2D3C-Laser Doppler sensor for highly spatially resolved flow field investigations

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We report about a novel flow field sensor based on laser Doppler velocimetry, which is capable of measuring the three-component (3C) velocity field in fluid flows in a two-dimensional area (2D) without mechanical traversing and without using a camera.
For non-invasive investigations of flow fields numerous usually imaging techniques like Particle Image Velocimetry (PIV) and recently Doppler Global Velocimetry (DGV) are employed, which are able to capture the velocity distribution inside a two-dimensional area by means of cameras. 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. Consequently only short working distances can be achieved and the depth resolution is influenced by the depth of focus, whereas the lateral resolution is limited by the diffraction and the pixel resolution of the camera. For PIV the uncertainty of the velocity is in the range of a few percent.
On the other hand, laser Doppler velocimetry (LDV) is an established and frequently applied measurement technique with much higher precision (typ. 1% … 0.1%) for pointwise velocity measurements.

In this paper we report about an extended LDV capable of measuring the three component velocity vector inside a two-dimensional area (field measurement) like at stereo-μ-PIV but with using only a single detector instead of a camera. 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.
The laser-Doppler velocity line sensor consists of two superposed fan-like interference fringe systems which have to be physically distuinguishable (e.g. by carrier frequency multiplexing or wavelength multiplexing), one with convergent, the other with divergent fringes. Consequently, the fringe spacings of both fringe systems are now a function of the axial position z: $d_{1,2}=d_{1,2}(z)$, where one curve is monotonically increasing, the other monotonically decreasing. Thus the Doppler frequencies $f_{1,2}$ obtained from both fringe systems depend on the axial position as well. The quotient of the Doppler frequencies is independent of the velocity and can be used for the determination of the axial position.
In contrast to conventional LDV this configuration allows to determine the lateral velocity component and the axial position of a tracer particle simultaneously and a high spatial resolution down to the sub-micrometer-range can be achieved.
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 since the fringe spacing varies with the axial position. It can be show that variation of the Doppler frequency with time (chirp) is directly proportional to the axial velocity component and can therefore be used for its determination.
With the laser Doppler line sensor with implemented chirp-detection it is therefore possible to determine

- the lateral velocity component
- the axial velocity component including its sign
- the axial position inside the measurement volume

of one single tracer particle.
An uncertainty of $<5\cdot10^{-4}$ can be achieved for the lateral velocity component, 3% for the axial velocity component (corresponding to an uncertainty of the flow angle of <3°) and a spatial resolution of <1 μm could be achieved.

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. This configuration is capable of measuring all three velocity components (3C) and the two-dimensional (2D) position inside the volume of intersection. Obviously a 2D3C image of the flow field measurement can be reconstructed by evaluating a sufficient number of tracer particles with a single detector without the use of a camera and without mechanical traversing.
Because of its high spatial resolution in the sub-micrometer range, its low uncertainty of the velocity and its larger working distance it turns out to an interesting alternative 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. The paper describes the details of the sensor setup, data processing and calibration and shows applications in micro-channels.