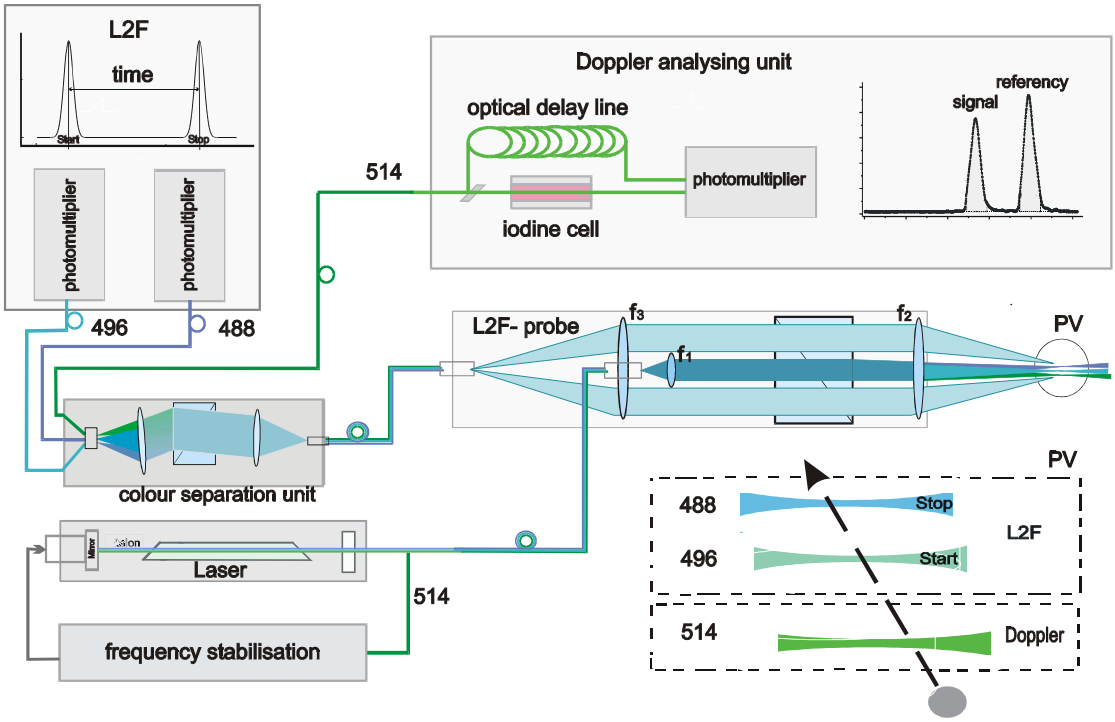

Fig. 6. Schematics of the 3C-Doppler-L2F device.

The velocity component V_Z along the optical axis is deduced from the Doppler frequency shift analysis using the scattering light pulses from the 514 nm laser beam in the probe volume (beam diameter 13 µm, separation from 496 nm laser beam 160 µm). In this Doppler analyzing unit the 514 nm scattering light is collimated and split by a non polarizing beam splitter into two beams of equal intensity. One beam guided through an iodine cell providing signal light pulses while the other beam is guided through a multimode fibre that serves as an optical delay line. Along this path the reference light pulses are transmitted. Both pulses are detected by a single photomultiplier with a constant time delay determined by the fibre. The amplitude ratio of these pulses is proportional to the transmission T(ν) of the iodine cell, from which the scattered light frequency can be derived.

An important and new aspect of this set-up is the use of the "delay fibre". Previous tests have shown, that the more common set-up with two photomultipliers, one for the signal pulse and one for the reference pulse , causes insufficient measurement accuracy because of time depending sensitivity variations of the two physically different detectors which occur due to temperature effects and due to changes of the supply voltage amplitude. The signals are collected and digitized by a 400 MHz transient recorder card placed in a PC. Further signal processing is done by software.

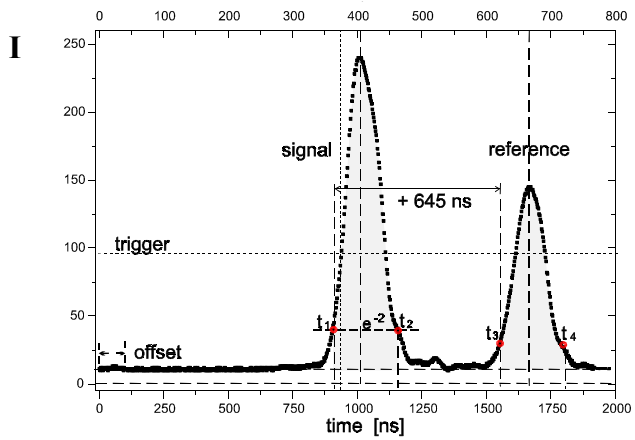

Fig. 7. Integration intervals of the two pulses.

The two successive signal and reference pulses have a nearly Gaussian shape (Fig. 7) and are separated by a known time interval of 645 ns determined by the delay of the fibre with a length of 120 m. This length was chosen to ensure that the pulses stay separated even at low velocities $V_\perp$ where the width of the pulses

$$t_2 - t_1 = t_4 - t_3 = \frac{d}{V_\perp}$$

increases (d represents the diameter of the laser beams in the probe volume).

Due to shot noise and photon statistics the shape of the pulses is often disturbed which causes errors when the transmission value T is determined by the amplitude ratio of the two pulses. In order to reduce the influence of noise the pulses are integrated and the transmission value T is then determined by

$$T = k \frac{\int_{t_1}^{t_2} I(t)dt}{\int_{t_3}^{t_4} I(t)dt}$$

The constant value k needs to be determined by a special calibration test. For this reason the laser frequency is established far outside the range of the absorption line where the transmission value is known to be one and constant over a wide frequency range. Under these conditions measurements are carried out and data are collected. With the known transmission the evaluation of the integrated pulses provides the value of k. Care is taken to set identical integration ranges for both signal and the reference pulse. These ranges can easily be matched to each other with the aid of the known time delay of the two pulses. In the presented system the signal processing of the time of flight measurement and the Doppler shift analysis is performed independently, however, correlated three component velocity measurements should be feasible in principle.

4. FREQUENCY STABILIZATION of the LASER SOURCE

Necessary requirements for accurate Doppler shift measurements are the precise adjustment of the laser frequency ν_0 to a selected transmission value T_0 of the iodine absorption line and a stabilization system that keeps the laser frequency constant during the measurement procedure. The following example gives an estimation of the required stability: a velocity component V_Z of 1m/s causes a frequency shift of 3,9MHz an extremely small value when compared to the laser frequency ν_0 of $5{,}8 \cdot 10^8$ MHz. A narrow linewidth of the laser frequency is also desired. An Ar^+-laser with an intracavity etalon operating at a wavelength of 514nm is, in general, a well suited light source.

The etalon selects one of the almost 70 modes of the laser gain profile. It functions as a second resonator inside the laser resonator. The mode can be chosen and changed by controlling the temperature and with it the actual length of the etalon. When changing the etalon temperature the laser 'hops' form one mode to the other in steps of the free spectra range (FRS) (typical 150 MHz).

Operating in a single mode the line width of the laser is very small (a few MHz), however, its center frequency is not stable. There is a high frequency jitter with a fluctuation frequency of about 1KHz. Since its amplitude is typically around 4 MHz corresponding to a velocity V_Z of only 1 m/s this fluctuation amplitude is considered to be practically negligible and therefore no effort is spent in the present set up to compensate for it.

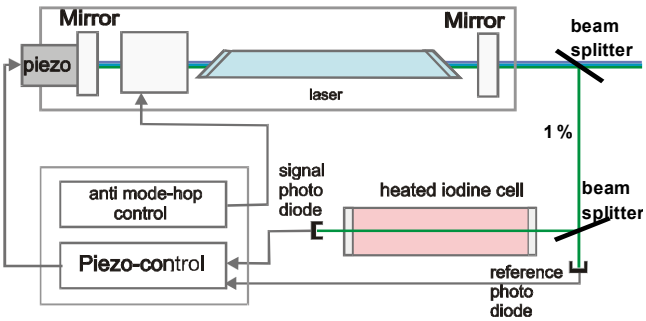

Fig. 8. The control loops of the frequency stabilisation.

Long term drifts of the laser frequency which occur due to temperature related changes of the resonator length can reach rather large values up to 100 MHz and must therefor be compensated. By placing the rear mirror of the resonator on a piezo translator the resonator length can be actively controlled thereby stabilising the laser frequency (Fig. 8).

For the control process a signal representing the actual laser frequency is required. Since the laser has to be operated at a frequency in the range of an iodine absorption line this signal can be deduced from the transmission of a second iodine cell placed in the control set up (Fig. 8). For this purpose a small amount (1%) of the laser power is split off from the laser beam and this part is guided through the cell. The transmission value results from the signal ratio of the signal and reference photodiode – the same principle as it is used for the Doppler shift detection. A PID controller stabilises the laser frequency to a desired transmission value. In order to avoid mode hops the etalon temperature must be controlled additionally in order to match the etalon length to the length of the laser resonator. A perfect match is indicated by the power when it reaches its maximum value. With the reference photodiode signal as an input a PI-controller continuously optimises the laser power thus preventing the laser from carrying out mode hops.

When both systems, the anti mode hop control and the piezo control, work together they can also be operated to tune the laser over a rather wide frequency interval of some thousand MHz. This capability is needed for the calibration of the iodine cell transmission function.

5. IODINE CELL

An iodine cell is a glass cylinder filled with a small amount of iodine. Normally both solid iodine and vapour is contained in the cell. With increasing temperature the vapour density in the cell rises which causes significant changes of the shape of the transmission function T(ν). Since the accuracy of the Doppler shift measurement is very much determined by the stability of this function, the temperature of the iodine cell must be controlled with a very high precision. This is practically very difficult to achieve. The stability of the transmission function becomes much less temperature sensitive when the cell is operated at temperatures higher than the so called saturation temperature T_{sat} at which all solid iodine is evaporated (in the case of the iodine cell used $T_{sat} \approx 60°$ C). Beyond this temperature the iodine vapour density which has the strongest influence on the shape of the transmission profile remains constant and a not very complicated control of the iodine cell temperature is then sufficient to ensure the required stability of the transmission function (remaining error of V_Z determination ± 0.5 m/s).

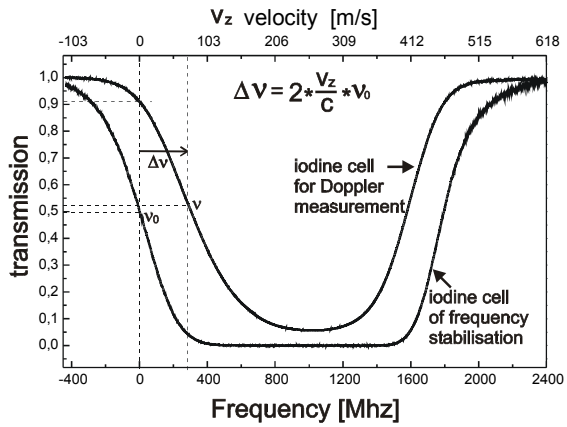

Fig. 9. Transmission profiles of iodine cells

The iodine cells are mounted in small ovens in which they are heated and temperature controlled. Figure 9 shows the experimentally determined transmission functions of the two iodine cells with different saturation temperatures Tsat. The iodine cell with the somewhat stronger absorption is chosen for the frequency stabilisation of the laser. The laser is stabilised at 50% transmission at the left slope of the wider curve. Since the expected mean V_Z-velocity in the centrifugal compressor experiment is about 70 m/s which corresponds to a frequency shift Δν of +265 MHz the transmission values of the Doppler shift measurements will be resulting also around 50% transmission at the left slope of the second transmission function with the smaller width (Fig. 9). In this way the frequency stabilisation and the Doppler shift analysis takes place in the region of the steepest slope of the transmission functions where the accuracy of frequency measurement is the best.

6. FIRST TESTS on a FREE JET and ACCURACY CONSIDERATIONS

The 3C-Doppler-L2F-system was initially tested in the core of a free jet flow. The free jet nozzle axis could be adjusted to different inclination angles β with respect to the plane normal to the L2F optical axis (Fig. 10).

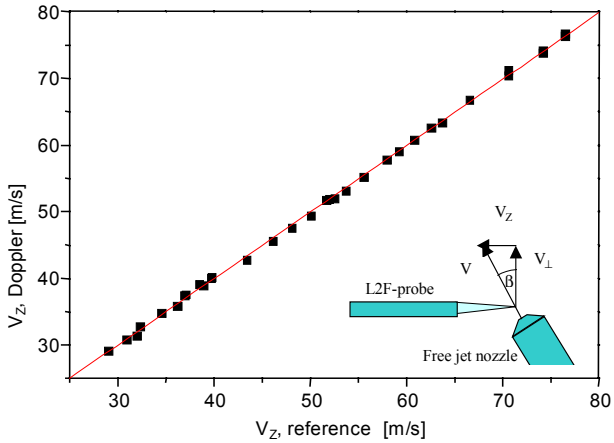

Fig. 10. Comparison of measured Doppler- and deduced reference velocity V_Z

The reference velocity V_Z, reference was calculated from the measured time-of-flight velocity , $V_\perp$, and the known inclination angle, β, of the assigned experimental set-up:

$$V_Z = V_\perp \tan\beta$$

$$V_\perp = V\cos\beta$$

In figure 10 the Doppler measured velocity component in direction of the optical axis V_Z, is plotted against the reference velocity V_Z, reference. Each point indicated in the plot represents the mean value of 1000 individual measurements. The scattering of the measured values is about ± 1 m/s and independent of the magnitude V of the velocity. In figure 11 a histogram of a set of 10.000 individual Doppler determined V_Z-velocities is shown for an arbitrarily given mean velocity of 75 m/s.

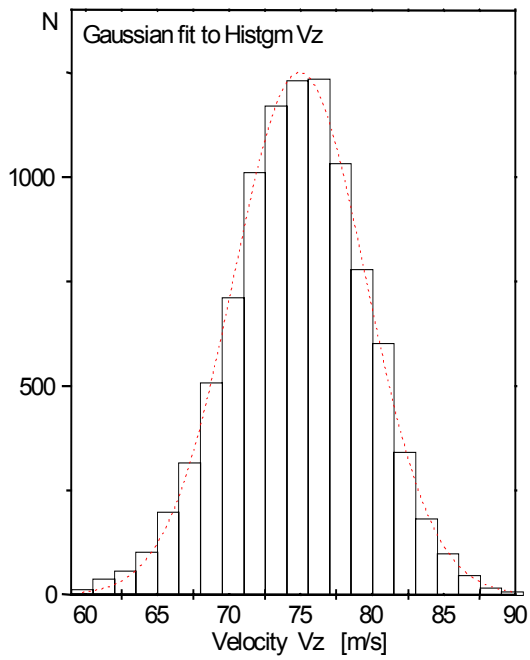

Fig. 11. Frequency distribution of V_Z-velocities measured in the core of a free jet.

The indicated standard deviation of the V_Z-velocity is 4,6 m/s. This value, which is found to be quite constant and independent of mean velocity, is rather large and exceeds by far the experimental velocity fluctuations found in the core of the free jet (turbulence intensity ≈ 1%, which corresponds to a velocity standard deviation of 0,75 m/s). Therefore the main part of the velocity standard deviation of 4,6 m/s is considered to be instrumental broadening

which is caused by many different influences as e.g. shot noise, photon statistics, numerical data evaluation, frequency fluctuation of the laser employed, etc. With this large and constant broadening value the turbulence determination of the flow velocity component V_Z is not practicable, especially at low mean velocities. At high speeds turbulence measurements might be reasonable since corrections of the broadening effect then become more effective.

Because of these reasons the processing of the time of flight data (the results are $\overline{V}_{\perp}, \overline{\alpha}$ and the turbulence intensities T_{α}, T_{V_Z}) and the Doppler data processing are performed independently and only the mean value $\overline{V}_Z$ is evaluated. With the further development of the system, correlated three component measurements might become possible.

7. APPLICATION to a TRANSONIC CENTRIFUGAL COMPRESSOR

The 3-C-Doppler L2F system was applied to a centrifugal compressor in order to measure the flow field in the rotating flow channels of a transonic splitter blade impeller of advanced design (Fig. 12) [see Krain (1999)]. These flow data are very much desired for the validation of 3D-Navier Stokes based numerical simulations.

The L2F system has optical access to the impeller via glass windows (diameter 8 – 20 mm) mounted at fixed positions in the compressor casing. While the L2F-probe volume is positioned at a certain location in the flow channel, the circumferential location varies permanently during the impeller rotation. To allow for circumferentially resolved measurements special synchronization electronics have been developed. Triggered by the measurement events these electronics identify the circumferential position and before storing the data combine these values with the assigned measurement data. In this way 64 different measurement regions distributed circumferentially over one blade channel width can be resolved and the further data processing results in phase averaged velocity mean values clearly assigned to each of the measurement positions. These electronics are also suited to distinguish between the two flow channels on both sides of the impeller splitter blades.

The measurements were carried out at the centrifugal compressors design conditions: Rotational speed 50,000 rpm, mass flow rate 2.55 Kg/s, total stage pressure ratio 5.9:1. The rotor (Fig. 12) with an outer diameter of 224 mm has 26 blades in total with every second blade shortened at the intake (splitter blade). The rotational speed at rotor exit was 586 m/s. The measurements were taken at four meridional locations (Fig. 13) and at 9 locations equally spaced between hub and casing.

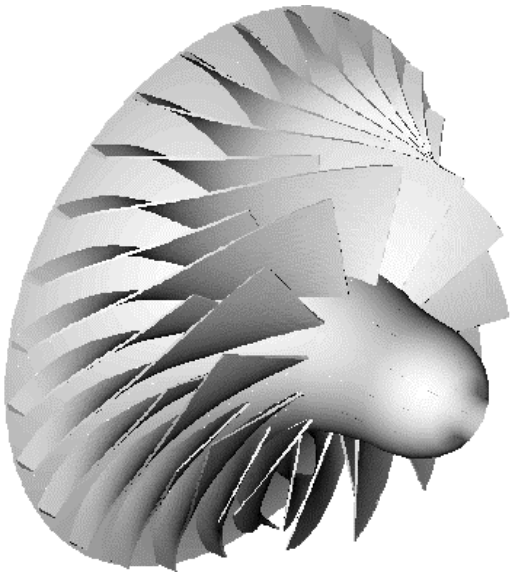

Fig. 12. Impeller of the transonic centrifugal compressor with splitter blades.

Typical L2F-seeding was applied (see Schodl ,1998), introduced in the settling chamber via a seeding probe upstream of the compressor. Since the probe feeds only a streamline the probe position must be adjustable in order to establish the maximum particle rate at the measurement location. The particle diameter is known to be less then 0,5 µm. Due to the high pressure ratio of the compressor the casing reaches temperatures up to 300° C. Therefore the L2F-probe was heat shielded by a cooling jacket on the front part of the probe.

Examples of measurement results are presented for 0 and 60 percent of the meridional length (Fig. 13). The 3-component absolute velocities are shown represented by the vector plot of the velocity components within the measurement plane and the color coded out of plane velocity component (CmL2F).

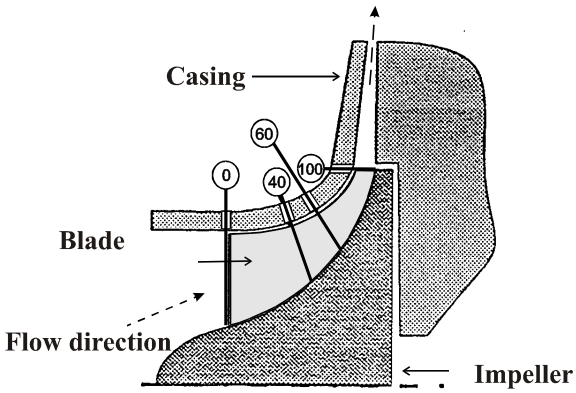

Fig. 13. Meridional cross-section of the compressor indicating the measurement locations in percentage of the meridional impeller length.

In figure 14 the velocity distribution between two main blades measured just in front of the rotor leading edge is plotted. The triangle shaped area in the central upper part of the plot is the region where the relative intake velocity is supersonic. The steep gradient on the left side of this region indicates the location of a compression shock where the supersonic relative velocity suddenly changes to subsonic. The splitter blades which are centered between two main blades (see fig. 12) are not shown in this plot since their leading edge is located further downstream at 30 percent of the meridional length. Their upstream influence on the flow at the location in front of the rotor, however, is presumably indicated by the in plane flow vectors pointing upwards between the two main blades.

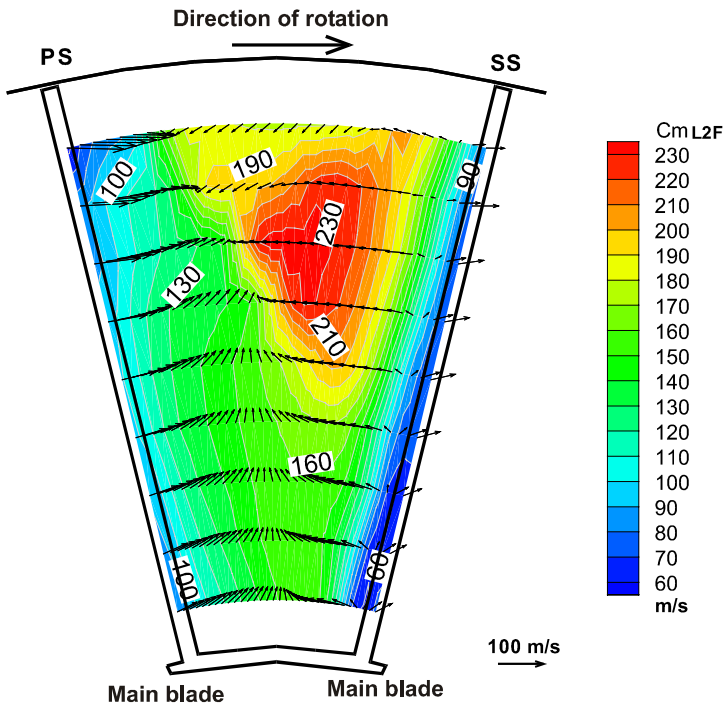

Fig. 14. Absolute velocity distribution measured at zero percent meridional length, just in front of the blades.

The data from the measurements at 60 percent meridional length are shown in Figure 15. In this case the splitter blades are already present. From the out-of-plane velocity distribution one can clearly recognize the differences in the flow channels on the left and the right side of the splitter blade, the high velocities on the suction side of the blades and the low velocity regions close to the casing which indicate the beginning wake regions, which are

well known in these kind of machines. All in-plane velocity vectors point in the direction of rotation. This is due to the energy imported into the flow by the impeller work. Since the velocity components in the circumferential direction are quite high, about 270 m/s, secondary flow effects cannot easily be recognized. To improve their visibility the mean velocity vector of the in-plane velocity components was calculated using all measurement data of the measurement plane, and subtracted from the local values. The resultant difference values of the in-plane velocity component are plotted and shown in Figure 16. Very clearly secondary flow effects can now be recognized as e.g. the vortices in the upper left corner of the flow channels. A more detailed interpretation of the actual 3D-flow processes occurring in transonic centrifugal compressors becomes now possible especially if the flow from impeller intake to impeller exit is taken into account. A further aid in the interpretation of the measured data is the comparison with 3D-Navier Stokes calculations. This data analysis is going to be performed as a next step.

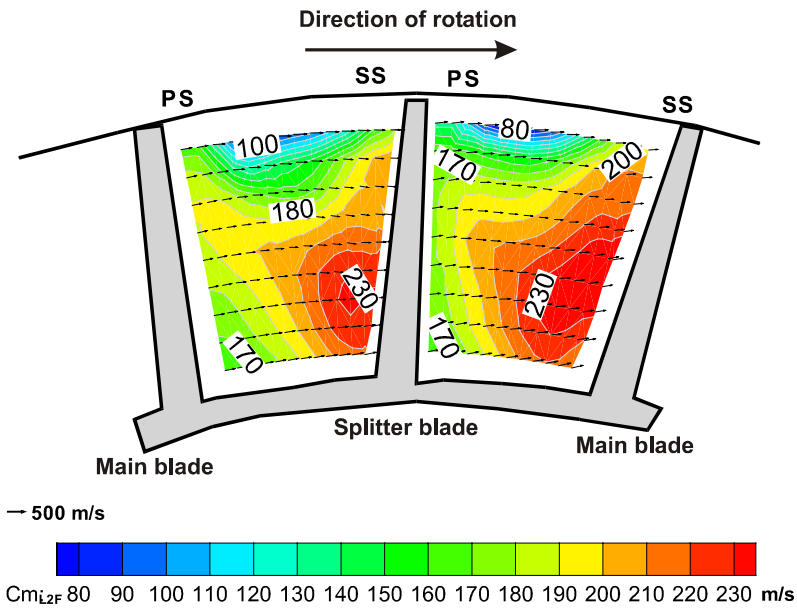

Fig. 15. Absolute velocity distribution measured at 60 percent meridional length

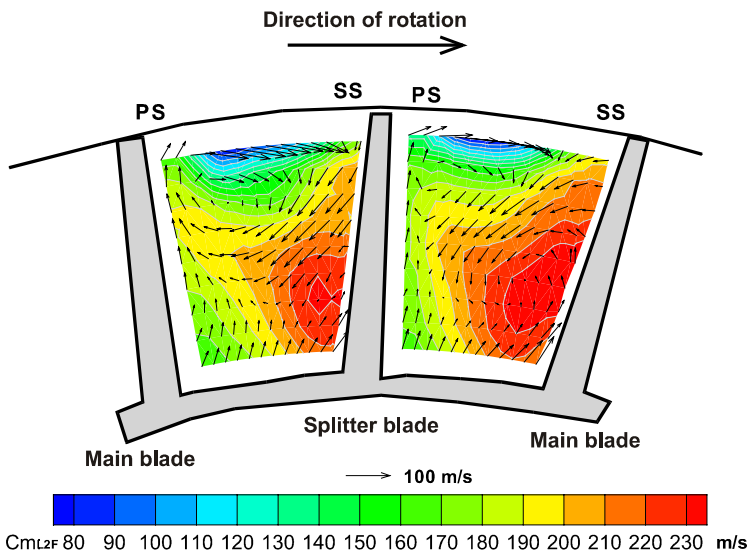

Fig. 16. Velocity distribution measured at 60 percent meridional length (in plane velocity value is obtained by substracting the mean value).

The presented measurement data are the first 3-component velocity data ever taken in such a compact high speed transonic centrifugal compressor. The results demonstrate the necessity of having full three component velocity data available since the flow itself is very complex and highly three-dimensional. Further detailed measurements

are planned with the aim to establish a complete three component velocity data base of a high speed centrifugal compressor which is very much desired for the validation of today's industrial design tools.

8. SUMMARY

A 3C-Doppler-L2F probe was described with the unique feature of being operational in internal flows via a single optical access port of a very small viewing angle of only 11°. The L2F probe is a result of a combination of the time of-flight principle and the direct measurement of the frequency of the Doppler shifted scattered light. The on axis velocity component is measured independently from the two other components. The measurement uncertainty of its mean values is ± 0.5 m/s.

For the application in a centrifugal compressor the electronics were extended with synchronisation devices, which enable phase-looked measurements before, behind and within the rotating impeller. The system was operated successfully in a high speed centrifugal compressor. The results demonstrate how useful three component velocity data are to improve our understanding about the physical flow processes in these machines.

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