

Three Component Flow Imaging by a 2D3C Laser Doppler Field Sensor

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ABSTRACT

We report about a novel laser Doppler field sensor, which is capable of measuring the three-component (3C) velocity field in fluid flows in a two-dimensional area (2D) without mechanical scanning and without using a camera. The sensor is based on laser Doppler velocimetry but employs four superposed fan-like interference fringe systems. A spatial resolution in the sub-micrometer range can be achieved enabling highly spatially resolved flow studies. Possible applications are investigations in micro-fluidics or precision flux measurements.

KEYWORDS: laser Doppler velocimetry, laser Doppler velocity profile sensor, flow imaging, micro-fluidics, flux measurement

1. INTRODUCTION

For non-invasive investigations of flow fields numerous optical measurement techniques are available. Camera-based techniques like Particle Image Velocimetry (PIV), which is a well established method, and recently Doppler Global Velocimetry (DGV) are able to capture the velocity distribution inside a two-dimensional laser light sheet.

On the other hand, laser Doppler velocimetry (LDV) [1] is a well established method for point-wise measurements and offers a significantly higher accuracy of the velocity than the imaging methods. LDV utilizes an interference pattern of nearly parallel fringes generated in the volume of intersection of two crossing coherent laser beams. Tracer particles carried by the flow scatter light which is amplitude modulated with the Doppler frequency f . The velocity is derived from $v = f d$, where d is the spacing of the interference fringes.

Especially in the field of micro-fluidics, where flows through channels of only a few 100 microns linear dimension are of interest, special effort is needed when imaging techniques like PIV are to be applied. At μ -PIV the flow is observed through a microscope objective [2]. Consequently only short working distances can be achieved and the depth resolution is influenced by the depth of focus and

the size of the tracer particles, so that it is not well determined.

In this paper we report, for the first time, about the combination of flow imaging as well as high precision of the velocity measurement without the use of a camera.

We present an extended laser Doppler sensor which is capable to measure the distribution of the three component velocity vector inside a two-dimensional area for a single tracer particle passing the measurement volume, i.e. that an image of the velocity distribution inside a two-dimensional area. It is based on two orthogonally aligned velocity line sensors each of which can measure the lateral velocity component, the axial velocity component and an axial position with respect to its optical axis.

2. THE LASER DOPPLER VELOCITY LINE SENSOR

The laser-Doppler velocity line sensor [3-6] works by superposing two fan-like interference fringe systems which have to be physically distinguishable (e.g. by carrier frequency multiplexing or wavelength multiplexing), one with convergent, the other with divergent fringes, see fig. (1).

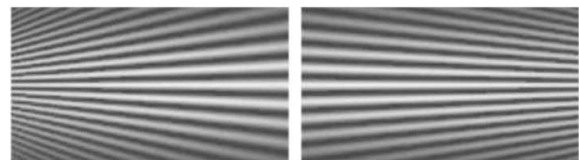
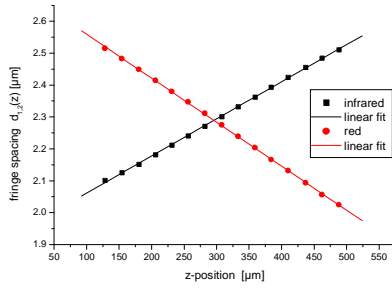
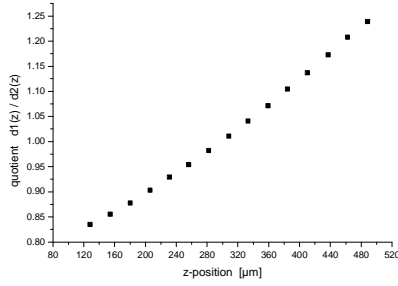


Fig. (1): Superposed fan-like interference fringe systems of the laser-Doppler line sensor

In order to generate the convergent and divergent fringes, the beam waists of the Gaussian laser beam have to be placed behind and before the crossing point of the LDA partial beams [7]. These non-homogeneous fringe systems are a consequence of the wavefront-curvature of the Gaussian laser beams.



a)



b)

Fig. (2): a) Increasing and decreasing fringe spacings $d_{1,2}(z)$ of the two superposed interference fringe systems as a function of the axial position. b) Quotient of the fringe spacings $q(z)=d_1(z)/d_2(z)$.

Fig. (2)a) shows the fringe spacing $d_{1,2}(z)$ as a function of the position along the optical axis z and fig. (2)b) the calculated calibration function, i.e. the quotient $q(z)=d_1(z)/d_2(z)$.

If a scattering particle, that is carried with the flow, passes the measurement volume perpendicularly to the optical axis it generates two burst signals, one from each fringe system. Doppler frequencies $f_{1,2}$ are now obtained from both of the fringe systems. If the quotient of the Doppler frequencies is considered,

$$q(z) = \frac{f_2(v_x, z)}{f_1(v_x, z)} = \frac{v_x / d_2(z)}{v_x / d_1(z)} = \frac{d_1(z)}{d_2(z)}$$

it becomes obvious that it is independent of the velocity v_x and depends only on the position z along the optical axis. The quotient of the Doppler frequencies can therefore be used to determine the axial position z . Fig. (2)b) shows the monotonic quotient function, calculated from the fringe spacing curves of fig. (2)a). The velocity of the tracer particle can be calculated by the Doppler frequencies and the local fringe spacing values at the known position z :

$$v_x(z) = f_1(v_x, z) d_1(z) = f_2(v_x, z) d_2(z)$$

In contrast to conventional LDV the axial position of the tracer particle inside the measurement volume can now be determined. Therefore the laser Doppler line sensor offers a significantly higher resolution than conventional LDV's [3,4].

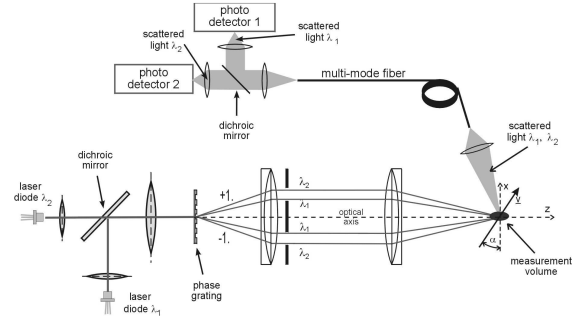


Fig. (3): Experimental setup of the laser Doppler line sensor.

Fig. (3) shows the experimental realization of the sensor principle. The beams of two laser diodes of different wavelengths (red: 660 nm and infrared: 785 nm) were collimated by aspheric lenses, collinearly superposed by a dichroic mirror and focused onto a diffraction grating. The ± 1 st diffraction orders were used as the LDA-partial beams, other diffraction orders were blocked by beam stops. A Keplerian telescope collimated the partial beams and made them intersect again. The four beams (two partial beams for each wavelength) intersected at one position so that two superposed interference fringe systems were generated. In order to obtain fan-like fringe systems (infrared: divergent fringes, red: convergent fringes) the beam waists of the Gaussian beams have to be placed before or behind the common crossing point, respectively. This was achieved by adjusting the laser diode collimating lenses individually. The scattered light from the tracer particles was coupled by a single lens into a multimode fiber and guided to a detection unit. Here the light was split by a dichroic mirror into the different wavelengths and each wavelength was detected by a single avalanche photo detector. The photo detector signals were acquired by a standard PC with a 12-Bit analogue/digital converter card. A LabVIEW program was used to process the data. For adjustment, characterisation and test of the sensor a thin wire acted as a scattering particle. It was fixed on an optical chopper, which rotated with stabilised angular speed, providing a velocity reference.

Test measurements revealed a spatial resolution in the submicrometer-range and an uncertainty of the velocity $<5 \cdot 10^{-4}$ [3].

Unlike at conventional LDV the mechanical scanning of the pointwise measurement volume can now be omitted and velocity profiles can be measured as a whole. The size of the measurement volume of the LDA line sensor can be adapted to the region of interest of the flow and velocity profiles can be measured without mechanical traversing of the sensor head.

The sensor was successfully applied to highly spatially resolved measurements of laminar [3] and turbulent [5] boundary layer flows.

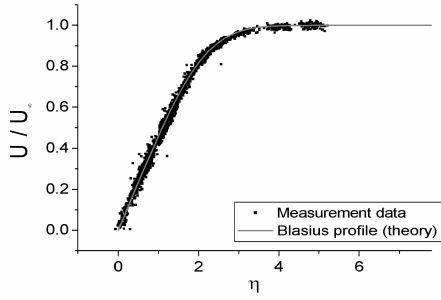


Fig. (4): Measured linear velocity profile of a laminar flat-plate boundary layer flow (normalized coordinates).

Fig. (4) shows the velocity profile of a laminar boundary flow around a flat plate (Blasius profile) measured with the laser Doppler line sensor. Each data point in the plot represents one single tracer particle, whose position and velocity were determined. Since the tracer particles are distributed statistically over the flow, the entire velocity profile can be recovered by evaluating a sufficient number of tracer particles. The measured profile agrees perfectly with the Blasius function (solid curve).

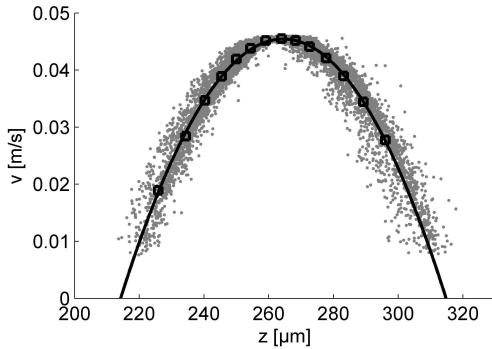


Fig. (5): Measured velocity profile inside a micro-channel of 100 μm width (solid line: fitted parabolic curve).

Another possible application field of the profile sensor is micro-fluidics. Fig. (5) shows the measured velocity profile along the short axis of a rectangular micro-channel of 100 μm x 2000 μm cross-section. Distilled water seeded with polystyrene particles of 2 μm diameter was used as a working fluid. The channel flow was driven by hydrostatic pressure. The solid curve shows a parabolic fit at the measurement data. The theoretical expected parabolic profile is in an excellent agreement with the measurement data. The channel width estimated from the fit at the velocity profile is 101.5 μm and agrees also well with the true channel dimension. From the scattering of the measured data the spatial resolution was estimated to ±3.5 μm.

This experiment clearly demonstrates the suitability for flow measurement with micrometer spatial resolution.

3. DETERMINATION OF THE AXIAL VELOCITY COMPONENT BY CHIRP DETECTION

The sensor principle can be extended to measure also the axial velocity component v_z . For the generalized case of inclined trajectories, i.e. for a significant axial velocity component the Doppler frequency of the burst signal will not be constant but will vary with time [6] since the fringe spacing varies with the axial position.

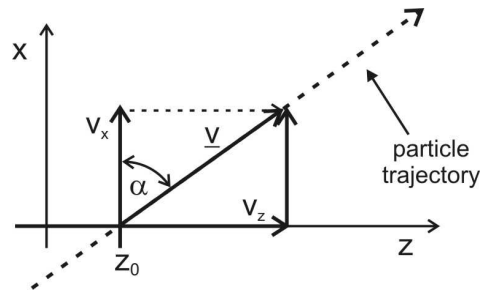


Fig. (6): Coordinate system and parameters of the tracer particle movement in the case of tilted trajectories.

Fig. (6) shows the coordinate system and the parameters of the tracer particle movement for the more generalized case that the velocity vector owns a finite axial component. The x - and z -velocity component are then linked to the angle α between the particle trajectory and the optical axis by:

$$v_x = v \cos \alpha \quad , \quad v_z = v \sin \alpha \quad , \quad \tan \alpha = \frac{v_z}{v_x}$$

The fringe spacing functions $d_{1,2}(z)$ are assumed to vary linearly with the axial position z , which is fulfilled in a very good approximation, see fig. (2)a):

$$\begin{aligned} d_1(z) &= d_{01} + c_1 \cdot z \\ d_2(z) &= d_{02} + c_2 \cdot z \end{aligned}$$

The particle trajectory can then be written by means of the time-dependent x -coordinate $x(t) = v_x \cdot t$ and z -coordinate $z(t) = v_z \cdot t + z_0$, where z_0 denotes the z -position for the time $t=0$, which in the following will be referred to as the “offset-position”. This will be the axial position at which the particle passed the optical axis. If these expressions and the fringe spacing functions $d_{1,2}(z)$ are substituted into the general expression for the Doppler frequency $f = v_x/d$ then the time dependent Doppler-frequency is obtained:

$$f_{1,2}(v_x, v_z, z_0, t) = \frac{v_x}{d_{1,2}(z(t))} = \frac{v_x}{d_{01,2} + c_{1,2}v_z t + c_{1,2}z_0}$$

Obviously, with non-vanishing axial velocity component v_z the frequency in the burst signal is no longer constant but varies with time (chirp-signal). Since the signs of the $c_{1,2}$ coefficients are opposite, the burst signal of one fringe system will exhibit an “up-chirp”, and the burst signal from the other fringe system a “down-chirp”. The frequency functions are, however, hyperbolically varying. In contrast, the period time – time functions $T_{1,2}(t) = f_{1,2}(t)^{-1}$ will exhibit a linear relationship.

If the equation is differentiated with respect to the time all constant addends vanish and a time-independent constant results as the derivative:

$$\frac{dT_{1,2}(t)}{dt} = c_{1,2} \frac{v_z}{v_x}$$

Obviously, the chirp can be used to directly measure the axial velocity component. From the preceding derivation it is evident that the method has the following properties:

- There is a direct, linear relationship between the change of the periodic time and the v_z -component.
- The amount of the chirp depends also on the v_x -component which means that the v_z -component can only be measured relative to the v_x -component. More precisely, the chirp is a measure for the ratio of or angle between both velocity components.
- The axial velocity component is directional discriminating. Usually, the lateral velocity component v_x has an ambiguity with respect to the direction, since only a positive frequency can be measured, so that a directional discrimination is not possible. To achieve a directional discrimination, additional frequency-shift-elements like AOMs can be included, which introduce a carrier frequency onto the Doppler signal. In contrast, the chirp $dT_{1,2}(t)/dt$ can be both positive and negative, so that the determination of the axial component v_z is a priori sensitive to the direction of the particle movement. No additional frequency shift elements or other extensions of the set-up are needed.
- From one single tracer particle the following variables of its trajectory can be determined:
 - the lateral velocity component v_x
 - the axial velocity component v_z including its sign (direction)
 - the position z_0 of the passage through the optical axis (“offset-position”)

For the determination of the axial velocity component no modification of the sensor setup is necessary, just the signal processing has to be extended by a chirp detection algorithm. It is based on a

Short-Time Fast-Fourier-Transform (ST-FFT, or sliding FFT). At first, the envelopes of the burst signals are calculated by means of a Hilbert transform. The point of time with maximum amplitude is detected, indicating the time when the particle passed the optical axis, where the maximum intensity occurs. Then the signals were truncated to their $1/e^2$ -borders and normalized. The ST-FFT was used to calculate the Doppler-frequency-time functions, which, after calculating their reciprocals, yielded the period time – time functions. The period time-time functions were fitted by linear regressions. From the regression parameters the frequencies at the time t_{Max} , where the maximum amplitudes occur, are calculated. These frequencies represent the momentary frequencies for that point of time, at which the particle passed the optical axis and are therefore used for the determination of the offset-position z_0 and the transverse velocity component v_x . From the slope of the linear regression curves and the v_x -component the axial velocity component v_z are derived. Fig. (7)a shows as an example the chirped burst signal pair of a particle, which passed under an angle of $\alpha=30^\circ$ through the measurement volume.

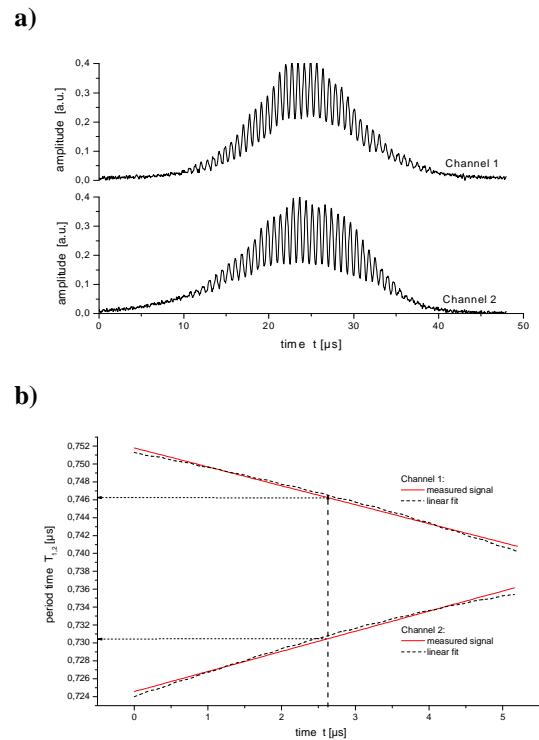


Fig. (7): a) Chirped burst signal pair from a particle passing with $\alpha=30^\circ$ to the optical axis. b) Period time – time functions for both channels, obtained from the short-time FFT. The momentary values at the marked point of time are used to calculate the offset position z_0 and the lateral velocity component v_x , whereas the slope of the functions yields the axial v_z -component.

Fig. (7)b) shows the resulting period time – time functions [6] including their linear regression curves (solid curves). The dashed line indicates the

point of time, at which the particle passed through the optical axis. From the momentary frequencies at this point of time the lateral velocity component v_x and the offset position z_0 are calculated, whereas the axial velocity component is derived from the slope of the linear regression curves.

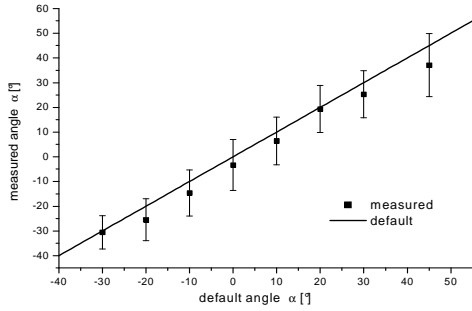


Fig. (8): Flow angle with respect to the optical axis measured at an atomizer nozzle.

Experiments with a wire used as a calibration object demonstrated that an uncertainty of 3% for the axial velocity component, an uncertainty of the flow angle α of 0.7° (angle between the axial and lateral velocity component) and a spatial resolution of the offset position z_0 in the micrometer range can be achieved [6].

Fig. (8) shows a flow measurement with an atomizer nozzle, whose flow direction was aligned at different angles α with respect to the optical axis of the sensor. The measured angle agrees well with the installed angle (default). The large uncertainty of the angular measurement (error bars) is caused by the high turbulence of the atomizer nozzle. The measurement proves, that the angle can be measured both positive and negative, since the chirp detection is directional discriminating with respect to the axial velocity component.

With the laser Doppler line sensor with implemented chirp-detection it is therefore possible to determine

- the lateral velocity component
- the axial velocity component
- the axial position inside the measurement volume

of one single tracer particle.

4. COMBINATION OF 2 LINE SENSORS WITH CHIRP-DETECTION TO THE 2D3C LASER-DOPPLER-FIELD SENSOR

The laser Doppler velocity line sensor in its form described above measures the (1D) velocity profile along one line. In order to achieve velocity measurements not only in a line but in a two-dimensional area two line sensors can be combined orthogonally such that their measurement volumes

overlap. Each of the line sensors can measure one component of the two-component position vector inside the plane which is spanned by the line sensors. Tab. (1) gives an overview of the quantities which can be measured when the two line sensors are oriented along the x- and y-direction.

	line sensor 1	line sensor 2
direction of optical axis	y	x
lateral component	v_z	v_z
axial component	v_y	v_x
position coordinate	y	x

Tab. (1): Combination of two line sensors to a 2D3C field sensor

The axial velocity component of each line sensor is obtained by means of chirp detection.

Obviously it is possible to determine all three velocity components and the two-dimensional position inside the volume of intersection, i.e. the size:

$$\vec{v}(x, y) = \begin{pmatrix} v_x(x, y) \\ v_y(x, y) \\ v_z(x, y) \end{pmatrix}$$

can be determined for a single tracer particle. By evaluating a sufficient number of tracer particles the entire three-component (3C) velocity distribution can be reconstructed in the two-dimensional (2D) plane of observation without mechanical traversing, see fig. (9). Even though no camera is needed, an image of the velocity distribution of the flow field can be measured.

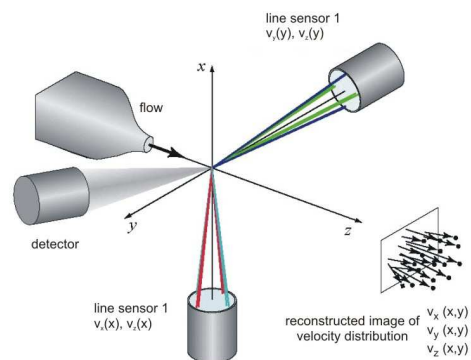


Fig. (9): Concept of the 2D3C-laser Doppler field sensor

The four interference fringe systems have to be physically distinguishable which can be achieved by wavelength division multiplexing (WDM) [4], carrier frequency division multiplexing (FDM) [5] or combinations of it. The number of single photo detectors needed depends of the realization of multiplexing and can range from one (if pure FDM is

used) to four (if pure WDM is used). In all cases just one detection unit is necessary consisting of a single lens to couple the light into one multimode-fiber, see fig. (3).

This sensor concept, presented here for the first time, offers several advantages compared to PIV:

- Since the sensor principle is based on LDA, only a single detector is needed. An image of the velocity distribution of a flow field can be gained without using a camera.
- Since the sensor is based on the difference Doppler technique, the signals will not depend on the observation vector. Consequently, the detector can be located arbitrarily around the measurement volume. In particular, detection can be realized in backward scattering arrangement, so that the detection unit can be integrated collinear in the sending optics and no additional optical access is required.
- At μ -PIV the longitudinal resolution is limited by the depth of focus, which is usually several micrometers. The lateral resolution usually does not subside 1 μm , even when sub-pixel interpolation is used. In contrast, the laser Doppler field sensor offers a higher spatial resolution down to the sub-micrometer range.
- μ -PIV offers only very short working distances (spacing between the sensor and the measurement volume) of a few millimetres due to the short focal length of the employed microscope objectives. In contrast, the working distance of the laser Doppler field sensor can be several centimetres [4].

5. SUMMARY

We presented for the first time an extended laser Doppler velocimetry (LDV) sensor which is capable to measure the distribution of the three component velocity vector inside a two-dimensional area, i.e. the quantity

$$\vec{v}(x, y) = \begin{pmatrix} v_x(x, y) \\ v_y(x, y) \\ v_z(x, y) \end{pmatrix}$$

for a single tracer particle passing the measurement volume. It is based on two orthogonally aligned line sensors each of which can measure the lateral velocity component, the axial velocity component and an axial position with respect to its optical axis. The measurement volume of one line sensor consists of two superposed fan-like interference fringe systems which have to be physically distinguishable. An uncertainty of $<5 \cdot 10^{-4}$ can be achieved for the lateral velocity component, 3% for the axial velocity component (corresponding to an uncertainty of the flow angle of $<3^\circ$) and a spatial resolution of $<1 \mu\text{m}$ could be achieved. The line sensor was successfully

applied for measuring laminar and turbulent boundary layer flow and also for measuring the velocity profile inside a 100 μm wide micro-channel with micrometer spatial resolution.

The 2D3C laser Doppler field sensor will be able to measure an image of the velocity distribution inside a two-dimensional area without using a camera. Because of its high spatial resolution it is superior to standard laser Doppler anemometry and even to μ -PIV.

Possible applications range from micro-fluidics (investigation of micro-fluidic devices like micro-mixers, etc.) over fundamental turbulence research (investigations of small eddies down to the Kolmogorov scale) to precise flux measurements.

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