Simplified DGV on-line profile sensor

by

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ABSTRACT

We present a real-time profile sensor capable of measuring the flow velocity at eight measuring points simultaneously. In contrast to standard Doppler Global Velocimeter applications the sensor described here uses only one detector unit, namely a single avalanche photo diode array, and requires no reference detector.

The simplified profile sensor uses a frequency modulation of the laser source for the stabilization of the laser frequency as well as for the measurement of the Doppler shift by evaluating the resulting amplitude modulation of the scattered light having been transmitted through the absorption cell. If the laser frequency is stabilized for example at the centre of the absorption line, a Doppler shift ν_D will directly change the amplitudes $A(1f_M)$ and $A(2f_M)$ of the 1st and 2nd harmonics of the amplitude modulated scattered light signal behind the absorption cell. Thus the quotients $(A(1f_M)/A(2f_M))_i$ evaluated simultaneously for all i pixels of the avalanche photo diode array deliver a complete velocity profile which can be measured in only 10 ms, a time corresponding to about ten periods of the modulation frequency f_M.

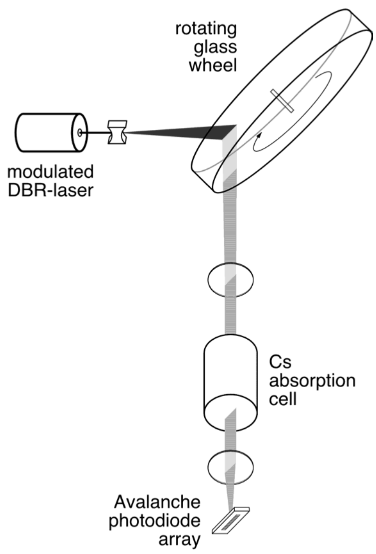

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Figure 1: *Set-up of the simplified DGV profile sensor and* $A(1f_M)/A(2f_M)$ *representing the velocity profile over a section of a rotating glass wheel, representing a linear velocity variation of 17 m/s..*

INTRODUCTION

Recently quite interesting velocity profile sensors for the investigation of boundary layers have been presented (Strunck et al., 1998; Czarske, 2001). These sensors achieve a high local resolution of about 10 µm within a measuring range of a few millimeters. Based upon difference or reference laser Doppler techniques such profile sensors measure velocity profiles by the evaluation of a sequence of LDA burst signals resulting from single tracer particles. As the tracer particles embedded in the flow pass statistically through the laser beams it takes some time to measure a complete velocity profile. Caused by the measuring principle to get velocities with a high local resolution for each tracer particle the obtained velocity profiles represent flow velocity values at different locations but unfortunately taken at different times.

In this paper we present a new sensor, which allows to enlarge the profile measurement range and to measure a complete velocity profile within a few milliseconds. Because this sensor measures the velocity at different points across a profile in parallel rather than sequentially, time-resolved measurements of the evolution of velocity profiles become possible. Furthermore the expense of the realized profile sensor is reduced drastically compared to conventionally used DGV-systems.

PRINCIPLE

In contrast to laser Doppler velocimeter systems based upon the Doppler difference or reference technique, laser Doppler velocimeters based on the Doppler global technique use a frequency stabilized laser and an absorption cell to analyse the Doppler shift of the laser light scattered by tracer particles. Using the slope of a calibrated absorption line filter for the frequency to intensity conversion, the intensity of the scattered light imaged through the absorption cell onto a detector gives the measuring information. In conventional systems, the influence of intensity fluctuations of the scattered light is eliminated by employing a signal and an additional reference detector (see figure 2).

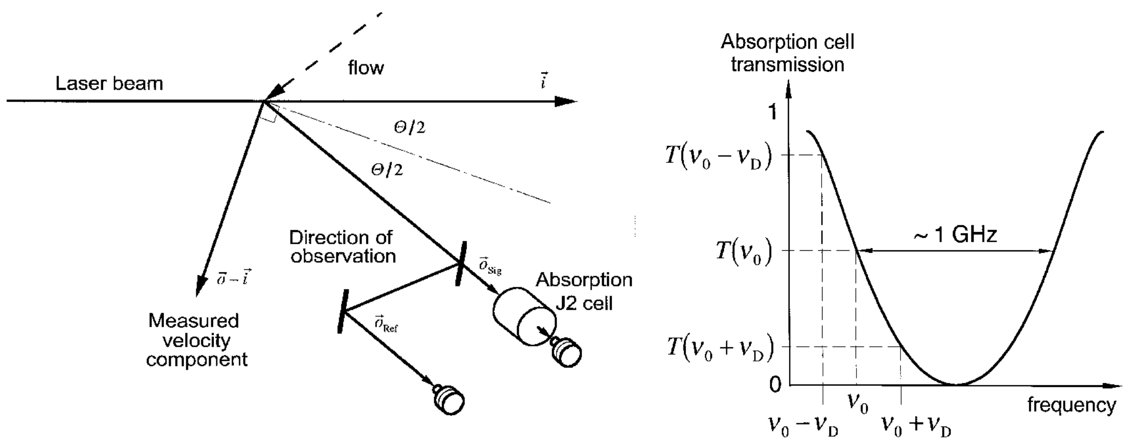

Figure 2: Principle of Doppler Global Velocimetry

The component of velocity which can be measured is given by the geometry of the set-up and depends on the angle between the incident direction of the laser light sheet and the observation direction:

$$\nu_D = \nu_0 \frac{\left(\vec{o} - \vec{i}\right)}{c} \vec{v}$$

The new simplified profile sensor described here uses only one detector unit, namely a single avalanche photo diode array, and requires no reference detector. The concept has firstly been presented in 1999 (Müller et al..) and is based on a laser frequency modulation for both, the frequency stabilization of the laser and the analysis of the scattered light frequency transmitted through the absorption cell. The principle can easily be described by the function of the absorption cell working as a frequency to intensity converter for frequency modulated laser light (see figure 3).

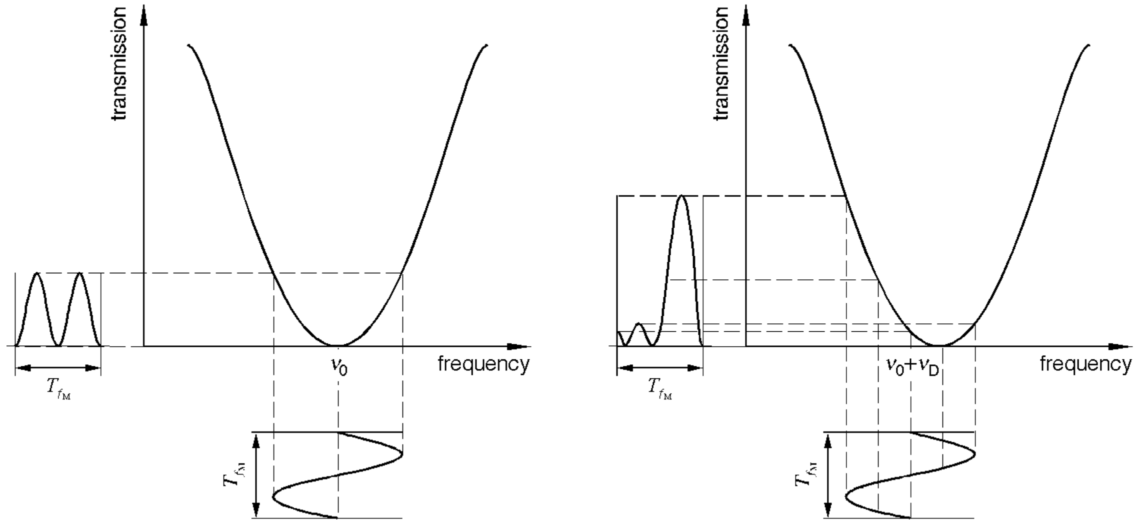

Figure 3: Amplitudes of the 1st and 2nd harmonic of the laser light transmitted through the absorption cell for different center frequencies of the laser

Considering a frequency modulation of the laser light with a constant modulation amplitude, the resulting amplitude modulation behind the absorption cell will depend on the centre frequency of the laser light. Figure 4 shows the resulting amplitude modulation amplitudes $A(1f_M)$ and $A(2f_M)$ of the 1st and 2nd harmonics of the laser light transmitted through the absorption cell when varying the centre frequency of the laser light within the absorption line.

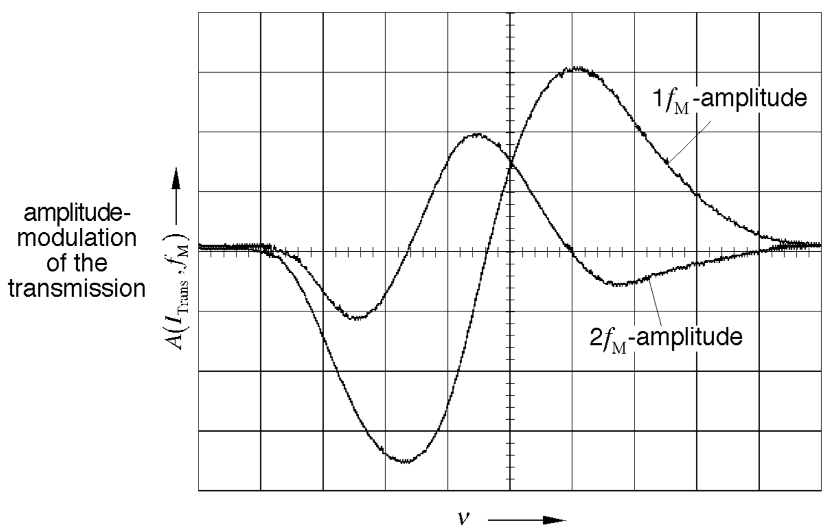

Figure4: Modulation amplitudes $A(1f_M)$ and $A(2f_M)$ of the 1st and 2nd harmonics of the laser light transmitted through the absorption cell when varying the centre frequency of the laser light

The dependence of the 1st harmonic amplitude $A(1f_M)$ on the centre frequency ν of the laser is used to stabilize the laser frequency and the quotient $(A(1f_M)/A(2f_M))$ to determine the Doppler shift for the velocity measurement.

EXPERIMENTAL SET-UP

The simplified DGV profile sensor has been realized by applying a DBR laser diode working at a wavelength of 852 nm, a Cs absorption cell and an Avalanche photo detector linear array with 24 pixels. In a first step three pixels of the APD array respectively were put parallel to get 8 measuring points for the velocity profile. To verify a velocity profile measurement a section of a radial line on a rotating glass wheel was illuminated by a light sheet (see figure 5).

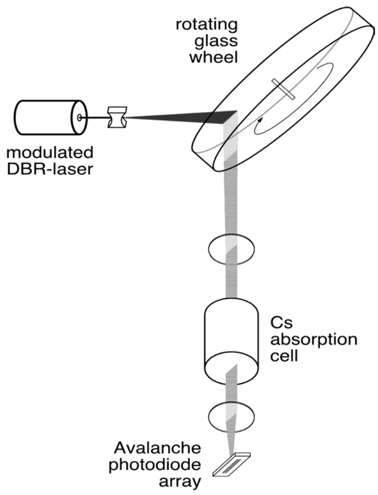

Figure 5. Experimental set-up of the simplified DGV profile sensor.

FREQUENCY STABILIZATION OF THE LASER

The laser frequency has been stabilised by evaluating the $1f_M$ signal of the amplitude modulation, which becomes zero and changes its sign in the centre of the absorption line (see figure 3 and 4). To generate a control signal, the $1f_M$ signal of the amplitude modulation has been detected by a lock-in technique. For this the photo detector signal behind the absorption cell was given to the input and the in-phase $1f_M$ signal used for the generation of the frequency modulation to the reference input of the lock-in amplifier. The lock-in amplifier output signal was then given to the laser current control unit (see figure 6).

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Figure 6: Block diagram of the absolute stabilization of the semiconductor laser.

SIGNAL EVALUATION

The centre frequency of the scattered light will vary depending on the Doppler shift given by the velocity to be measured. Thus the amplitudes of the 1st and 2nd harmonic of the amplitude modulated scattered light signal behind the absorption cell will also change as shown in figure 4. By evaluating the quotient of the amplitudes of the harmonics in the photo detector signal, intensity fluctuations in the scattered light can be eliminated, so that the conventionally used additional reference detector unit – with all its inherent problems, such as offset-drifts –

can be saved. The function of the quotient ($A(1f_M)/A(2f_M)$) depending on the centre frequency of the laser light is well defined for the applied absorption cell and can be used as calibration curve for the velocity measurement in a given DGV geometry (see figure 10). The amplitudes $A(1f_M)$ and $A(2f_M)$ can be detected by a lock-in amplifier and easily be evaluated if only one measuring point in the profile is considered corresponding to one pixel of the Avalanche photo detector array. To measure a complete velocity profile simultaneously a multi channel lock-in amplifier would have to be used and the expenditure of the experimental signal processing equipment would be high. Therefore a 16 channel transient recorder card has been used for a parallel signal processing of the APD array output signals. The measurement of the 1^{st} and 2^{nd} harmonic amplitudes of the scattered light and the evaluation of the quotients $A(1f_M)$ and $A(2f_M)$ for each pixel has then been carried out by a Lab View program implemented on the PC used for the signal processing. Figure 7 shows the block diagram of the signal processing unit for measuring a velocity profile by taking 40.000 samples per second and 400 samples for each channel.

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Figure 7: Block diagram for evaluating a velocity profiles simultaneously

EXPERIMENTAL RESULTS

To verify profile measurements a known velocity gradient in the radial direction on the surface of a rotating wheel was observed. (see figure 8). The wheel had a radius of r = 6 cm and it could be tuned up to 150 revolutions per second. Thus velocities up to 55 m/s could be realized. The optical lay out of the profile sensor allowed to image the scattered light from a section of 2 cm onto the Avalanche photo detector.

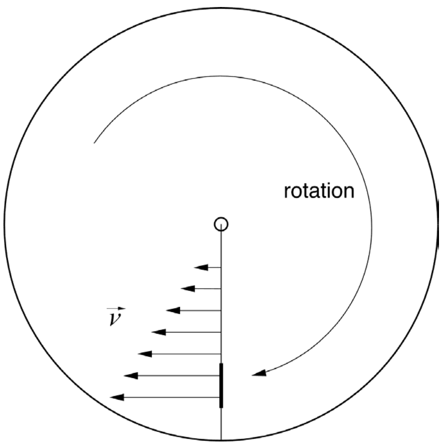

Figure 8: Rotating wheel with a well defined velocity profile; the marked section of the radial profile was illuminated by the laser light sheet and imaged through the absorption cell onto the Avalanche photo detector array where each pixel corresponds to one position in figure 9..

The evaluation of the 1^{st} and 2^{nd} harmonic of the detected signal of each avalanche detector pixel (position 1 to position 8) is shown in figure 9. The values of the quotient $A(1f)/A(2f)$ represented for each detector pixel in figure 9 correspond to a velocity value. The velocity of the wheel varies approximately 20 m/s over the observed length scale of 2 cm between position 1 and position 8.

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Figure 9: Quotient $A(1f_M)/A(2f_M)$ of the harmonics in the avalanche detector signal of each pixel 1, ..., 8 of the array corresponding to the radial position (distance from the axis) of the rotating wheel.

The relationship between the quotient $A(1f_M)/A(2f_M)$ and the Doppler shift is given by the calibration curve (see figure 10). It was easily obtained for the applied absorption cell in dependence of the modulation parameters and a well defined sweep of the centre frequency of the laser. Knowing the Doppler shift the velocity to be measured is for the geometrical arrangement shown in figure 5 directly given by $\nu_D \lambda = v$. With $\lambda = 852$ nm one gets:

$$\nu_D \text{ [MHz]} = 1{,}17\ v \text{ [m/s]}.$$

For the measurement of the radial velocity profile the values for quotients $A(1f_M)/A(2f_M)$ vary between 1,05 and 1,45. As the relationship between the measuring position and the quotient $A(1f_M)/A(2f_M)$ of the corresponding APD pixels shows a linear behaviour, the calibration curve defining the relationship between $A(1f_M)/A(2f_M)$ and frequency shift is also assumed to be linear in the measured velocity range (see figure 10).

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Figure 10: Calibration curve showing the quotient $A(1f_M)/A(2f_M)$ as a function of the frequency shift.

The variation of the measured quotients (see figure 9) corresponds to a variation of the Doppler shift of 21 MHz (see figure 10). Considering the relation above for the geometry of the experimental set-up shown in figure 5:

$$0{,}85\ \nu_D \text{ [MHz]} = v \text{ [m/s]}$$

one gets in the measured velocity profile a velocity variation of 18 m/s in a good agreement with the velocity variation of 17 m/s determined be the number of revolutions per second for the rotating wheel and the radial distance of the measuring points.

CONCLUSIONS

A new profile sensor has been presented. The measurement information is given by the output signals of at least eight pixels of an Avalanche photo diode array, which can be simultaneously frequency analysed. The verification of the sensor concept has been demonstrated by the measurement of the velocity profile on a rotating wheel.

The main features of the presented profile sensor are:

- the simultaneous multipoint measurement capabilities for time resolved profile measurements
- the simplified set-up by saving the conventionally used reference detector unit
- the use of modulation techniques for the laser stabilisation, sensor calibration and signal evaluation

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