New Developments in the Laser-2-Focus Technique for Non-Intrusive Velocity Measurements in Gasturbine Components

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Abstract

Further improvement of aircraft engines with respect to fuel consumption and emission reduction requires costly and difficult investigations which are impossible without modern measuring techniques. The Institute of Propulsion Technology is primarily concerned with investigations on turbomachinery components (e.g. compressors, combustors, turbines), where very often extremely difficult conditions prevail (high flow velocities, complex geometries, rotating flow channels). For this reason non-intrusive measuring techniques play an important role. The Laser-2-Focus technique for non-intrusive velocity measurements developed in the institute has won high regard worldwide. Developments in optics and electronics have resulted in this technique having a considerably greater area of application.

Introduction

In the experimental investigation of flows the application of conventional probes is still very often necessary today although these, depending on the test conditions, more or less greatly disturb the flow field under examination or do not endure the hot ambient conditions. To avoid these disadvantages there is a great interest in non-intrusive measuring techniques. In the course of the last two decades where many approaches to velocity measurement in flows have been applied, only two techniques have really become generally accepted:

1. Laser-Doppler technique (LDA)
2. Laser-2-Focus technique (L2F)

When taking measurements in turbomachinery high velocities in narrow flow channels must be determined. Due to the complicated housing geometry very often optical access is only available from one side, so that the backscatter systems with their typical, extremely low signal levels are suitable. The application of the LDA technique is more complicated in this case as a result of the greater measuring volume and the following disadvantages arise:

1. Insufficient spatial resolution.
2. Sensitivity to stray light from walls.
3. Small particles which adequately follow the flow are no longer detected.

These restrictions are only then avoidable if the size of the measuring volume is drastically reduced.

For this purpose a principle as proposed by THOMPSON [5] in 1968 has been further developed to the Laser-2-Focus technique at the Institute of Propulsion Technology with which flow velocities and turbulence intensities at extreme experimental conditions may be determined. The measuring principle of this method enables the 2-dimensional flow vector perpendicular to the optical axis to be determined. The small size of the measuring volume causes a high spatial resolution and facilitates the suppression of parasitic stray light from walls and windows. As a result of the high light intensity in the measuring volume particles as small as 0.1 to 0.2 μm may still be detected.

The applicability of the L2F technique especially in velocity measurements has been demonstrated in several individual cases since the first compressor tests carried out by SCHODL [2]. L2F systems are meanwhile commercially available. Furthermore there have been some industrial and research organizations which have constructed devices for special application, e.g. for wind velocity measurements, for investigations in heat exchangers, in steam flow, in water pumps, in plasma flow, in diesel motors and in wind tunnels. Most publications however, of course deal with the application in turbomachinery. Literature on the L2F technique up to 1986 is presented in [3].

Data resulting from L2F measurements which in some cases are most detailed, have contributed greatly to the understanding of flow in turbomachinery. This holds especially for the flow within the rotating components (e.g. turbine rotors), which generally cannot be investigated at all using conventional measuring methods. Comparisons between laser anemometer data and theoretical calculations have resulted in improved mathematical models and design procedures. Results from a turbine investigation are shown here as an example of a detailed flow measurement using the L2F technique. The tests were carried out in a cold-air turbine test rig with a rate of revolutions of 7800 1/min [1]. Figure 1 shows an instantaneous distribution of the turbulence intensity in the mid-section of the turbine rotor. The dot marked areas result from the turbulent wake of the preceding stationary guide vanes.

The current work on the further improvement of the L2F technique has two main objectives:

1. Reduction in the measuring time to save test costs.
2. Development of the measuring technique to include three dimensional velocity vectors.

REDUCTION IN MEASURING TIME

The great advantage of the L2F technique in its application at high velocities and in narrow flow channels is accompanied by the disadvantage of a comparably long measuring time. The causes for this can be found for one, in the measuring volume geometry (very small beam diameter, limited axial extension of the beams), and in the measuring procedure, i.e. the necessity for multiple adjustment of the beam plane during a measuring procedure. Although the causes are of a fundamental nature, a series of steps taken have lead to a considerable reduction in the measuring time.

One step was the optimization of the optic system. A reduction, e.g. of the beam diameter in the measuring volume first of all decreases the measuring rate. On the other hand, the light intensity in the measuring volume is consequently increased and thus the threshhold at which the smallest particles in the measuring volume may be detected is lowered. As the number of small particles in the usual particle distribution is very much greater than that of the big particles, a reduction in the beam diameter results in a higher measuring rate and thus a shortening of the measuring time. A reduction in the beam diameter was possible by optimizing the beam path and using special objectives. The measuring time was consequently reduced to about 1/2 or 1/3. Furthermore this also resulted in the spatial resolution of the L2F system being improved so that measurements up to a minimum distance of circa 0.2 mm normal to the wall are possible today.

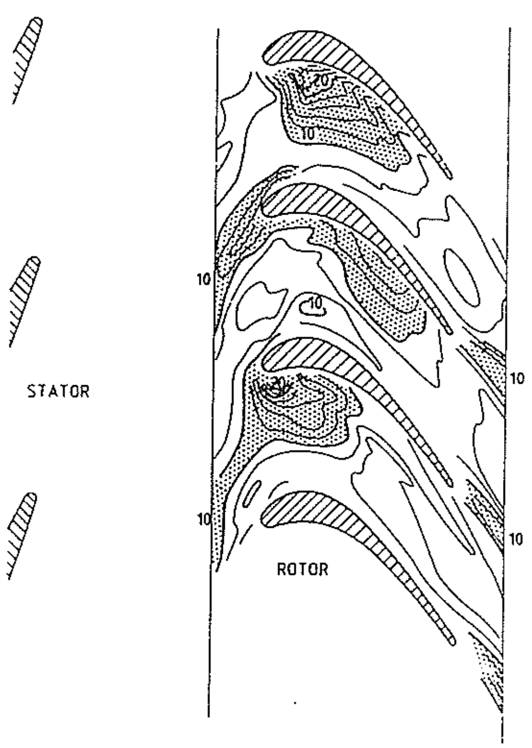

Figure 1: Distribution of the turbulence intensity in a turbine rotor measured with the L2F technique (stator wake regions dotted).

A new electronic concept with automized measuring procedure has proved to be particularly advantageous in application in the rotating turbomachinery components. By increasing the number of measuring channels it was possible to simultaneously measure 16 different segment positions instead of taking measured values from one single position as had been the case up to then. A further approach to a reduction in the measuring time resulted from the following idea: If in the evaluation of the measured data we limit ourselves to the magnitude and the direction of the mean flow velocity and the degree of turbulence - that is to say disregard the determination of the Reynold's shear stress and high order moments of fluctuation velocity - it can be shown that at almost constant measuring accuracy the number of individual measurements required per measuring position may be reduced considerably. The two measures together, namely reduced data uptake in connection with the new automated electronics resulted in a further reduction in the measuring time to 1/4 to 1/5 of the value obtained after the first step.

A further reduction in the measuring time of about the same order of magnitude was obtained in a development step recently carried out. In the L2F technique it is found that measuring time increases with increasing flow turbulence as a result of the increasing angle area, due to increasing turbulence , in which the flow vector fluctuates. Thus on the one hand the number of angle positions in which the beam plane has to be adjusted in a measuring procedure increases, on the other hand the frequency of successful individual measurements decreases. The reason for this is the specified angle range determined by beam diameter and beam separation and within which valid measuring values may be registered. Should the beam separation in the measuring volume be decreased then this increases the angle range at constant beam diameter. Consequently the measuring frequency is increased and additionally the number of necessary angle positions of the beam plane is decreased, i.e. the measuring time decreases. However the measuring error increases with the beam separation becoming smaller and smaller.

It can now be shown that when a maximum measuring error of e.g. 1% is assumed, the measuring time can be minimized when the separation of the beams is adjusted to the flow turbulence. Thus with a constant beam diameter of 10 μm, e.g. at 1% turbulence the best separation is 350 μm and at 10% turbulence 70 μm. In both cases measuring times are the same. If a measurement was carried out with a system with a beam separation of 350 μm in a flow with 10% turbulence then the measuring time would almost be fivefold. Thus the minimization of the measuring time requires the adjustment of the beam separation to the degree of flow turbulence.

A concept for an optical device incorporating continuous beam separation variations is hardly possible. A gradual variation in the beam separation could be achieved with exchangeable beam dividers (Rochon prisma), but this is coupled to expensive constructions. The solution found also enables stepwise beam separations and by using fiber optics results in a simply assembled, very stable optical head of small dimensions. The light of an Argon laser operating in multi-color mode is coupled in the optical fiber *LI* and conducted to the optical head (Figure 2). The diverging multi-color laser light emerging from the fiber is collected by lens *L*1, aligned in parallel, and arrives at a beam divider prism, in this case a dispersion prism. Here the various colors of the Argon laser experience different angular deflections, so that with the aid of lens *LS*1, five parallel, varicolored beams with differing separations - see detailed graph - are projected in the measuring volume. The multi-colored scattering light emitted by the particles traversing these beams is collected by the outer area of lens *LS*1 and sent through the same dispersion prism where the various colors are again deflected such that the light produced at various places in the measuring volume is projected in one single point with lens *LS*2 and thus may be coupled into the optical fiber *LII* which functions as a spatial aperture.

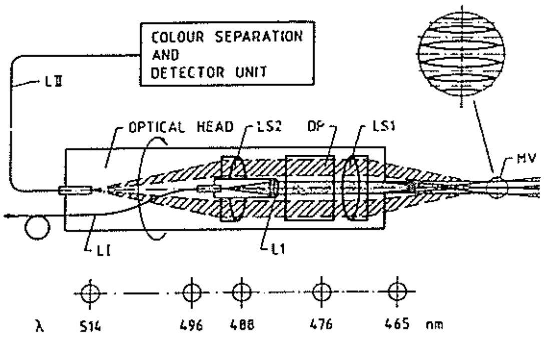

Figure 2: Beam path of the multicolor-L2F volocimeter with variable beam separation.

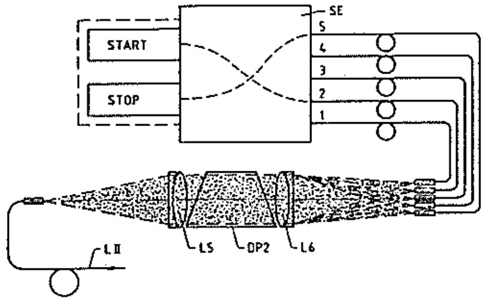

Figure 3: Color separator and detector.

This fiber conducts the scattering light to a color separation and detector unit (Figure 3). Here a dispersion prism separates the colors into the five colors which are then each conducted in an assigned fiber to a switching arrangement. This allows the freely selectable assignment of the various colors going to the photodetectors which provide the start or stop signals for the time-of-flight measurements.

In this way, by selection of a certain color combination the associated beams in the measuring volume are used for the measurement and consequently the associated beam separation is determined. The optical system is designed such that beam separations between 70 μm and 400 μm may be selected. A special achromatic design of the optic system is required to minimize the differences in the axial position of the varicolored focal points. The successful testing of the device confirmed the forecast reduction in the measuring time at high degrees of turbulence. As a result of all the measures described in this section the measuring time has been reduced on the whole to 1/50. Today, for a single measurement point e.g. in wind tunnel investigations, it requires a mere 15 seconds.

Three-Dimensional Technique

To determine three-dimensional velocity vectors with a laser measuring technique, a method is usually selected in which two two-dimensional systems observe the same measuring volume from different directions. The desired velocity vector is determined from a geometric transformation of the two measurement results . To obtain sufficient accuracy for all components of the velocity, the angle difference between the two systems must be at least 30°. This method requires relatively big measuring windows.

Yet access to the measurement location is limited in many cases, e.g. in turbomachinery, where the measurement location is usually only accessible via relatively small windows in the housing of the machinery. In these cases only those laser velocimeter which can operate with an extremely small solid angle, determined by the measuring window size, are applicable for the 3D velocity measurements.

Two methods on the basis of the L2F technique have been put forward to achieve this objective. In the first technique two L2F systems are placed together in one casing. As shown in the diagrammatic sketch in Figure 4, the two systems are each set at an angle of circa 6° to the optical axis of the receiving part. Both velocimeters operate at different wavelengths so as to enable the signal received from the measuring volume to be assigned to the appropriate device. $1g$ stands for the green start beam and $2g$ stands for the green stop beam. Corresponding terms apply to the system with the blue wavelength. At point A, beams $1g$ and $1b$ intersect, at point B, beams $2g$ and $2b$. Thus, as a result of the two systems, measuring planes located obliquely to each other are spread over the space. For flow vectors perpendicular to the optical axis the two systems each behave like a standard L2F device. However, when the velocity vector also has a component in the direction of the optical axis, then the two systems still measure the same velocity magnitude but different angles. Using the measured angle difference

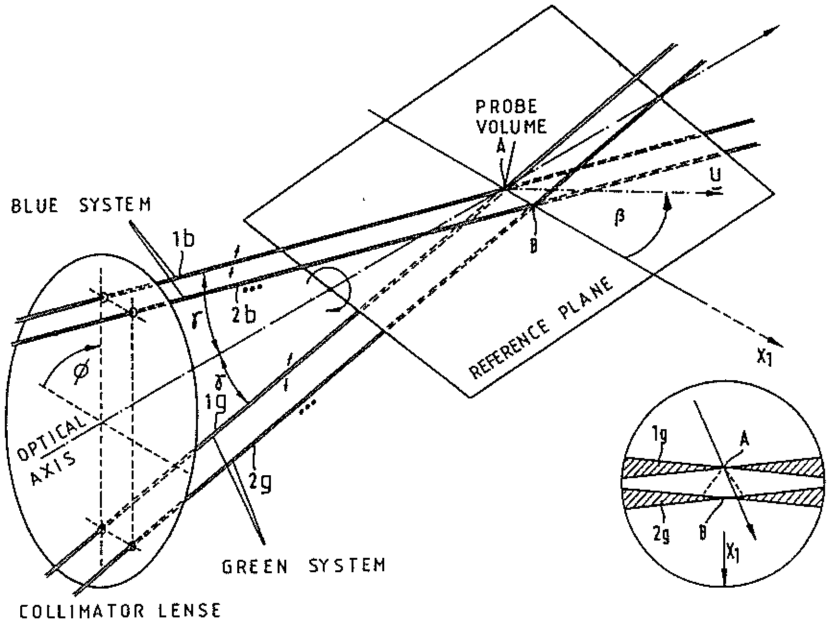

Figure 4: Basic principle of the 3D-L2F with inclined measuring planes.

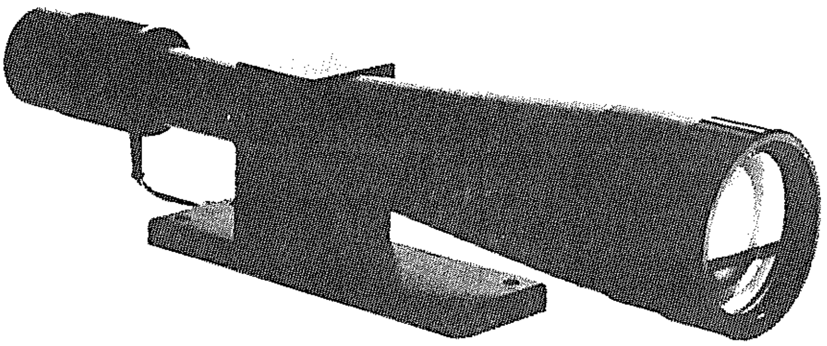

Figure 5: Optical head of the 3D-L2F with inclined measuring planes on a glass fiber base.

and the inclination of the beam axis to the optical axis, the actual 2D flow angle as well as the angle of the flow vector with respect to the optical axis can then be ascertained [4], resulting in complete determination of the velocity vector.

The practical implementation of this concept, which goes back to the beginning of the 80s, foundered first of all on the considerable light scattering in the image rotating prism, so that application of the device in turbomachinery was practically out of the question. But by using glass fibers it was possible to design an improved device. The disturbing influence of the image rotating prism was eliminated by an optical head which could be rotated as a whole (Figure 5).

Following first tests in simple nozzle flow, which confirmed the operational efficiency, the new device was recently tested under difficult conditions in a Propfan test rig. Figure 6 illustrates a distribution measured in this test rig of the flow angle in radial direction, which 2D devices so far have not been able to detect. The measured flow angles, reproducible within ±1.5°, are also compared to a theoretical calculation in the figure. These results record the first successful application of a 3D-laser velocimeter in turbomachinery.

When access to the measuring point is even more difficult, then the second 3D-L2F technique may be applied. Figure 7 shows a schematic longitudinal section of the measuring volume of two L2F systems which differ from a standard measuring volume in the axial displacement of the start- and stop focus. The focussing areas usable in measurements, resulting from the light intensity distribution and the apertures in the receiving beam path, are section lined in the figure. For an assumed flow vector $\vec{v}$ the resulting effectively usable lengths of the measuring volume L_A, L_B are indicated by dotted lines. In the case shown here, system A had a considerably higher rate of successful start - stop occurences than did system B. The normalized difference in the two observed data rates stands for not too great flow angles ($|\beta| < \gamma_{A,B}$) in near linear relation to the flow angle β. The slope of the resulting calibration curve must be determined in this technique because of the unknown absolute length of the focussing area and the particle size distribution which is not previously known. To produce the measuring volume with axial displacement a similar test set-up is used as in the L2F technique with variable separations (see above). By exchanging the front lens for a lens not corrected for the wavelengths of the laser light, the individual color beams are focussed at variable distances and thus a system is set up corresponding to for example System A.

By turning the optical head 180° and exchanging the start and stop beams System B is automatically obtained. The required difference in the data rates is determined from two consecutive measurements with both arrangements and then the flow angle relative to the beam axis can be calculated from the calibration carried out beforehand. In both arrangements the same flow angle perpendicular to the flow axis, the same velocity magnitude as well as the same fluctuation values are measured. To establish the accuracy of this technique a special test was carried out in which a sphere (d = 30mm) was placed in the potential core of a free jet (D = 150mm) at a distance of one nozzle diameter behind the outlet. The flow field in front of the sphere is practically free of boundary-layer influence and axially symmetric. Thus when positioning the L2F device with the optical axis perpendicular to the plane of symmetry of the sphere, a flow angle of 0° is to be anticipated in the beam direction, i.e. a flow vector exactly perpendicular to the beams. As a result of the axial symmetry of the flow field the flow angles measured in the plane perpendicular to the beam axis (standard 2D measurement case) must also appear in a plane of symmetry parallel to the optical

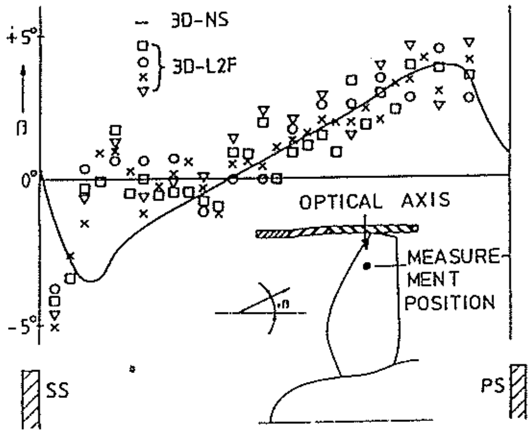

Figure 6: Measured distribution of the radial flow angle β in a Propfan test rotor and comparison with the theoretical calculation on NAVIER-STOKES basis.

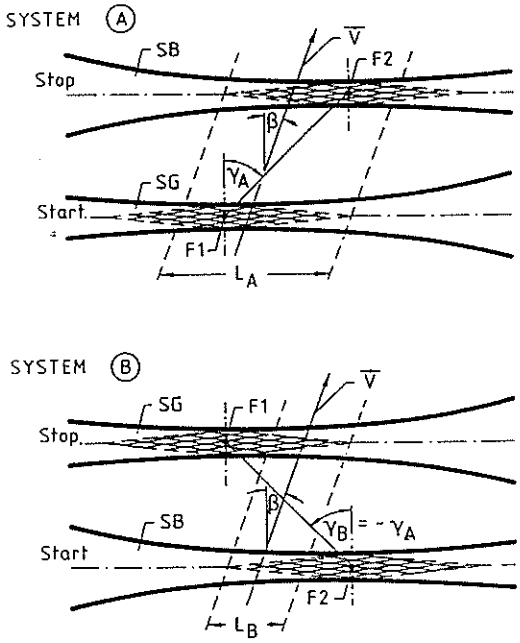

Figure 7: Axial arrangement of the measuring volume in the 3D-L2F with shifted focus areas.

axis, but are now flow angles in beam direction (3D case). Furthermore there is an exact solution of the incompressible potential flow theory for this case which can also be used for comparison. Results of the test are shown in Figure 8 together with the theoretical flow pattern. Lines *A* and *B* indicate the axial position of the measuring planes in front of the sphere. The measured flow angles in the 2D mode (+ - symbols) are consistent with the theoretical prognosis and can thus be used as reference for the 3D case. The measured flow angles in the 3D mode (o -symbol) also agree with the theory although there was a high degree of spread in the measured values. The absolute measuring accuracy for the flow angles relative to the optical axis was ±1° in this test. Applications in rotating turbomachinery components were also successful.

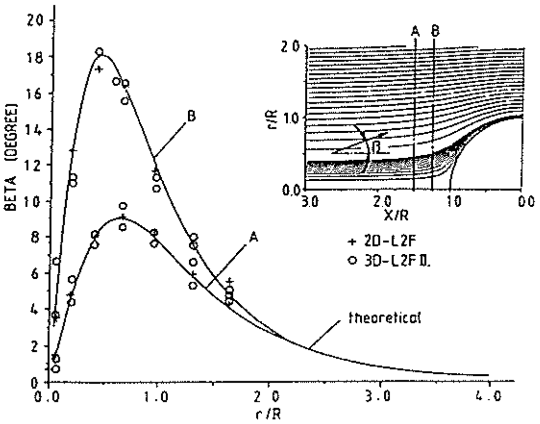

Figure 8: Measured flow angle in the axial symmetric flow field in front of a sphere.

Future Developments

The availability of the 3D techniques will lead to an increased demand for their application. This does not mean the 2D techniques will be completely neglected. 2D-velocimeters usually exhibit better signal-to-noise ratios as a result of their simple set-up and thus in borderline cases have an advantage. Furthermore they are easier to handle. In the further improvement of the Laser-2-Focus technique, besides the areas already mentioned the following key tasks are in the foreground:

1. **Mini-L2F-Probe for Application in Extremely Unfavourable Access to Measuring Point**

   This consists of an L2F measuring head extremely reduced in size with a diameter of 12 mm (Figure 9), corresponding to the dimensions of conventional probes. This can be positioned in the proximity of the measuring point with a standard probe traversing device. The front lens has a focal length of 60 mm, which ensures that the probe will not cause any disturbances in the flow at the actual measuring point.

2. **Projection of the L2F Measuring Beam in a Rotating System**

   For the analysis of the flow profile in a test rig for determination of the heat transfer in a cooling channel such as found in turbine blades the use of the standard arrangement of the laser measuring system in the stationary system was out of the question. In a beam path specially designed for this purpose, the measuring volume of the L2F system is projected in the rotating system with an image rotating prism, which revolves by means of tooth-belt drive at exactly half the speed of the test sample. A first test carried out with this method at revolutions up to 1000 min^{-1} has already been concluded producing successful velocity measurements.

3. **Theoretical Simulation Calculations for the L2F Technique**

   For verification of the evaluation process and analysis of the accuracy of the L2F technique simulation calculations are carried out. The computer program used is based on a numerical integration of the three-dimensional probability density function of a turbulent flow. Here the measuring volume dimensions and the particle size distribution must be regarded as accurately as possible. Thus, among others, the parameters which have an important influence and are essential for the optimization of the L2F technique should be found and further investigated as to whether further interesting flow values can be determined from the measured time-of-flight distribution.

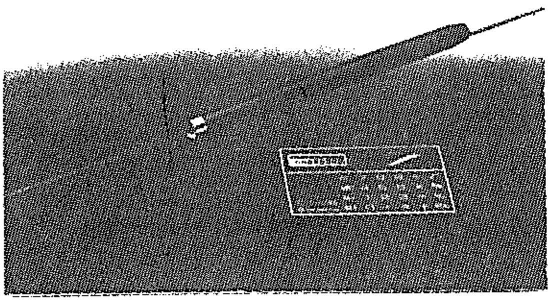

Figure 9: Mini-L2F probe.

4. **Application of the Laser Technique in Gases with very high Temperatures/Pressures**

   Urgent questions such as appropriate scattering particles and access to measuring place must be cleared up before the technique may be applied here. Calculations for the flow following behaviour of the particles in the desired gas pressures and temperatures lead to the conclusion that also in this application, measurement may only be carried out with very small particles ($< 0,5\mu$m).

References

[1] A. Binder, W. Förster, H. Kruse, und H. Rogge. An experimental investigation into the effects of wakes on the unsteady turbine rotor flow. *ASME paper No. 84-GT-178*, 1984.

[2] R. Schodl. A laser dual beam method for flow measurement in turbomachines. *ASME paper No. 74-GT-159*, 1974.

[3] R. Schodl. Laser-two-focus velocimetry. In *Advanced Instrumentation for Aero Engine Components*, Philadelphia, 1986. AGARD-CP-399, paper 7.

[4] R. Schodl und W. Förster. A Multi-Color Fiberoptic Laser-Two-Focus Velocimeter for 3-Dimensional Flow Analysis. In *Fourth Intl. Symp. on Appl. of Laser Anemometry to Fluid Mechanics*, Lisbon, 1988.

[5] D.H. Thompson. A tracer particle fluid velocity meter incorporating a laser. *J. Scientific Instruments (J. Phys. E), Series 2*, p.929–932, 1968.