Time resolved DGV based on laser frequency modulation

by

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ABSTRACT

We present a simplified Doppler Global velocimeter system, which allows to measure velocity fields or profiles with a resolution of better than 0,3 m/s and a temporal resolution of 0,5 s (velocity field image rate of 2 s^{-1}). Based on frequency modulation techniques the performance compared to conventional DGV-systems can be improved as no reference camera as additional error source is required and new calibration capabilities of the system can be realized.

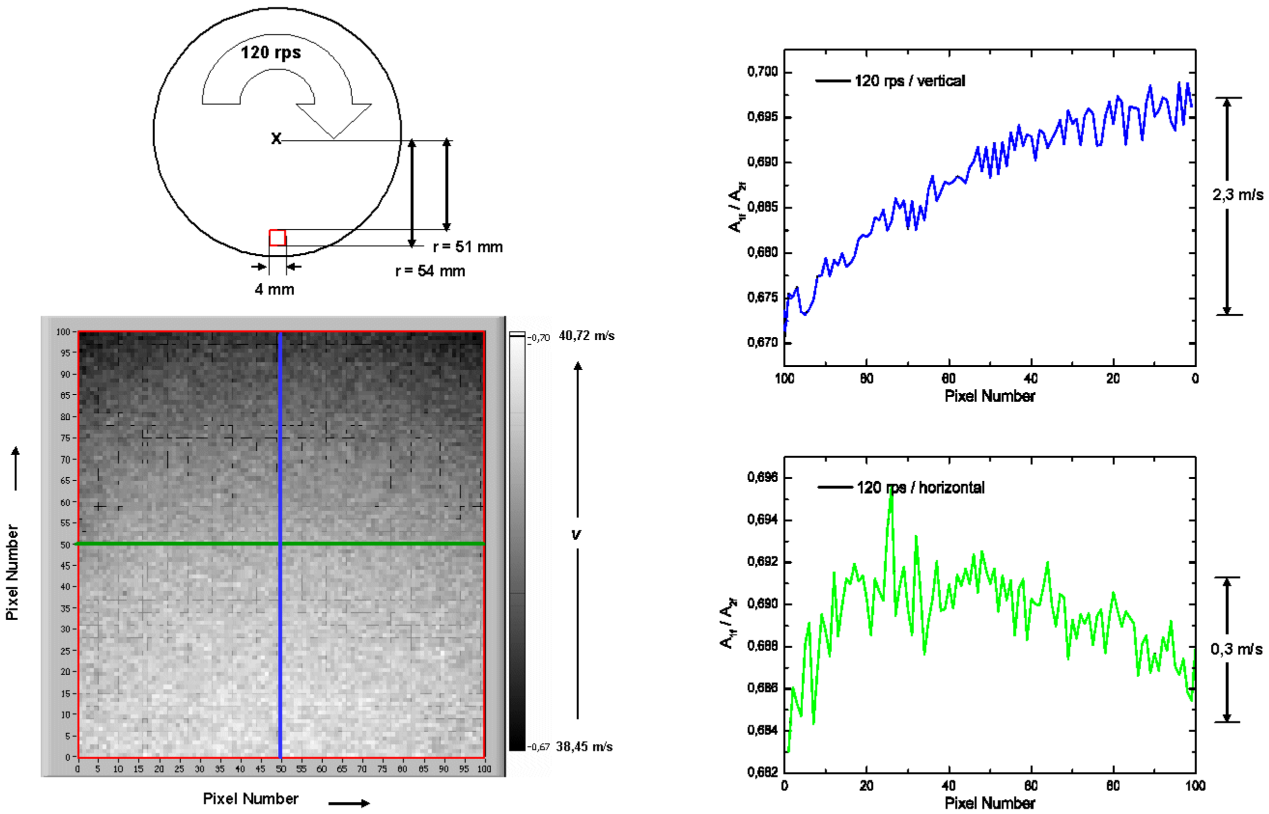

Fig. 1. Velocity field on a rotating glass wheel detected with a FM-DGV-system in 0,5 s. The radial (blue line) and the horizontal (green line) velocity profile of the marked velocity field demonstrate the achieved resolution.

1. INTRODUCTION

As a spectroscopic method for the evaluation of Doppler shifts, Doppler Global Velocimetry has successfully been applied especially for the investigation of high speed flow fields in wind tunnels. The increasing interest to apply this technique for manifold applications in the whole field of engineering enforced the efforts to decrease the measurement uncertainty of DGV as a low diagnostic tool. (Ainsworth et al. (1997))

Theoretical and experimental investigations were conducted to determine methods to increase measurement accuracy and repeatability, to improve the system calibration and to eliminate influences caused by instabilities of the laser frequency output, variations in the optical transmissivity and optical distortions in the data images. The culmination of these investigations was an 1,75% error in the mean with a standard deviation of 0,5 m/s (Meyers et al. 2001). Röhle and Schodl (1994) found the uncertainty to be about 2,5 m/s and Morrison et al. (2001) investigated the effects of light intensity gradients and pixel location accuracy upon the DGV measurement accuracy and estimated the overall uncertainty of the DGV system to be approximately 4 m/s.

An approach to avoid pixel alignment errors was presented by Ford et al. (2001), who presented a single-camera planar Doppler velocimeter based on acousto-optic frequency switching. Using a spinning disc they achieved a velocity resolution of +/- 1 m/s.

A similar approach for saving the reference camera was based upon the frequency modulation of a tunable high power DBR laser diode at 852,6 nm and was firstly presented by Müller et al. (1999). By evaluating the first und second harmonic of the resulting amplitude modulation of the scattered light transmitted through the absorption cell this technique allowed to omit the reference detector unit and to increase the accuracy of the velocity measurement compared to conventional systems. Based upon this technique a simplified DGV flow profile sensor was realized and presented by Müller et al. in 2002.

This paper describes the further development of the FM-DGV flow profile sensor and the devolution of the technique for being applied with a single CCD camera for the investigation of velocity fields. In a first step the capability of the FM-DGV-technique for the investigation of velocity fields has been shown. Measuring the velocity field in a small section on the surface of a rotating acrylic glass wheel (see figure 1) a velocity resolution of better than 0,3 m/s was achieved.

2. DOPPLER GLOBAL VELOCIMETRY – DGV PRINCIPLES

2.1 Conventional DGV-principle

The Doppler global technique is based on the application of 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 an absorption line filter for the frequency to intensity conversion, the intensity of the scattered light imaged through the absorption cell onto a detector yields the measuring information. Thus scattered light generated by ensembles of tracer particles can be evaluated and multipoint measurements can be performed simultaneously.

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.

As the intensity of the light transmitted through the absorption cell directly gives the measuring information, small intensity variations caused by parasitic intensity fluctuations in the observed light sheet have serious effects on the accuracy of the velocity measurement. Thus in conventional systems, the influence of intensity fluctuations of the scattered light is eliminated by employing a signal and an additional reference detector unit (see figure 2), where the image alignment of both detectors on each other is of particular importance.

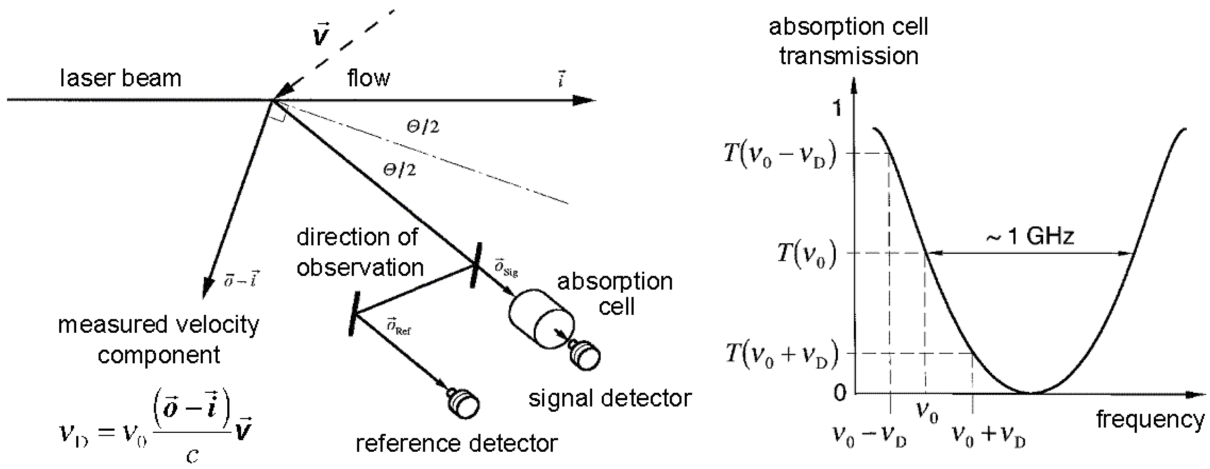

Fig. 1: Principle of Doppler Global Velocimetry

2.2 DGV based upon frequency modulation of the laser

The FM-DGV technique uses a frequency modulation of the laser light. The frequency modulation will be transformed into an amplitude modulation of the laser light transmitted through the absorption cell presumed that the centre frequency is stabilized on a working point within the absorption line. As the Doppler shift of the scattered light will vary corresponding to the instantaneous flow velocity, the working point on the absorption line filter curve will also change. Thus the amplitude modulation of the modulated scattered light signal behind the absorption cell, which is mainly composed of the 1st and 2nd harmonic of the modulation frequency, will depend on the Doppler shift and contain the information about the magnitude and sign of the velocity component to be measured (see figure 3 and 4).

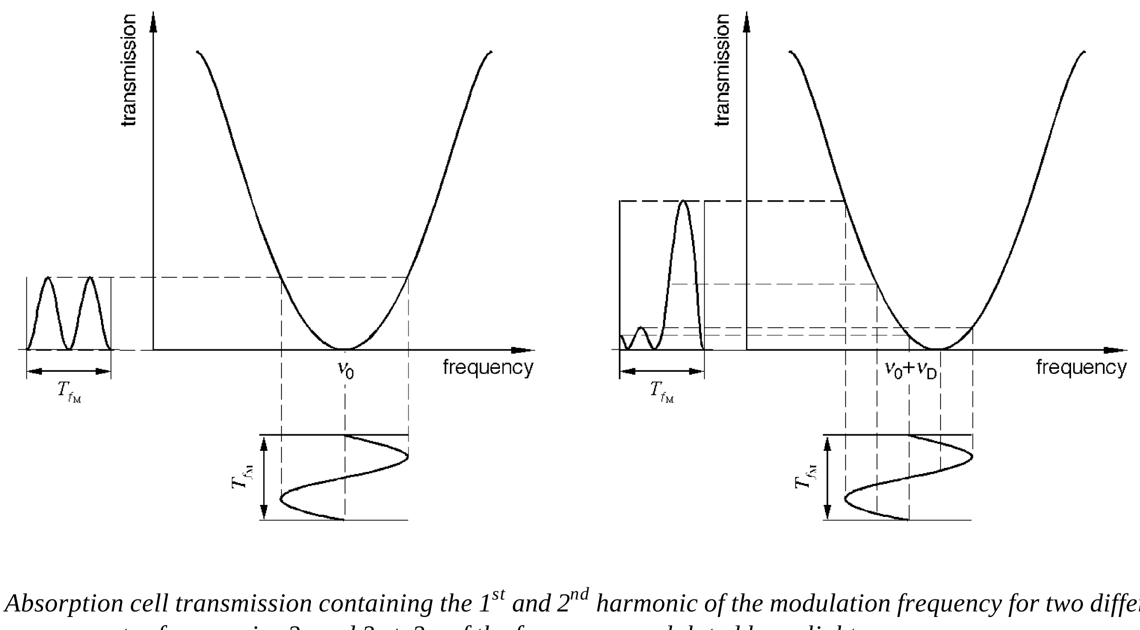

Fig.3: Absorption cell transmission containing the 1st and 2nd harmonic of the modulation frequency for two different center frequencies $?_o$ and $?_o + ?_D$ of the frequency modulated laser light

If we consider a frequency modulation of the laser light with a constant modulation amplitude, the resulting amplitude modulation behind the absorption cell will mainly contain the first two harmonics depending 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 (red) and 2nd (green) harmonics of the laser light transmitted through the absorption cell when varying the centre frequency of the laser light within the absorption line continuously.

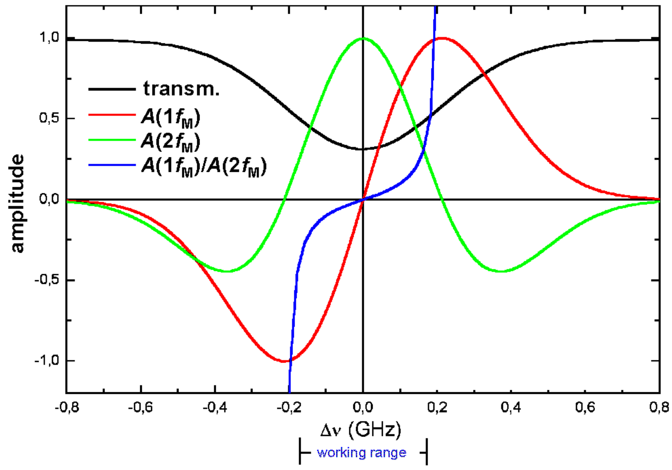

Fig. 4: Modulation amplitudes $A(1f_M)$ and $A(2f_M)$ of the 1st and 2nd harmonics of the laser light transmitted through the absorption cell when varying the centre frequency of the laser light. The quotient $A(1f_M)/A(2f_M)$ uniquely determines the frequency shift in the marked working range

By evaluating the quotient of the amplitudes of the harmonics $A(1f_M)/A(2f_M)$ in the photodetector 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 and alignment problems - can be omited.

3. EXPERIMENTAL SET-UP AND MEASUREMENTS

3.1 Experimental set-up und calibration of the FM-DGV

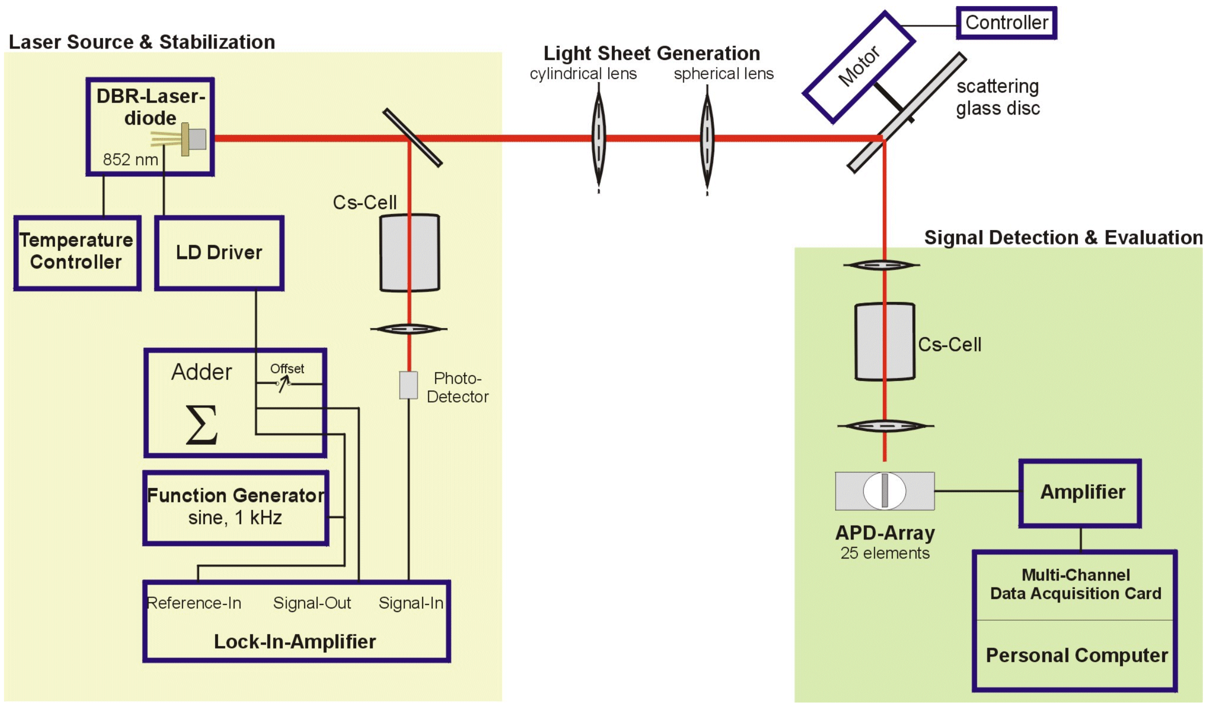

Fig. 5: Experimental set-up of the FM-DGV system for velocity profile measurements. The motor drives an acrylic wheel. A section of a radial line on the rotating wheel was illuminated by the light sheet (see fig. 6)

The FM-DGV system had been realized by applying a temperature and current controlled DBR laser diode (Distributed Bragg Reflector) featured by its high output power (SDL 5712 typically 100 mW) and tuning possibilities. The centre frequency of the laser diode was adjusted to the absorption maximum of a Cs absorption cell at 852,6 nm and stabilized with a lock-in-amplifier. The modulation frequency was 1 kHz and the modulation amplitude corresponded approximately to the half of the absorption line edge. To measure velocity profiles an Avalanche photo detector linear array with 24 pixels had been used. In a first step three pixels of the APD array were connected in parallel to get eight measuring points for the representation of a velocity profile. The signal evaluation was based upon the simultaneous analysis of the 1st and 2nd harmonics of the amplitude modulation of each APD pixel signal by FFT algorithms and the computation of the quotients $A(1f_M)/A(2f_M)$ for each pixel. For the data acquisition a multi-channel data acquisition card was used and the signals were evaluated under LabVIEW. Figure 5 shows the experimental set-up of the FM-DGV system for velocity profile measurements.

A rotating acrylic wheel was used to verify first time resolved velocity profile measurements as well as to calibrate the complete FM-DGV set-up including all electrical and optical parameters of the system (see figure 6).

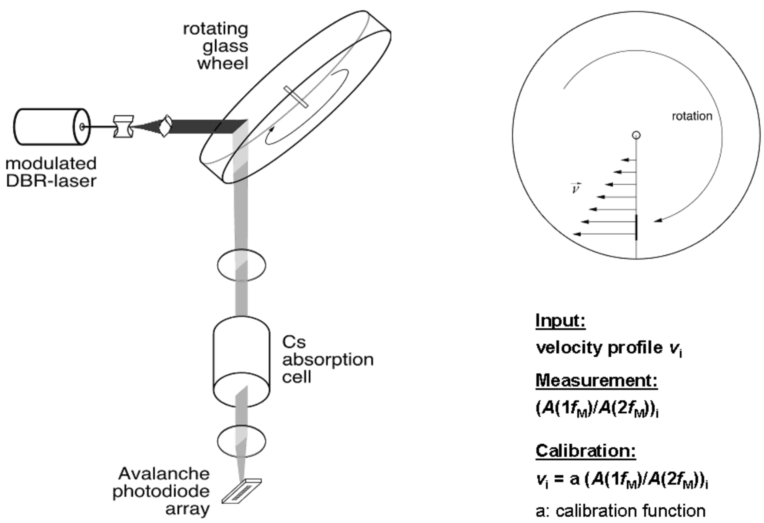

Fig. 6: Simplified block diagram of the FM-DGV set-up used for the calibration with a well defined velocity profile. The corresponding calibration function is presented in figure 7.

A well defined linear velocity profile was achieved by controlling the number of revolutions of the rotating wheel and the precise knowledge of radial position of each measuring point along the observed radial line on the surface of the wheel. Figure 6 shows the simplified block diagram of the set up for the calibration of the FM-DGV system. The calibration is performed by allocating the calculated quotients $A(1f_M)/A(2f_M)$ to the corresponding predetermined velocity values (see figure 7).

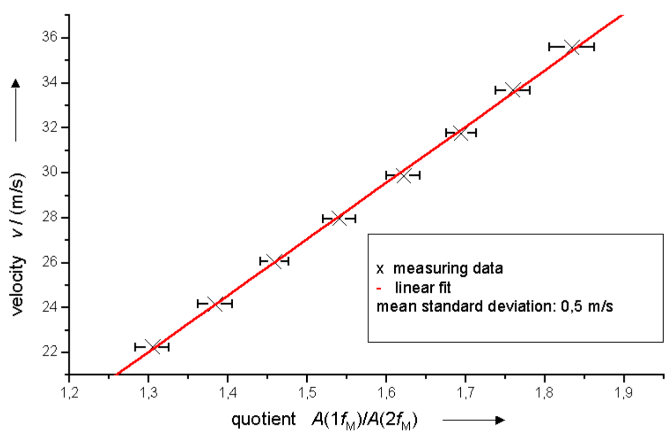

Fig. 7: Calibration function for the FM-DGV set-up presented in figure5 .

The Doppler shift range which corresponds to the realized velocity range covers only a fractional amount of the working range marked in figure 4. Thus the calibration function can by represented by a straight line obtained by a linear fit of the measuring data shown in figure 7. Remarkably the uncertainty of the velocity measurement was determined to be only 0,5 m/s with the relatively simple FM-DGV system.

3.2 Time resolved velocity profile measurement

In order to demonstrate the capability of performing time resolved velocity profile measurements the experimental set-up shown in figure 5 and figure 6 had been used. By averaging twenty data acquisitions for each velocity profile the temporal resolution was 0,5 s. Figure 8 demonstrates a sequence of measured velocity profiles over a period of time showing the acceleration process of the rotating wheel from zero up to the adjusted constant velocity and the deceleration process after switching off the rotation of the wheel.

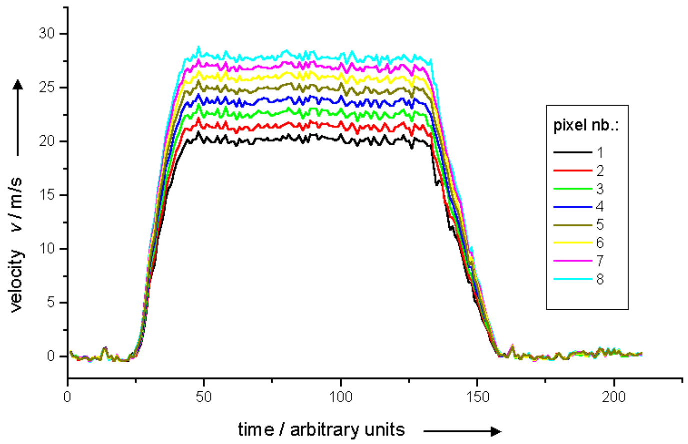

Fig. 8: Time resolved velocity profile measurement on the rotating wheel including the acceleration and deceleration process in order to give an impression of the resolution of the FM-DGV system.

In a second step the rotating wheel was replaced by a circular shaped nozzle with an output diameter of 10 mm. The velocity profile over the nozzle outlet was simultaneously measured over eight measuring points (see figure 9).

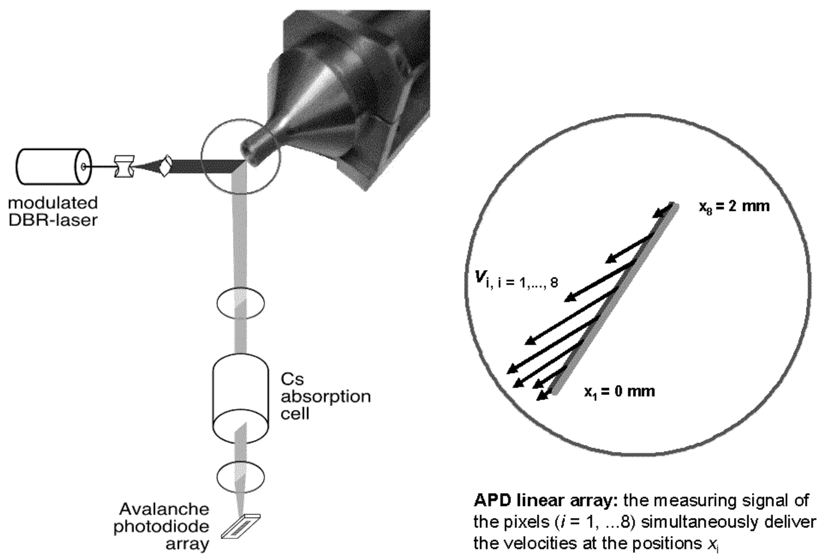

Fig. 9: FM-DGV set-up used for time resolved velocity profile measurement at the outlet of a nozzle. The velocity profile is obtained by the simultaneously measured evaluated output signals of the APD linear array

Figure 10 shows the measured velocity profile across the nozzle outlet corresponding to the scheme in figure 9 before and after turning on the fan whereas figure 11 shows the velocity profile as a function of time for the whole procedure of turning up the flow to its maximum speed and turning off in a time period of about fifteen seconds.

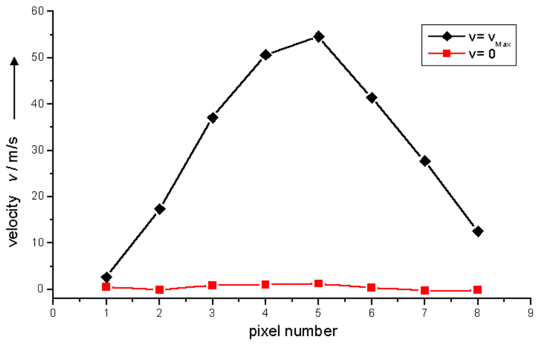

Fig. 10: Velocity profile of the free jet across the nozzle outlet before and after turning on the blower of the nozzle

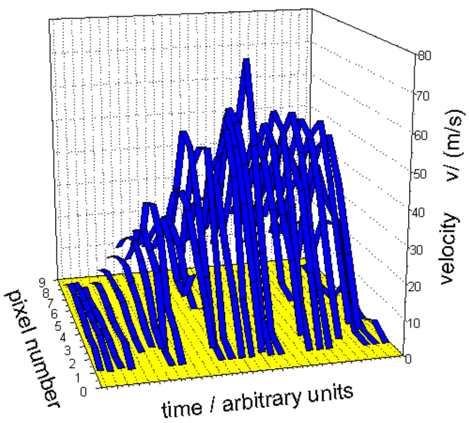

Fig. 11: Time resolved FM-DGV velocity profile measurement at the outlet of a nozzle over a time period of about fifteen seconds while turning on and turning of the blower (velocity profile rate: 2,2 Hz)

3.3 Time resolved velocity field measurement

In order to transfer the FM-DGV method from the measurement of velocity profiles to the measurement of velocity fields the ADP linear array has to be replaced by a CCD camera. Instead of evaluating simultaneously measured continuously varying signals of an APD array, the application of a CCD camera requires the evaluation of a sequence of images. The temporal resolution is then given by the required image acquisition time and the maximal achievable image rate. In analogy to the evaluation of $A(1f_M)$ and $A(2f_M)$ by FFT algorithms to determine of the quotient $A(1f_M)/A(2f_M)$ a discrete FT has to be realized when using a CCD camera. Considering the possibility of on-line velocity field measurements with high temporal resolution and obtainable frame rates of commercially available cameras it is useful to minimize the number of images during one modulation cycle. The minimal number of images to detect both the 1st and the 2nd harmonic in the amplitude modulated scattered light signal behind the absorption cell in a sequence of images during one frequency modulation cycle T_{fM} is given by the Nyquist criterion. Thus four images per modulation cycle will be enough to evaluate the quotient $A(1f_M)/A(2f_M)$ in order to get the velocity information. To optimize the image acquisition time and to have constant conditions during that time it makes sense not to modulate the laser frequency continuously but to switch the laser frequency to at least four discrete frequencies describing four samples of one frequency modulation cycle. Thus the frequency modulation technique transferred to whole field measurements by the application of CCD cameras can be interpreted as a modified frequency switching technique. A similar technique which uses only one camera by switching the laser frequency has firstly been described by Ford, Nobes and Tatam (2001). Figure 12 shows the principle of the frequency switching technique as modified frequency modulation technique (see figure 3 and figure 4) with maximized discretization.

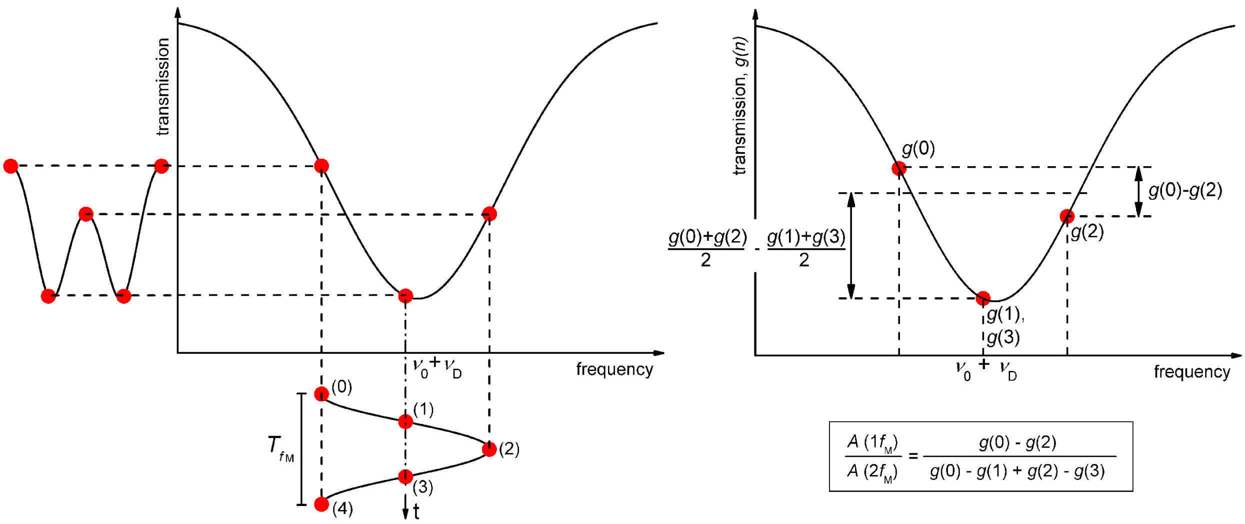

Fig. 12: Maximized discretization for the FM-DGV method to apply CCD-cameras for velocity field measurements. The determination of the quotients $A(1f_M)/A(2f_M)$ containing the velocity information for each CCD-camera pixel can be obtained by evaluating a sequence of four "transmission images" g(0), …, g(3).

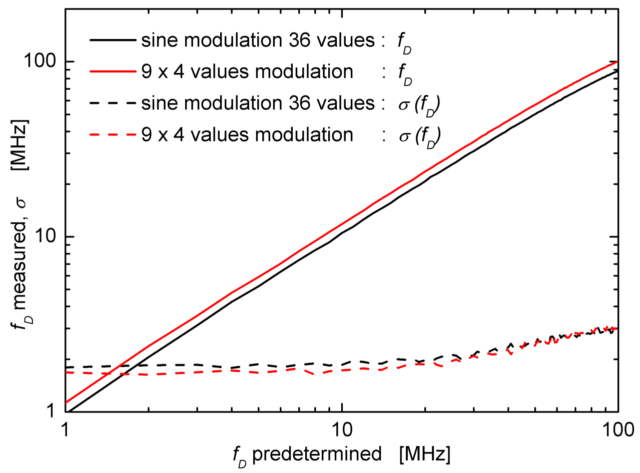

Fig. 13: Comparison of the Doppler frequency determination based on frequency modulation between a sine modulation using 36 samples over one modulation periode and a frequency switching method containing 4 steps over 9 periods under the consumption of an absorption line width of 500 MHz, a minimal Transmission of 10%, and 1% noise

The simulation presented in figure 13 shows that based on the same number of samples there is no remarkable difference in the determination of the Doppler frequency f_D between a sine modulation using 36 samples and the method of switching the laser frequency between the three marked values (g(0), …, g(3); $g(1) = g(3)$) in figure 12 over nine modulation cycles.

Thus the FM-DGV technique can be simplified by the described frequency switching technique (see figure 12). Furthermore we can assume that the images $g(1)$ and $g(3)$ are the same so that one modulation cycle can be approximated by taking only three images.

In that case the information about the velocity field can be obtained by calculating $A_{i,j}(1f_M) / A_{i,j}(2f_M)$ for each camera pixel (i, j) from the relationship given in figure 12. This relationship can directly be derived from the equation for the discrete fourier transformation. Considering only the three transmission images g(0), g(1), g(2) one gets:

$$A_{i,j}(1f_M) / A_{i,j}(2f_M) = g_{ij}(0) - g_{ij}(2) / (g_{ij}(0) - g_{ij}(1) + g_{ij}(2) - g_{ij}(1))$$

In order to verify the simplified FM-DGV technique by taking only a sequence of three images, a section of a rotating wheel has been illuminated and imaged onto the CCD camera. The image acquisition time for each image was 100 ms so that the information about the velocity field could be obtained in less than 0,5 s. Figure 14 shows the experimental result of one of these first measurements.

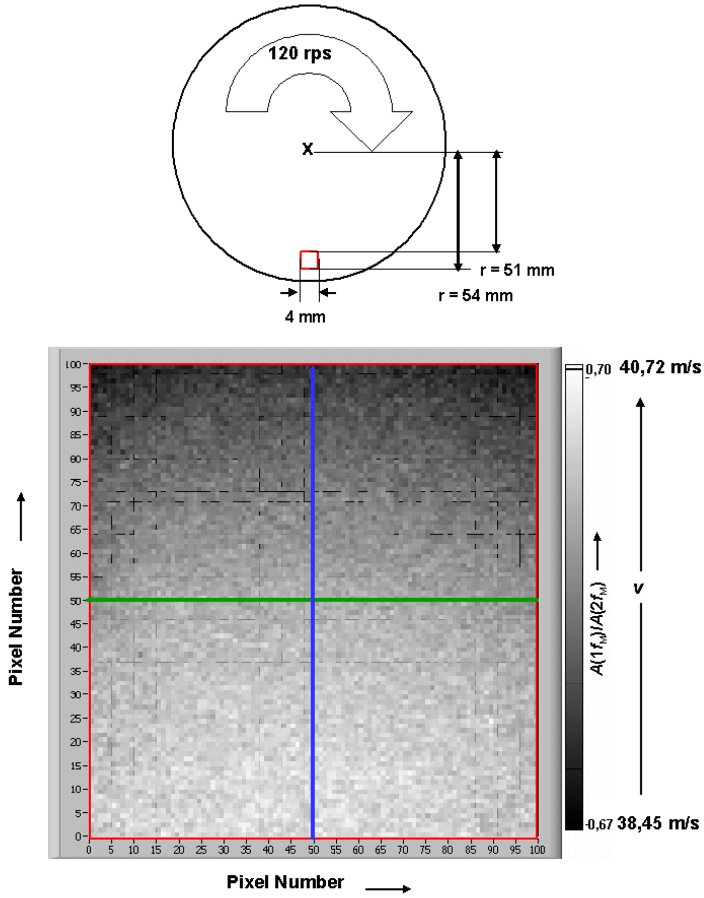

Fig. 14: Measured velocity field in the marked area on the surface of an acrylic wheel rotating with 120 revolutions per second. The blue and the green line mark the vertical and the horizontal velocity profile presented in figure 15. The velocity field was evaluated of a sequence of only three images with an acquisition time of 100 ms so that the temporal resolution for the FM-DGV measurement is less than 0,5 s

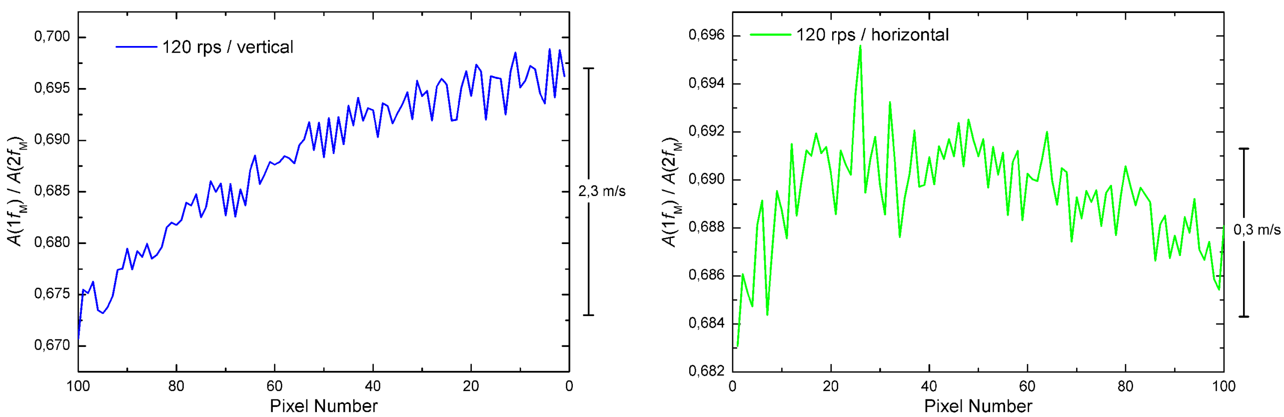

Fig. 15: Vertical and horizontal velocity profile in the observed area (see figure 14). Remarkable is the high velocity resolution of better than 0,3 m/s achieved with a temporal resolution of better than 0,5 s.

4. CONCLUSIONS

It has been shown that the FM-DGV technique is a promising technique for the on-line measurement of velocity profiles and velocity fields with high temporal resolution and with an increased accuracy compared to other DGV-systems presented up to now. By evaluating the quotient of signal amplitudes or images corresponding to a frequency modulation cycle of the laser source the conventionally used reference detector unit can be saved.

Thus the main contributions to the uncertainty of DGV-systems caused by pixel alignment errors, different image distortions of the signal and the reference image as well as polarization effects of beam splitters for the optical reference path generation can completely be eliminated. Furthermore the frequency modulation technique provides an additional opportunity of an on-line calibration of the FM-DGV system.

Though the presented FM-DGV has not been optimized so far it was possible to obtain a velocity resolution of better than 0,3 m/s and to achieved a temporal resolution of better than 0,5 s.

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