Direct Laser-Doppler Measurement of Spatial Velocity Difference for Gradient and Vorticity Analysis

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Abstract

A measurement technique is proposed and its suitability is experimentally demonstrated for the direct measurement of local and instantaneous fluid-velocity differences at spatially separated locations. This relatively simple method is an LDA technique which makes use of the interfering scatter-light fields emitted from two spatially separated spots. The technique is a differential Doppler technique but it does not make use of the well-known stationary fringe-pattern of conventional multiple-beam LDA. Nevertheless the measurement accuracy is similar to that of conventional LDA.

Test measurements in the exit flows of a pipe and of a nozzle are presented. The results prove that velocity differences can be directly measured giving the velocity gradients. A comparison is made with mean gradient results calculated from a mean axial velocity profile. A two-component extension of the measurement technique is applied to the nozzle exit flow in order to demonstrate its suitability for vorticity measurements.

The related optical configurations seem to be simple but a number of physical demands have to be considered for a reliable measurement. All this is discussed in detail in the paper.

1. Introduction

Hot-wire and laser-Doppler measurement techniques allow locally and temporally highly resolved velocity information to be acquired from flow. The techniques also enable us to measure and to correlate the data from spatially different locations. This serves for the estimation of instantaneous small-scale velocity gradients and may lead, by example, to the measurement of local vorticity.

Different techniques have already been applied to solve this problem experimentally with the means of hot-wire anemometry (HDA) as well as with the means of laser-Doppler anemometry (LDA). Antonia et al. (1993), among many others, used two parallel hot wires and Rajagopalan et al. (1993) built up a probe consisting of four hot-wires. Each hot-wire produces an electrical signal and the technique requires individually related electronics or computers to correlate the individual signals. The sensor lengths and the mechanical stability of the hot-wires together with their relative separation limit the spatial resolution of such experimental analysis.

Laser-Doppler techniques have been applied by forming systems of two or more spatially separated optical probe volumes. Compared with the hot wires such arrangements offer increased spatial resolution as well as directional sensitivity related to the velocity components and insensitivity to the flow temperature. Examples are given, among others, by Cenedese (1991), by Pfeifer (1986) and by Nakatani et al. (1985). An overview of different experimental solutions of both techniques, HDA and LDA, is given by Wallace & Foss (1995).

The experimental solutions reported up to now, which relate to laser-Doppler techniques, commonly work by measuring the individual velocity information simultaneously at the different locations in the flow. The differences between the local information are calculated in succession. This implies that the errors of the two individual measurements cumulate to the resulting measurement error of the velocity difference. Technically, the amount of optical and electronic apparatus required increases with the number of related measurement locations.

In this paper the principle of a technique is described and demonstrated to measure directly instantaneous and spatial velocity differences. The suitability of the technique is proved by means of a two-channel extension for the instantaneous measurement of local vorticity in the air flow downstream of a nozzle exit.

The reported technique is not conventional because the measuring light beams do not intersect. Therefore the working principle cannot be explained by the help of the well-known stationary “fringe-pattern” of optical interference in a probe volume. Here we look for a region of the interfering scatter-light fields which offers optimum conditions to form interference signals with optimum modulation and signal-to-noise properties.

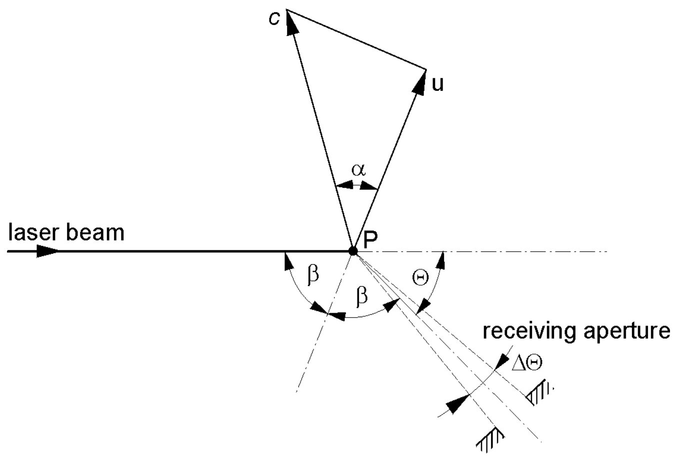

Fig. 1. The optical Doppler effect (Yeh & Cummings,1964)

2. The measurement principle

Referring to the arrangement presented by Yeh & Cummings (1964, Fig.1) the frequency of Doppler-shifted scatter light is

$$f_{sc} = f_o + (2c/\lambda_o) * \cos\alpha * \sin\theta/2 \quad . \qquad (1)$$

The original laser-light frequency is f_o and the wave-length is λ_o. In the common plane of the angles α and θ and together with the magnitude c of the velocity vector *c* the expression

$$u = c * \cos\alpha \qquad (2)$$

is the velocity component which bisects the angle 2β between the incident and the received laser light directions. It follows

$$f_{sc} = f_o + (2u/\lambda_o) * \sin\theta/2 \quad . \qquad (3)$$

The very high light frequency f_{sc} cannot be directly analyzed by electronic means. Therefore the scatter light is commonly made to interfere with a second light field which may be part of the original laser light or a second scatter-light field. The resulting power spectrum of the interference field contains the frequency difference Δf of both fields at the measurement frequency band of interest.

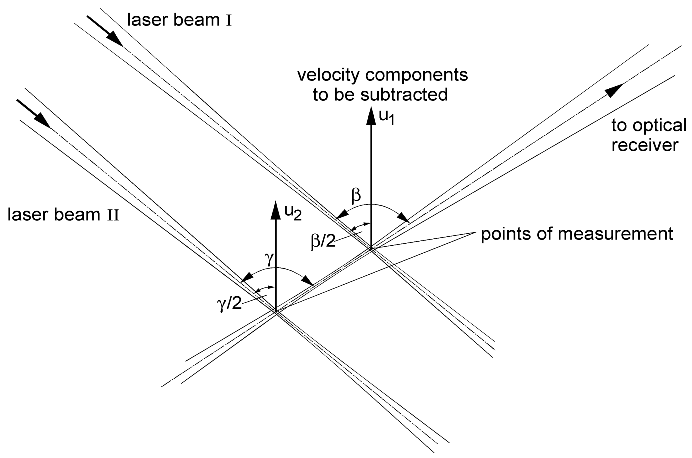

Fig. 2. Principle to measure directly the velocity difference Δu

The dual beam technique uses the interference of two Doppler-shifted scatter-light fields which are emitted by an individual scatter particle when it passes the common intersection area of two measuring light beams (Lehmann, 1968). Optimum optical mixing with maximum interference contrast occurs due to the optimum conditions of two concentric interfering wave fields providing a directionally independent difference in Doppler shift. The well-known fringe pattern model leads to the same result without considering the Doppler effect at all.

In the reported case also two different scatter-light fields are also brought to interference. These light fields are scattered by and emitted from two spatially separated scatter particles which are simultaneously hit by two different light beams. The resulting frequency difference represents the instantaneous difference of the velocities of both particles at their different localities. This relates to the velocity components which bisect the angles between the directions of the incident and of the received scatter light.

An optical receiver is focused on both locations where the particles appear. For an optimum SNR it should receive the scatter-light fields under optimum geometrical conditions. The related optical constellation is shown in Fig. 2. The two locations of the scatter particles are positioned on the intersection points of the two measuring light beams and the optical axis of the receiver. A Doppler-difference signal frequency develops only if the individual scatter particles are coincidentally present in each of the intersection volumes. If only one of both probe volumes is occupied by a particle, we obtain a scatter-light signal without any analyzable Doppler modulation.

If the light beams in Fig. 2 are parallel the measurement frequency is directly proportional with the indicated two velocity components which bisect the angle between incident and the received light. We are also sure that this difference is measured with the high accuracy as it is usual in conventional laser-Doppler anemometry.

3 Experimental verification

3.1 The model flow

In order to realize and to study the proposed method a flow was inspected exiting from a tube with the diameter D_t = 17 mm and with a length of L=30 D_t. The mean exit velocity of this seeded flow was about 10 m/s. Another tube with an inner Diameter of 25 mm concentrically enveloped the first one. Its very weak annular exit flow was also seeded and served to simulate the ambient fluid forming the entrainment of the jet.

Both partial flows were seeded with SiO_2 particles having a relatively constant diameter of 800 nm.

At x/D_t=1 downstream of the inner pipe's exit the profile of axial velocity was measured by means of an single-component LDA device. Then the direct measurement of the velocity difference profile was performed along the same traverse and using the same flow condition.

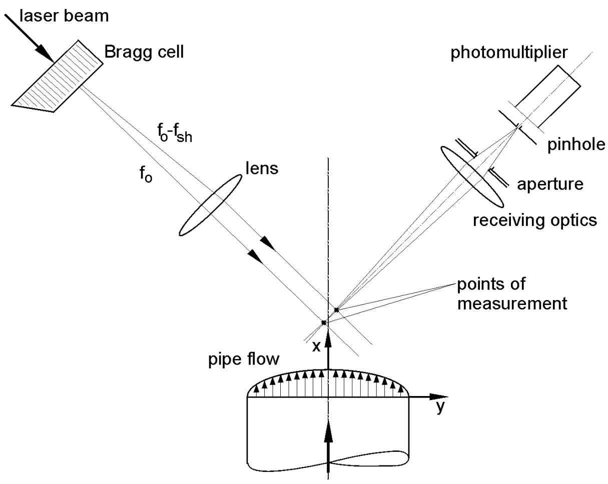

Fig. 3. Scheme of verification experiment

3.2 Optical arrangement

Fig. 3 shows the optical arrangement which served to realize the technique of velocity difference measurement. Argon-laser light was led through a light fiber and the emitted beam passed a Bragg cell which was excited with 40 MHz. The zero and the first diffraction order of light were adjusted for equal light power. An f=200 mm lens together with the exit optics of the light-fiber served to focus the light beams individually onto the area of measurement and to align them as parallel measurement beams. Their individual diameters were made small compared with the separation Δr=1 mm of both beams.

At the exit of the light fiber the power of the argon-laser light was 180 mW. It still contained the green and the blue wavelengths and the Bragg cell split it into measurement beams with a power of less than 80 mW each. For the measurement only the green wavelength (λ_o=514,5 nm) was needed and selected by means of a color filter in front of the photomultiplier at the optical receiver. Thus the effective power of the individual measuring beams was of the order of 50 mW each.

No problems arose due to the coherence lengths of the scattered light, which is the fundamental demand for optimum interference. The optical path-length difference of both measuring beams was nearly zero up to the probe volumes. Thus the scatter-light path's difference along the receiving direction attained the order of the measuring-beam separation Δr. This value was 1 mm and small enough compared with the coherence length of the laser light in order not to reduce considerably the interference contrast.

In fact, the demand of sufficient coherence length may restrict the applied beam separation Δr especially if the laser light is multimode. It is well known that a growing optical path difference increasingly reduces the visibility of the interference effects if multimode laser light is used with an increasing number of longitudinal modes. Further discussion will show that another condition can limit this value Δr to the order of Δr=10 mm. This results from the minimum admissible phase difference of the scatter-light wave fronts relative to the optical receiving aperture (see Fig. 6 and Fig. 7).

The exact separation of the light-beams was measured by help of two spots burnt into a piece of paper when exposed to the light at right angle to in the measuring region. The spots' distance could easily be measured using a microscope.

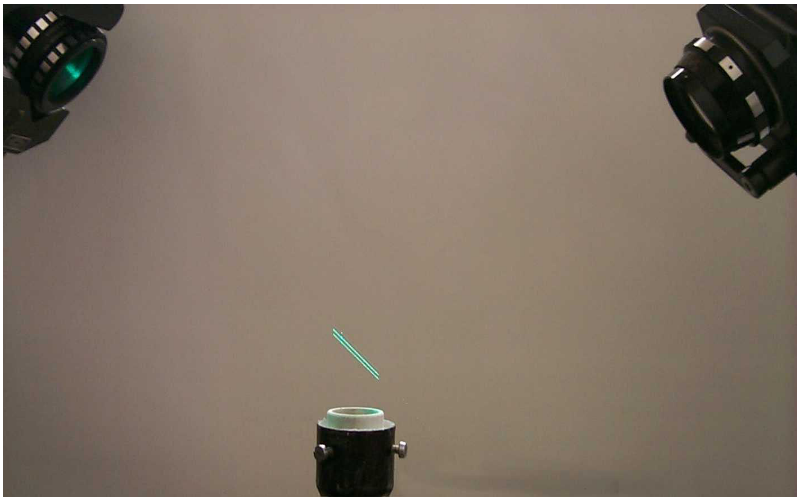

Fig. 4. View of experimental arrangement with dual laser-light beams

The photomultiplier was carefully positioned in the common plane of the measuring beams and directed at right angle to their focus areas. In this way the intersection volumes of the receiver's focus and the beams' focii formed the two measuring spots (Fig. 3). The axis of the pipe flow bisected the angle between the incident light and the received light which means that the axial velocity components were detected at both probe volumes.

A receiving optic was used with a focus length of 105 mm, and applied aperture diameter of the order of 8 mm. The measurement distance was about r_1= 200 mm. Behind the already mentioned green wave length optical filter the light passed through a 0.3 mm diameter pinhole positioned in front of the photomultiplier.

Fig. 4 is an image of the pipe exit with the measurement area together with the emitting and the receiving optics.

3.3 Frequency analysis

Frequency analysis was done by the use of one DANTEC burst spectrum analyzer. Because the beam splitting Bragg cell was supplied with the 40 MHz excitation frequency the frequency shift of the signal light was directly adapted to the BSA's technology without the need for frequency correction.

For the special optical arrangement of Fig. 3 the angle $\theta=90^o$ was chosen. Thus the trigonometric expression in (3) gives

$$\sin(\theta/2)= \sqrt{2}/2 \quad .$$

With the wave length of the green argon-laser light we obtain from (3) the frequency-velocity relation

$$\Delta f/u = (f_{sc} - f_o)/u = 2{,}749 \text{ MHz/(m/s)}.$$

This is a relatively high value in practical laser-Doppler anemometry. It indicates that the total available band width of signal processors is easily occupied by signals from flows with medium turbulence. If necessary, an adaptation can be obtained in practical cases by increasing the band width of the signal processor, by reducing the beam separation Δr or by receiving more forward-scattered light by using an angle $\theta < 90^o$.

Finally, the use of the frequency shift caused sensitivity to the sign of the measured velocity difference in the same way as in conventional LDA.

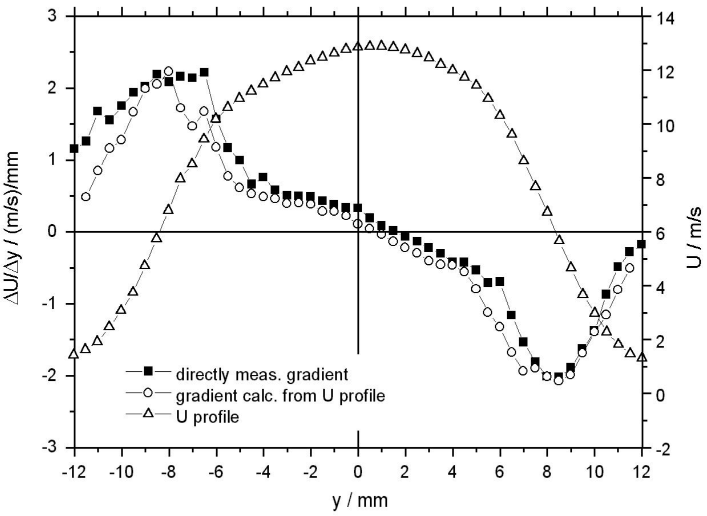

Fig. 5. Comparison of directly measured velocity-gradient profile

4 Results of measured velocity difference

Fig. 5 is the measurement result taken from the pipe exit flow at x/D=1. One profile shows the velocity gradient calculated from the directly measured velocity differences. The calculation is based on Δr=1 mm and considers the fact that the two probe volumes are aligned at 45 degrees in respect to the pipe axis.

The profile's shapes compare with those expected. Due to the small value of Δr=1mm of the probe volumes the mean velocity differences are relatively low and the related Doppler frequencies were well adapted to the frequency-band width of the BSA analyzer.

Fig. 5 also shows the separately LD-measured velocity profile. The maximum gradients of directly measured results compare fairly well with the regions of maximum slope of the mean velocity profile. A second gradient profile was calculated from the neighboring data of the mean velocity profile and their radial distances. Both gradient profiles, the directly measured and the calculated ones are similar in the order of magnitude. At the edges of the flow problems existed due to the incompletely seeded entrainment, this problem is responsible for the existing scatter of the directly measured data.

A fundamental source of deviation between the compared gradient profiles exists as a consequence of the slightly different traverses of both separated measuring volumes for the direct measurement. In this way the velocity difference along two densely neighbored but axially displaced velocity profiles was measured. The result, however, is compared with gradient results calculated from the mean velocity data along a single traverse.

In addition, because the measured velocity difference data were taken under 45 degrees related to the radial direction they had to be numerically projected on the radial traverse direction. This projection causes an additional source of deviation because it can only be a rough estimate in non-isotropic flow turbulence.

5 Discussion of experimental details

5.1 The receiving aperture

For the technique proposed the most simple optical arrangement is one which uses parallel measuring light beams. In that case maximum contrast across a sufficiently large area of the scatter-light fields' interference may be expected only along a straight line imbedded in the common plane of the laser beams. Both propagating spherical light waves enter the receiver optics with different curvatures of their wave fronts due to the relative separation Δr of the two measurement volumes.

Fig. 6 demonstrates how the different curvatures form a variable phase difference of the two wave fronts which does not change its sign inside the first spatial knot line of intersection with the diameter D. In the ideal case this phase difference is maximum and chosen to be Δh along the receiving direction. For maximum SNR Δh should be $\lambda/2$ maximum and D should be as large as possible for a high signal power. These conditions restrict the receiving aperture A to be A=D in maximum case.

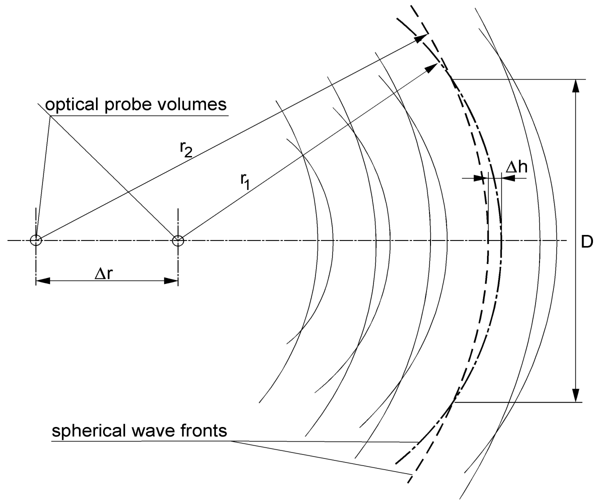

Fig. 6. Model for the estimation of optimum receiving aperture

In reality, Δh varies with time because the arriving and interfering light fields fluctuate in their frequencies and wave lengths due to the locally fluctuating velocities to be measured. For the order of technical velocity magnitudes, however, these fluctuations are small enough to be neglected and it is enough simply to take into consideration the wave length λ_o of original light for the estimation above.

Fig. 7 is the result of a simple geometrical calculation based on Fig. 6. Along the measuring distance r_1 between the probe volumes and the receiver optics the maximum permissible aperture diameter is D. The separation of the two scattering volumes is Δr and Δh is the maximum phase difference inside the first knot line of interference. If we assume $\Delta h=\lambda_o/2$, λ_o=514,5 nm, r_1=200 mm and Δr=1 mm, we find from Fig. 7 that D/r_1=0,046. The result is a maximum recommendable aperture diameter D=9,2 mm.

This is a rather small aperture compared with the optical receivers as usually applied in LDA. It needs a sufficiently high light power of the measuring beams in order to obtain an acceptable signal power which in addition is received preferably of a right angle scattering direction. On the other hand the small aperture reduces the disadvantageous frequency broadening effect which is introduced by the aperture diameter into the Doppler shifts due to the dependency on the receiving angle θ (see equ. (1)).

From Fig. 6 it is obvious that the receiving aperture's axis has to be well aligned related to the positions of the measuring volumes. A shift of the aperture off-axis by only D/2 would already destroy the signal contrast because the aperture then covers an increasing number of knot lines of the interference field. Thus the adjustment of the receiver's position must be performed more carefully at larger values of r_1 and Δr.

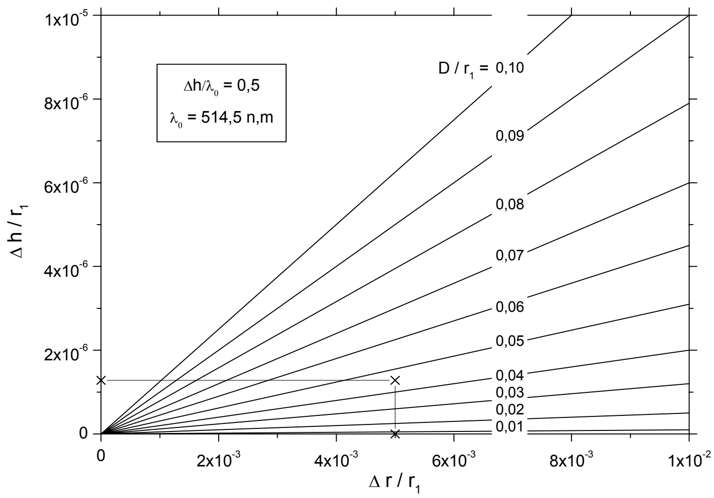

Fig. 7. Parameter field of optical arrangement

5.2 Seeding concentration and signal power

Due to the necessary coincidence of the two scatter-light fields a high effective rate of measurement events demands a sufficiently high seeding concentration. In the ideal case this means an almost continuous presence of at least one scatter particle in both probe volumes. This condition is independent of the number of probe volumes because it also holds for two or more probe volumes if it is realized for one.

In addition, however, both contributing particles together with the receiving optics must be instantaneously aligned on a common axis within narrow geometrical limits which are narrower than given by the dimensions of the probe volumes. This follows from the model of optimum interference given by Fig. 6. Therefore the smallness of the individual particle relative to the probe volumes reduces the statistical probability of an optimum constellation of the particles and the receiving optics. A simplified estimation results in an increase of seeding concentration by the order of 10^2 or even 10^3 compared with the ideal case of conventional LDA.

A further problem could arise from the interference of scatter light emitted by two or more particles being instantaneously present in only one of both probe volumes. In that case only rarely achievable ideal linear particle-particle-sensor alignment would be able to produce a sufficiently clear beat-signal modulation. A condition like this seems to have a much lower probability of occurrence than in the case of particles in two probe volumes. This can be concluded from the measurements made far outside the jet axis where zero-velocity events were not contained in the pdfs of the velocity-differences. Such zero or near-zero events should be expected because the velocity differences of multiple particles in only one probe volume should be zero or at least very small.

In Fig. 7 for constant D/r_1 an obvious linear dependency exists between the parameters $\Delta h/r_1$ and $\Delta r/r_1$. This leads to the conclusion that, if once all parameters of the measuring optics are well adapted and the original laser-light power is constant, a variation of the distance r_1 does not change signal power and signal quality. In other words: a loss of signal intensity due to an increase of r_1 can be compensated with the same relative increase of D because the received light power depends on the squares of both parameters. This fact makes the measurement technique suitable also for large-scale wind tunnel flows.

The general need for a high seeding density might reduce the penetration of measuring light beams into the flow and could restrict the measurement in large cross-section applications. In that case a reduction of the particles' diameters together with an increase of the light power of the measuring beams might help to overcome the problem.

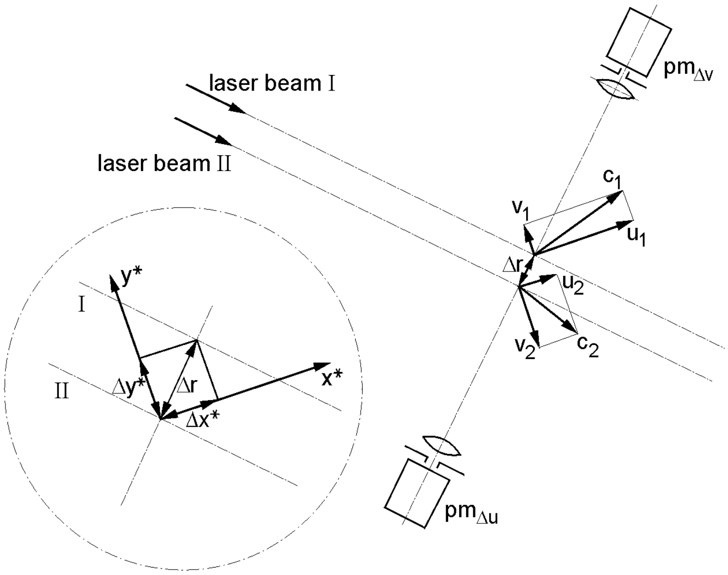

Fig. 8. Dual component scheme for the measurement of vorticity

6 The technique to measure vorticity

6.1 Dual component arrangement

The measurement of spatial velocity differences is the basis of the measurement of the instantaneous vorticity ω, which is expressed in the plane case by

$$\omega = \Delta u/\Delta y - \Delta v/\Delta x \,. \qquad (4)$$

For its measurement we need the instantaneous differences of two velocity components at two spatially separated measurement locations. Together with the knowledge of the spatial coordinate differences the vorticity can be calculated.

A dual-component extension of the proposed measurement technique offers this possibility. If, as shown in Fig. 8, two optical receivers are directed from opposite directions on the same probe volumes, we receive the optical difference signals of two rectangular velocity components. If, in addition, both acquired measuring signals are coincident they meet the conditions to estimate vorticity.

In Fig. 9 the coordinate intervals Δx^* and Δy^* form a rhombus the diagonal of which is given by the separation Δr of the measurement locations. For the discussed case of parallel light beams and perpendicularly scattered signal light the measurement refers to a rectangular coordinate system which is coupled with the directions of the incident and of the received laser-light directions.

If the common axis of the optical receivers is not rectangular in respect to the incident light the optical sensors receive different scatter-light power due to their positions in the more backscatter and in the more forward-scatter directions.

6.2 The experiment

Fig. 9 is a photographic picture of an optical arrangement the scheme of which is described by Fig. 8. Measuring light beams come from the upper left after having passed the Bragg cell. The resolution of the picture does not suffice for a recognition of the individual beams. Again the nozzle-flow axis bisects the angle between the direction of the incident measuring light beams and the one of scatter-light reception. The second photomultiplier opposes the first one. In this way the differences are measured of the axial and of the radial velocity components.

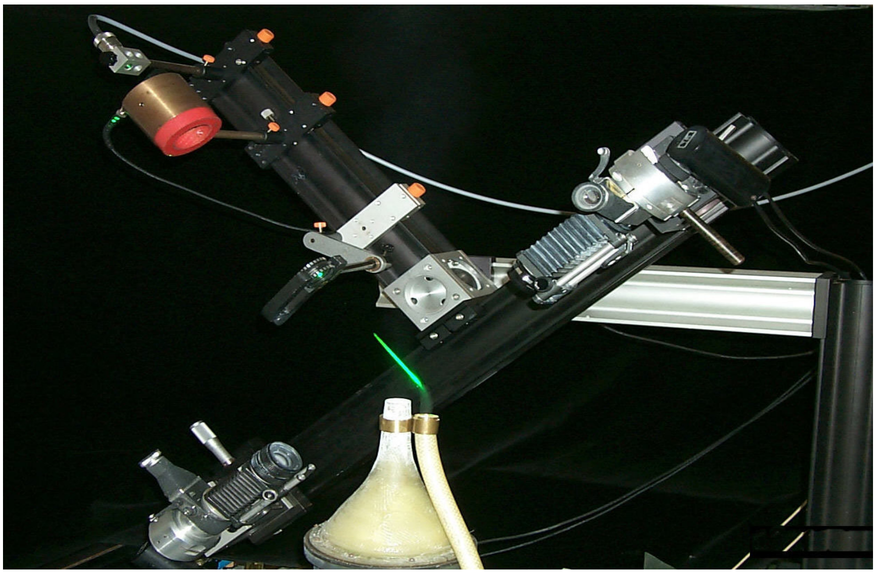

Fig. 9 : Dual-component arrangement for the measurement of vorticity

The flow issues from the nozzle with a diameter of D_n=25 mm and with a mean velocity of about 15 m/s. It is seeded again with the 800 nm SiO_2 particles. Fig. 9 shows also a second tube aside from the nozzle which discharges a very slow seeded partial flow in order to provide a seeded entrainment. For the measurements reported here the focused probe volumes were relatively traversed by moving the nozzle along a diameter at x/D_n=2.

The photomultiplier signals were acquired simultaneously and analyzed by means of two DANTEC BSAs. Later the tabulated coincident data of velocity differences served to calculate the vorticity data.

6.3 Vorticity results

In Fig. 10 the measured velocity-difference profiles of both measuring channels are plotted. We observe a nearly antisymmetrical profile which represents the differences of the axial velocity components. The second profile is attached to the radial velocity components and it is symmetrical. The fact that it shows a negative sign is simply a result of sign definition.

Both profiles do not cross the coordinate origin but show finite and almost equal values on the jet’s axis. This follows from the dual-point difference, which remains finite also on the axis of the flow if the probe volumes’ alignment deviates from the radial direction. The increasing scatter of measurement results at the jets' edges shows again existing difficulties to produce a sufficiently homogeneous seeding in those regions.

The calculated vorticity results are given in Fig. 11. We observe an antisymmetrical slope of the vorticity profile as is to be expected. It crosses now the coordinate zero point and tends to descend towards zero at the jet's edges. The sign of vorticity results from the sign conventions for the coordinates and for the velocity components.

A very rough estimation of the expected vorticity can be made as follows: If we suppose a vortex extending along half the jet's diameter D_n=25 mm and traveling with half the mean flow velocity of U=15 m/s we can estimate $(U/2)/(D_n/2)$=0,6 (m/s)/mm which is the order of maximum vorticity obtained from the measurements.

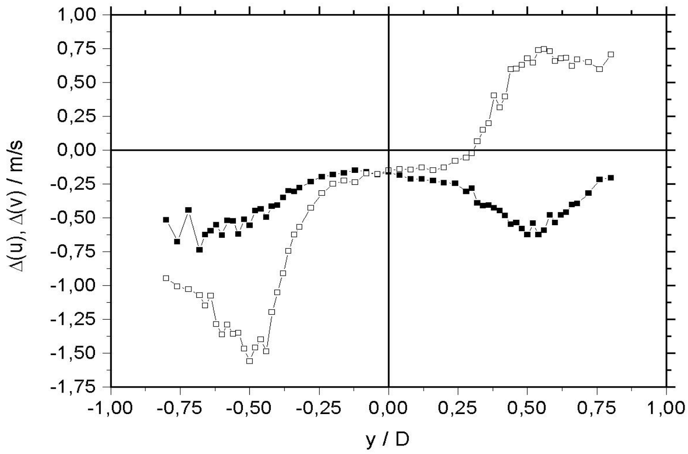

Fig. 11 : Velocity differences measured with dual-component technique

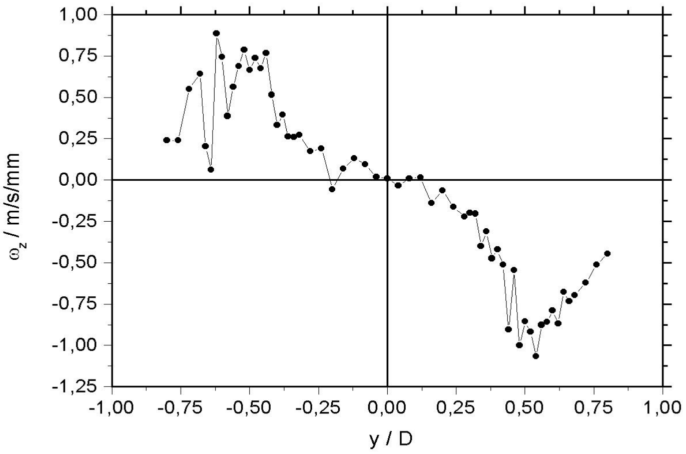

Fig.12: Plot of vorticity, calculated from measured velocity differences

It should be mentioned that the vorticity profile must be insensitive to rotations of the measurement apparatus relative to the flow direction. This, however, does not hold for the velocity-difference profiles.

7 Conclusions

The proposed laser-Doppler measurement technique offers a simple possibility to directly measure instantaneous velocity differences from spatially separated flow volumes. The method is a relative measurement technique because it forms a measurement signal from the beat frequency of two interfering scatter-light fields. Therefore it is as accurate as conventional multiple-beam LDA and needs no calibration.

A minimum of simple and conventional optical and electronic equipment is needed from the field of LDA in order to perform a verification experiment of the proposed technique. Some fundamental conditions are to be considered for a successful measurement. The properties enable the technique to be applied in small as well as in large-scale experimental geometries.

The disadvantage of the need of an increased seeding density might be compensated in larger flow's cross-sections by means of smaller scatter particles together with an increased laser-light power. Due to the simple emission optics some hundred milliwatts up to the order of a watt or more may be applied for the measuring beams.

The optical arrangement applied for the reported measurements used complanar measuring light beam and scatter-light receiving directions. Apart from this most simple experimental situation a large variety of modified optical schemes may be constructed. The condition of linearly aligned probe volumes on the axis of the receiving optics may be fulfilled also by means of mutually inclined measuring beams which implies the measurement of the difference of not complanar velocity components.

The experiment to measure the vorticity in a jet demonstrates the capability to perform such kind of experimental analysis successfully. An extension of the described arrangement by means of a third measuring beam and additional optical receivers and LDA analyzers might be useful for a multiple-component measurement even of the instantaneous vorticity vector.

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