Single Camera DGV based on FM- and FSK- Techniques

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Abstract The main feature of the described Doppler Global Velocimeter systems based on frequency modulation (FM) or frequency shift keying (FSK) is that no reference detector unit is required. By the use of a single photo detector unit it is possible to reduce the uncertainty of the velocity measurement remarkably compared to conventional DGV systems employing a signal and a reference photo detector unit.

Depending on which type of detector unit is applied, an Avalanche photo detector array for performing a highly resolved multipoint velocity measurement in a locally limited region or a CCD camera for measuring a velocity field in an enlarged investigation area, the laser is modulated in its emission frequency continuously (FM) when using an APD array or discretely (FSK) when using a CCD camera.

By evaluating the periodical amplitude variations in the output signals of each photo detector pixel of the applied photo detector unit it is furthermore possible to perform time resolved multipoint velocity measurements in a flow field with a resolution depending on the signal to noise ration and the bandwidth of the APD array or the frame rate of the CCD camera and the available laser power in the laser light sheet.

Based on the frequency modulation the well defined frequency variation of the laser light during one modulation period additionally allows an on-line calibration of the complete DGV system including the absorption cell and the image acquisition system.

Exemplified for a single Avalanche photo detector pixel it is shown that using the FM technique with optimized parameters for the frequency deviation and the modulation frequency a standard deviation for the velocity of approximately 0.02 m/s was achieved.

Applying the FSK technique and a conventional CCD camera with a frame rate of 10 Hz, time resolved velocity measurements on a spinning disc were realized with a resolution down to 0.3 s. Analyzing timely resolved data over a measuring time of 180 seconds standard deviations of approximately 0.1 m/s were achieved when looking at one CCD camera pixel and approximately 0.02 m/s when realizing a pixel binning of 20 x 20 pixel.

Finally first experimental results of a 3 component velocity field measurement in a tube behind a double elbow are presented where velocities in a swirl down to approximately 0.2 m/s were resolved.

1. Introduction

The 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 flow diagnostic tool. (Ainsworth et al. (1997)) Theoretical and experimental investigations were done to find out 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 and second harmonic of the resulting amplitude modulation of the scattered light transmitted through the absorption cell this technique allowed to save 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 and first velocity field measurements were demonstrated by Müller et al in 2004. This paper describes the further development of the frequency modulation based DGV technique which we will characterize as FM DGV technique when using an APD array and as FSK technique when using a CCD camera with a modulation realized by discrete frequency steps of the laser light source.

2. Principle of DGV

The Doppler global technique is based on the application of a frequency stabilized laser and an absorption cell to analyze 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 gives 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 (see figure 1).

![Fig. 1: Principle of Doppler Global Velocimetry](image)
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 1), where the image alignment of both detectors on each other is of particular importance. When applying frequency modulation techniques to the Doppler Global velocimetry it is possible to omit the reference detector unit and to reduce the uncertainty of the velocity measurement. The following section will give a short review about the principle of the technique already presented by Müller et al in 2004.

3. Doppler Global Velocimetry based on FM- and FSK-techniques

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 provided 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 1\textsuperscript{st} and 2\textsuperscript{nd} 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 2 and 3).

![Figure 2: Absorption cell transmission containing the 1\textsuperscript{st} and 2\textsuperscript{nd} harmonic of the modulation frequency for two different centre frequencies $v_0$ and $v_0 + v_D$ of the frequency modulated laser light](image)

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 3 shows the resulting amplitude modulation amplitudes $A(1f_M)$ and $A(2f_M)$ of the 1\textsuperscript{st} (red) and 2\textsuperscript{nd} (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. 3: 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 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 and alignment problems – can be omitted.

The FSK technique is derived by transferring the FM-DGV method for multipoint velocity measurement using an APD array with continuous frequency modulation to a discrete frequency modulation using 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 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 $T_M$ 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 4 shows the principle of the frequency switching technique as modified frequency modulation technique (see figure 2 and figure 3) when minimizing the number of discrete frequencies within one modulation period.
Fig. 4: FSK-DGV method with discrete frequencies during one modulation cycle when applying a CCD-camera 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” $g(0), ..., g(3)$.

The FSK technique can be described as a frequency switching technique (see figure 4). 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 $A_{ij} (1f_M) / A_{ij} (2f_M)$ for each camera pixel $(i, j)$ from the relationship given in figure 4, which 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:

$$A_{ij} (1f_M) / A_{ij} (2f_M) = \frac{g_{ij}(0) - g_{ij}(2)}{g_{ij}(0) - g_{ij}(1) + g_{ij}(2) - g_{ij}(1)}$$

As the frame rate of the used CCD camera was 10 Hz and the acquisition time for each image was approximately 100 ms, the maximum resolution in time for the velocity field measurement was about 0.3s.

4. FM DGV: Experimental results concerning parameter optimization

In this section simulated as well as experimental results of some investigations concerning the optimization of the frequency modulation parameters of a realized FM DGV system are presented. The investigated FM DGV system has been realized by using a frequency modulated DBR-laser diode at a wavelength of 852 nm and a Cs absorption cell. A spinning disc generated the predetermined velocities which in the presented results were observed representatively by a single Avalanche photo detector pixel at one location on the spinning disc. The aim of this investigation was to investigate the influence of the frequency deviation and the modulation frequency of the frequency modulation onto the uncertainty of the velocity measurement. Both, the simulation data as well as the experimental data show that the frequency deviation can be optimized and that the influence of instabilities in the scattered light, for example caused by vibrations in the system, can be reduced by choosing higher modulation frequencies. While figure 5 shows the block diagram of the set-up for measuring a complete velocity profile based on the application of a linear APD array with 25 pixel, figure 6 illustrates the set-up used for the presented experimental results.
Fig. 5: Block diagram of the FM DGV system based on the application of a frequency modulated DBR laser diode and an APD linear array. The scattering glass disc is used to generate a well known velocity for the investigation of the complete FM DGV system.

Fig. 6: Experimental set-up of the FM DGV system according to figure 5 based using fibre coupled components for the optical set-up. For the investigations set figures 6 and 7 the APD array was replaced by a fibre coupled APD detector.
Figure 7 shows the comparison results between the measurement and the simulation in order to determine the uncertainty of the velocity at one position of the scattering disc for a modulation frequency of 2 kHz and different frequency deviations. Two velocity values were realized, 5 m/s for a constant number of revolutions of the disc and 0 m/s at the same position for the non-rotating disc. While in figure 6b the simulation of the standard deviation of the velocity includes the detector noise as well as scattered light fluctuations figure 6a solely considers the detector noise.

Thus figure 7 shows that it is necessary to consider the detector noise as well as the scattered light fluctuations and that the scattered light fluctuations have a remarkable influence on the obtained standard deviation for a velocity unequal to zero. Furthermore the data show that the standard deviation of the measured velocity can by minimized by choosing an appropriate frequency deviation. The measured data in figure 8a as well as the measured and simulated data in figure 8b show that the standard deviation for the velocity measurement based on the FM DGV method can obviously be reduced when the modulation frequency is increased.

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**Figure 7:** Measured and simulated standard deviation of the velocity to be measured (modulation frequency 2 kHz)  
(a) when considering the detector noise and  
(b) when considering the intensity fluctuations in the simulation model as well.

**Figure 8:**  
(a) Measured standard deviation of the velocity for different modulation frequencies 2 kHz and 20 kHz;  
(b) Measured and simulated standard deviation of the velocity for a modulation frequency of 20 kHz.
The investigation results presented in figures 7 and 8 show that the FM DGV technique allows to reduce the influence of scattered light intensity fluctuations on the measuring result. The standard deviation of the velocity measurement can be reduced remarkably when the frequency modulation frequency is increased and if the frequency deviation is the range of 300 MHz in the realized set-up. In the presented set-up standard deviations of 0.02 m/s for the velocity measurement were achieved.

4. FSK DGV: Experimental results

In this section experimental results of velocity field measurements based upon the application of the FSK DGV technique are presented. Figure 9 represents the block diagram of the realized FSK DGV system using a frequency switched MOPA (master oscillator power amplifier) laser with an output power of approximately 500 mW at an emission wavelength of 852 nm.

![Block diagram of the FSK DGV system based on the application of a MOPA laser](image)

![Single camera detector unit of the FSK DGV system according to a)](image)

Fig. 9: a) Block diagram of the FSK DGV system based on the application of a MOPA laser
b) Single camera detector unit of the FSK DGV system according to a)
In a first step the FSK-DGV system was investigated with a well defined velocity field generated by a rotating scattering disc as shown in figure 9a. The velocity field was observed with the single camera detector unit of the FSK DGV system as shown in figure 9b. In the detector unit as well as in the laser frequency control system temperature controlled Cs absorption cells were used for the frequency discrimination in the receiving optics as well as for the adjustment of the discrete laser emission frequencies. According to figure 4 three discrete laser frequencies were generated by the laser frequency controller which also triggered the image acquisition of the CCD camera.

Figure 10 shows the experimental results of a velocity field measurement on a rotating scattering disc. The temporal resolution (3 s) of the presented measurement result was given by a sequence of three images and a CCD camera frame rate of 1 s.

![Figure 10: a) FSK DGV velocity field measurement on a rotating disc, frame rate 1s (measurement time 3s); separately drawn is the achieved velocity profile along the radius of the disc; the standard deviation of the proportional fit corresponds to a standard deviation of the velocity of 0.2 m/s; b) time resolved velocity measurement at one position on the wheel during a measuring time of 180 s; considering one pixel the standard deviation over the measuring time corresponds to approx. 0.1 m/s while pixel binning with 20 x 20 pixel leads to a reduced standard deviation corresponding to 0.02 m/s](image)

While figure 10a gives an impression about the already achieved accuracy of the single camera FSK DGV system including local uncertainty and velocity uncertainty contributions, figure 10b demonstrates the temporal stability of a velocity measurement at one position of the scattering disc.

The described single camera FSK DGV system has already been applied for time resolved flow field measurements in a pipe. Assuming stationary flow conditions in the pipe, a 3 component velocity field measurement can be performed by illuminating the measuring plane by three different incident light sheets sequentially. In the particular case shown in figure 12 the measurement plane was located 20 pipe diameters (d = 0.2 m) behind a double elbow where the distortion of the axial flow profile already decayed while swirl components were still present in the pipe flow. To realize a 3 component velocity field measurement an observation section with three optical accesses for the light sheet illumination was implemented in the pipe (see figure 11b) and the light sheet head was mounted at the different positions successively. The scattered light was imaged by a mirror which was placed 4 pipe diameters downstream from the measuring plane into the single camera FSK DGV detector unit. During the complete measurement the flow velocity in the pipe was stabilized by an assembly of critical nozzles. The maximum flow velocity in the centre of the flow profile was adjusted to approximately 13 m/s. Figure 11a shows the principle of the 3 component single camera FSK DGV pipe flow measurement by using three light sheets successively.
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Fig. 11:  
a) Principle of the 3 component single camera FSK DGV velocity field measurement in a pipe;  
b) set-up of the complete single camera FSK DGV system including MOPA laser and light sheet head.

Fig. 12:  
a) 3 c FSK DGV: measured axial velocity profile in a pipe flow 20 pipe diameters behind a double elbow;  
b) 3 c FSK DGV: measured in plane velocity components of a swirl in the pipe flow.

The experimental result in figure 12 shows that the 3 component single camera FSK DGV technique allows to resolve swirl structures in a pipe flow with velocity components noticeably less than 0.5 m/s with a simplified system compared to conventional DGV systems.

5. On-line calibration

Using the FSK DGV technique the emission frequency of the laser is sequentially adjusted to discrete frequencies within one measurement cycle. Provided that the emission frequency of the laser is controlled by generating the beat frequency between the laser for the light sheet generation and an absolutely stabilized master laser, precise frequency shifts $\Delta \nu$ can be realized.
Based on the precise frequency shifts $\Delta \nu$ between the discrete laser emission frequencies on both edges of the absorption line filter an absorption line calibration is included in the measurement cycle and the Doppler shift can be determined according to the shown principle in figure 13.

![Fig.13: Principle of an on-line calibration of the complete FSK DGV system by using well defined optical frequency differences $\Delta \nu$. The Doppler shift $\nu_D$ can be determined by a sequence of four images $g(0), ..., g(3)$ according to given relationship.](image)

### 6. Conclusions

The main feature of the described Doppler Global Velocimeter techniques based on frequency modulation (FM) and frequency shift keying (FSK) is that no reference detector unit is required. Thus the uncertainty of the velocity measurement can remarkably be reduced compared to conventional DGV systems as their uncertainty is mainly affected by normalizing the pixels of the signal detector unit to the corresponding pixels of the reference detector unit.

Using the FM DGV technique with optimized parameters for the frequency deviation and the modulation frequency a standard deviation for the velocity of approximately 0.02 m/s was achieved. Furthermore it is possible to perform time resolved flow field measurements with a resolution depending on the frame rate of the camera and the available laser power in the light sheet.

Applying the FSK DGV technique with a conventional CCD camera with a frame rate of 10 Hz, time resolved velocity measurements were realized with a resolution down to 0.3 s. Analyzing timely resolved data over a measuring time of 180 seconds standard deviations of approximately 0.1 m/s were achieved when looking at one CCD camera pixel and approximately 0.02 m/s when realizing a pixel binning of 20 x 20 pixel.

Finally first experimental results of a 3 component velocity field measurement in a tube behind a double elbow are presented where velocities in a swirl down to approximately 0.2 m/s were resolved.

A future improvement of the FM and the FSK DGV technique will be possible by using the well defined frequency shifts of the laser emission frequency during one modulation cycle to perform an on-line calibration of the complete DGV system including the absorption cell and the image acquisition system.
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8. References


