Measurements of velocity spectra using Doppler Global Velocimetry with laser frequency modulation and a detector array

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Abstract We describe a Doppler Global Velocimeter setup with sinusoidal laser frequency modulation, consisting of a diode laser emitting at 852 nm wavelength, a caesium cell as frequency to intensity converter and a fibre coupled array of 25 avalanche photo diodes. The spatial resolution depends on the optics, which map the scattered light onto a 2d arrangement of the fibre ends, and is currently 1 mm. The designed avalanche photodiode array and the modulation frequency of 100 kHz allow high temporal resolution up to 10 µs. Thus, the measurement system is capable of synchronously measuring velocity spectra at multiple points in turbulent flows as is demonstrated in a wind tunnel experiment. The velocity spectra measured with a measurement rate of 500 Hz and a total measurement time of 2 s agree well with the comparison measurements accompanied with a Hot-Wire Anemometer within ± 0.1 m/s. A relation between the desired time resolution and the achievable measurement uncertainty is further given. The promising results open new perspectives for turbulence and correlation studies in flows such as the turbulence characteristics behind a truncated cylinder attached to a plate or the inlet of an aircraft turbine for characterization in industry.

1. Introduction

One focus of our current research is the turbulence spectrum analysis. A standard method for measuring velocity spectra is Hot-Wire Anemometry. One advantage of this technique is the temporally equidistant capture of velocity values with rates up to several 100 kHz without having to use tracer particles [1]. Due to this, velocity spectra can be calculated easily for a sufficient frequency range by harmonic analysis of a velocity time series captured. However, it is an invasive measurement technique, thus disturbing the flow characteristic, and only a pointwise technique. Common measurement uncertainties are quoted to about 2%. Lower measurement uncertainties down to about 0.5% can be achieved with the non-invasive Laser Doppler Anemometry. The measurement of velocity spectra is much more complicated though, since the data rate is not constant due to the statistical arrival of single scattering particles. Furthermore, it is a pointwise measurement technique also. As a result, alternative contactless measurement techniques for measuring turbulence spectra are necessary achieving a constant measurement rate, a high temporal resolution and a low measurement uncertainty. Furthermore, a multipoint (1D or 2D) measurement would be advantageous allowing e.g. correlation measurements.

A novel approach for measuring velocity spectra in a flow was presented by Cavone et al. [2] using a modified Doppler Global Velocimeter (DGV). They reduced the system capability to one measurement point, since fast photomultipliers instead of slow cameras are used for achieving a
constant measurement rate of 50 kHz. Two photomultipliers were necessary for the single measurement point, since a reference measurement is necessary.

In order to extend this approach to a 25 point measurement technique, we suggest the use of a new Doppler Global Velocimeter with laser frequency modulation (FM-DGV) [3]. This technique reduces system immanent errors of conventional DGV such as image misalignment errors and beam splitting errors as described in [4]. One system simplification is the use of avalanche photo diodes, which are cheaper than photomultipliers in an array configuration and also allow high data rates in comparison to cameras. Using additionally fibre-coupled detectors, the fibre ends can be arranged flexible for 1D (1x25) or 2D (5x5) velocity measurements with data rates up to 100 kHz as will be shown in the following sections.

Firstly, a brief explanation of the DGV measurement principle is given. Secondly, the measurement principle of an FM-DGV system is described. In the next section follows a detailed discussion of the experimental setup and the maximum achievable temporal resolution. Measurement results for an uncertainty analysis in dependence of a desired temporal resolution are presented subsequently. Furthermore, the results of a turbulent flow measurement are presented. The article closes with final conclusions.

2. Principle of DGV

The conventional DGV method is schematically illustrated in figure 1. A laser is frequency stabilised to the edge of a transmission profile of a molecular absorption cell, where the laser line width is narrow in comparison to the line width of the transmission profile. Mainly argon-ion lasers at 514.5 nm or frequency-doubled Nd:YAG lasers at 532 nm are used in combination with iodine absorption cells. The laser beam is spread to a laser light sheet, illuminating the measurement plane in the flow to be investigated. After being scattered by tracer particles, the light is Doppler shifted in frequency. The frequency shift reads

$$f_D = f_L \frac{\vec{v}(\vec{o} - \vec{i})}{c}$$

and depends on the laser frequency $f_L$, the light velocity $c$, the particle velocity $\vec{v}$, the laser light incident direction $\vec{i}$ and the observing direction $\vec{o}$. The observed scattered light is split up into two parts and each is measured with a camera. The splitting ratio is mostly close to 50:50. The reference camera measures the scattered light intensity directly. The signal camera measures the

![Fig. 1 Principle of DGV](image)

![Fig. 2 Measured transmission of our caesium absorption cells at $f_i = 351.73$ THz (caesium D$_2$ line)](image)
light intensity after the light passed the absorption cell. The latter signal depends on the light frequency as, in correspondence with the specific transmission behaviour of the absorptions cell, a change in frequency is converted to a change in light intensity. The principle is illustrated in fig. 2 at the spectral transmission of a caesium cell, which we will use later. The pixel-wise division of the simultaneously captured signal and reference image results in an acquisition of the transmission coefficient of the absorption cell, which does not depend on the scattered light intensity. Intensity dependent saturation effects are assumed to be negligibly small.

According to the equation (1), it is possible to measure one velocity component using the illustrated set-up. An extension of the set-up by two further camera pairs with different observation directions enables the measurement of all three velocity components in the illuminated flow region, but is not considered here further.

3. Principle of DGV using sinusoidal laser frequency modulation (FM-DGV)

The Frequency-Modulation Doppler Global Velocimetry (FM-DGV) method is drafted in figure 3. In comparison with fig. 1, its simpler receiving unit is obvious since only one detection unit is necessary. The omission of the reference detector unit and the beam splitter is afforded by a sinusoidal frequency modulation of the laser light:

\[ f_L(t) = f_c + f_h \cos(2\pi f_m t), \tag{2} \]

with \( f_c \) as laser centre frequency, \( f_h \) as modulation amplitude and \( f_m \) as modulation frequency. Like in conventional DGV systems, a laser light sheet illuminates the measuring plane in the flow, and the laser light is scattered by tracer particles. The scattered light is shifted in frequency according the equation (1). The resultant laser centre frequency \( f \) then reads

\[ f = f_c + f_D. \tag{3} \]

Because of the frequency-intensity conversion according to the transmission curve of the absorption cell, the photodetector array detects an intensity modulated signal as illustrated in fig. 4. As the transmission curve is non-linear, the measured intensity signal contains not only the first but also higher order harmonics. A detector signal, which is usually sampled by a data acquisition card, was calculated and is given in fig. 5 in time and frequency domain as an example. For this simulation, the measured transmission curve from figure 4, the parameters \( f_m = 100 \text{ kHz} \), \( f_h = 450 \text{ MHz} \),
The value $f_0$ depicts the frequency 351.73 THz.

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The first and second order harmonic amplitudes $A_1(f)$, $A_2(f)$ can be calculated from the sampled detector signal $s(kT_a)$ by

$$A_i(f) = \frac{2}{N} \sum_{k=0}^{N-1} s(kT_a) \cos(2\pi f_m kT_a), \quad i = 1, 2$$

and are used here for further signal evaluation. In figure 6a, $A_1(f)$ und $A_2(f)$ are plotted with respect to the laser centre frequency. Obviously, a velocity dependent change in laser frequency caused by the Doppler effect leads to a change of the amplitudes $A_1(f)$ and $A_2(f)$. As these amplitude values are both directly proportional to the average scattered light intensity, a division of $A_1(f)$ through $A_2(f)$ eliminates this disturbing factor. This finally results in our measurand

$$q(f) = \frac{A_1(f)}{A_2(f)}.$$  

A diagram of the calculated quotient $q(f)$ as a function of the laser centre frequency is shown in figure 6b. For the modulation amplitude $f_h = 450$ MHz, the mapping between the quotient $q(f)$ and the laser centre frequency $f$ is bijective in the interval [-310 MHz, 550 MHz] referred to $f_0$. As a result, velocity dependent changes of the laser frequency can be measured by evaluating the quotient $q(f)$ providing a measurement range of about ± 430 MHz in principle or approximately ± 200 MHz when only the roughly linear portion of the curve is used, respectively. For a laser wavelength of $\lambda = c/f_c \approx 852$ nm, which we will apply later, and a perpendicular arrangement of the incident laser light sheet and the observing direction, this corresponds to a measurement range of...
about ± 260 m/s or ± 120 m/s according the equation (1). An additional evaluation of the inverse quotient \( 1/q \) enhances the available measurement range, but is not considered here.

Measuring all three velocity components of a velocity field is also possible with FM-DGV by adding two additional receivers with different observing directions. It was finally shown, that no reference detector and beam splitter is necessary for FM-DGV thus eliminating image misalignment and beam splitting errors.

Fig. 6 a) Calculated first and second order harmonic amplitudes \( A_1(f) \), \( A_2(f) \) (compare eq. (4)) and b) the quotient \( A_1(f)/A_2(f) \) w.r.t. the laser centre frequency according the transmission as given in fig. 4 and \( f_h = 450 \text{ MHz} \) as modulation amplitude

4. Experimental setup and maximum time resolution

After the measurement principle of an FM-DGV system was described in the previous section, we now explain the set-up of such a system consisting of a high power diode laser and a fibre-coupled avalanche photodiode array with 25 elements. Furthermore, the maximum time resolution is discussed in order to reveal the system capabilities for multipoint velocity measurements with high temporal resolution e.g. for turbulence analysis.

In fig. 7, the set-up of our FM-DGV system is given schematically. It consists of a laser source and stabilization module and a signal detection and evaluation module. The first one’s main part is a DFB diode laser emitting light at 852.3 nm wavelength. This laser was chosen, because it is a single frequency, high power, narrow band laser and can be fast modulated in frequency. Other laser sources usually can be modulated in frequency only up to 10 kHz, because of the cut-off frequency of the piezo actuators varying the laser resonance length. Additionally the available laser wavelength is suitable to an absorption line of caesium, which is used for frequency-intensity conversion here.

The laser is capable to generate up to 126 mW. The laser line width was measured to be less than 2.4 MHz und is thus sufficiently small in comparison to the molecular absorption line width, which is about 850 MHz (compare fig. 4). Hence, the absorption line can be spectrally resolved, which is a fundamental requirement for our measurements. The diode laser power and frequency can be adjusted by its temperature and current. The used current input allows fast frequency modulation up to 5 MHz. Here, a stable sinusoidal modulation signal with the modulation frequency up to \( f_m = 100 \text{ kHz} \) is provided by a digital function generator based on direct digital synthesis technology and is connected to the laser diode current driver. The laser centre frequency \( f_c \) is stabilized by a PI-controller, whose control variable is the first order harmonic amplitude of the detected laser light.
power after passing a molecular absorption cell filled with caesium gas. The first order harmonic amplitude $A_1(f_c)$ is approximately directly proportional to the laser centre frequency around the transmission minimum and thus appropriate for stabilizing the laser centre frequency (compare fig. 6a). A lock-in amplifier with a cut-off frequency of 120 kHz is applied for measuring the first order harmonic amplitude out of the detector signal.

The emitted laser light is spread by a cylindrical and spherical lens to a laser light sheet. Depending on the measurement task, the light sheet height and thickness can be varied. The thickness usually amounts about 0.5 - 1 mm. The height is adjusted to usually 7 mm, but can be lowered down to 1 mm for velocity profile measurements with maximum laser power. The laser power in the measurement volume is about 80 mW.

The absorption cells contain caesium gas. They are temperature stabilized in order to keep the spectral transmission constant in time. The remaining temperature standard deviation measured by an NTC element over 1 h is 4 mK. The temperature drift is about 7 mK. The aperture of the cells is 25 mm, the lengths amount about 50 mm. The cell in the signal detection and analysis module has a cold finger [4] and its windows are angled and wedged in order to reduce optical resonance effects. By setting the cold finger temperature to 25°C and the cell body temperature to 45°C, the cell transmission as given in fig. 4 results. A similar shape of the transmission curve is provided by the second caesium cell for laser stabilization. It has no cold finger and is adjusted to 30°C cell temperature.

The signal detection unit consists of a Keplerian telescope arrangement. The light sheet is therewith mapped through a caesium cell onto the ends of 25 fibres, which are connected with avalanche photodiodes. Each photodiode detects the scattered light power from a small volume of the light sheet. The diameter of its cross section is about 0.93 mm, due to the fibres’ diameter of 400 µm and the magnification factor 14/6 of the optics. The numerical aperture of the optical set-up is 0.09.

The fibres can be arranged freely in accordance with the measurement task. We designed two fibre

![Fig. 7 Schematic set-up of a FM-DGV array system](image-url)
holders: one for 1d measurements and one for 2d measurements. The linear arrangement provides velocity profile measurements at 25 point in a row, separated each by about 1 mm. The array arrangement provides 5 x 5 velocity field measurements. The row and column distance equals 2.9 mm here. First measurements have been conducted with the 1d arrangement as shown in fig. 8, since the light intensity of the light sheet can be maximized by reducing the light sheet height down to 1 mm for maximum signal to noise ratio.

The assembly of the avalanche photodiode (APD) array is partly shown in fig. 9. The high voltage module generates about 150 V for biasing all APD elements. It is connected to five APD modules (one is shown in the picture as an example) containing five APDs and transimpedance amplifiers each. The transimpedance amplifiers are self-designed and well adjusted to the requirements of the FM-DGV system: a high sensitivity and a low noise spectral density for detecting low light power signals, a sufficient bandwidth in order to resolve the first and second order harmonic and low signal crosstalk.

The signal crosstalk between two channels of one APD module equals -80 dB at 100 kHz. As a result of the chosen modulation frequency of 100 kHz, the original photo detector bandwidth of 25 MHz could be reduced by approximately two orders of magnitude. Hence, the first and second order harmonic still can be resolved, but a low noise amplifier and a high gain could be used for the
transimpedance stage. The frequency response of the seventh APD element is shown in fig. 11 as an example indicating a cut-off frequency of 440 kHz. This lead to a minimum noise equivalent power of 35 fW/√Hz compared to previously 260 fW/√Hz, so the minimum resolvable light power signal is now one seventh smaller. The detector sensitivity at 100 kHz was increased from 2.6 MV/W to about 232 MV/W ensuring that noise e.g. resulting from the analogue to digital conversion remains negligible. The measured sensitivity of all 25 APD elements at 100 kHz is given in fig. 10. It varies within 170 MV/W and 310 MV/W due to the different characteristic of each APD. However, this variation does not disturb the measurement results, because the influence of the detector sensitivity is eliminated by the division of the first and second order harmonics, which both are directly proportional to the sensitivity. The quotient of the sensitivities at 100 kHz and 200 kHz may vary between the different APD elements, but can be finally calibrated.

The 25 output voltage signals of the APD array are acquired by four sampling boards as parts of a whole computer based data acquisition system. The four sampling boards allow synchronous 14 bit sampling of 26 channels up to 50 MS/s. Usually, a sampling rate of 2 MS/s is applied to prevent aliasing of the detector signals, which would degrade the signal to noise ratio. Together with the current memory of 16 MS per channel (which can be expanded in future if necessary), we can record continuously up to 8 s.

As result an experimental set-up of an FM-DGV measurement system consisting of a frequency modulated diode laser, caesium absorption cells and a fibre coupled APD array with 25 elements was described. Hence, the spatial resolution of the system is given and we now focus on the temporal resolution of it. As part of this section we subsequently describe the maximum achievable temporal resolution, whereas measurement results referring to this matter are given in the next section.

In contrast to slow CCD cameras with frame rates typically below 50 Hz, our APD elements have a much higher bandwidth. Although this in general means less sensitivity and higher noise spectral densities, we can achieve higher input signals per ‘pixel’ due to the lower spatial resolution in comparison with CCD cameras. Thus we expect a higher signal to noise ratio and the capability of time resolved measurements. The minimum measurement time equals one modulation period, since at least one period is necessary for determining the harmonic amplitudes according equation (4). Hence, the measurement rate \( f_{\text{meas}} \) is limited by the modulation frequency \( f_m \):

\[
f_{\text{meas}} \leq f_m.
\]  

From this conclusion, the current maximum measurement rate equals 100 kHz and is sufficient for many flow applications. If necessary, the modulation frequency can be increased further. The diode laser itself can be modulated up to 5 MHz or up to several GHz using a Bias-T, respectively, and thus constitutes no significant limitation here. A higher modulation frequency would require a different lock-in amplifier with higher border frequency for laser frequency stabilization and maybe new detector designs with higher bandwidths. However, a larger detector bandwidth will generally lead to higher noise equivalent powers and therefore should not exceed the current setting further. Decreasing the modulation frequency would allow lower detector bandwidth, but will degrade the maximum temporal resolution and will lead to higher measurement uncertainties due to fluctuations of the scattered light. The modulation frequency of 100 kHz was therefore chosen as a tradeoff between sufficient time resolution, minimum detector noise and minimum measurement uncertainty due to scattered light fluctuations.

5. Measurement results

In this section, measurement results demonstrating the measurement capabilities of our FM-DGV
system concerning the time resolution and the corresponding measurement uncertainty are presented. The calibration at a rotating glass disc is not described here, but can be found in [4].

Firstly, the measurement of a nozzle flow was conducted 2 cm from the nozzle outlet to avoid disturbing light reflections. The nozzle diameter is 1 cm. The modulation frequency was chosen to 80 kHz and a single APD element was applied together with traversing techniques. For one velocity value, 16000 samples of the detector signal were acquired with a sampling rate of 1 MHz. For statistics, the measurement at each position was repeated 25 times. The average radial velocity profile of the nozzle flow with about 23 m/s maximum velocity was additional measured with a laser Doppler anemometer (LDA) for validation. The results are shown in fig. 12. Both profiles qualitatively coincide well. Excluding the boundary positions, the deviations are below 0.4 m/s. The remaining errors are mainly due to the in-stationary of the flow, because the nozzle was originally designed for higher speeds and the FM-DGV and LDA measurements were obtained in sequential order. The minimum velocity standard deviation at the flow centre was 0.1 m/s, which also includes the flow remaining flow turbulence of about 5 %. The velocity standard deviations achieved with FM-DGV and LDA are both given in fig. 13. Due to the longer measurement time with LDA and the flow instability, the measured velocity standard deviation is higher than with FM-DGV. Furthermore, a spatial averaging is done by the DGV technique since multiple scattering particles are always evaluated instead of one single particle. Both results indicate correctly the rising turbulence at the edges of the nozzle flow, but the standard deviations of the FM-DGV measurement do not decrease finally. This is due to a lower seeding concentration, which reduces the scattered light power and thus increases the measurement uncertainty. The measured velocity field of the nozzle flow with about 17.7 m/s maximum velocity is shown in fig. 14. In the flow centre, the minimum velocity standard deviation was 0.04 m/s.

The measurement uncertainties were observed to be strongly dependent on the scattered light power. Therefore an investigation of the achievable measurement uncertainty w.r.t. the scattered light power was accomplished at a rotating glass disc as calibration object. The results achieved with one APD having a minimum noise equivalent power (NEP) of 260 fW/√Hz and one APD element of the improved detector array with a minimum NEP of 35 fW/√Hz are given in fig. 15. The measurement time was 16 ms. Additionally, the estimated minimum measurement uncertainty (Cramér-Rao lower bound, CRLB) based on thermal noise of the detectors and quantum shot noise are shown [6]. For low scattered light powers below 10 nW, which is usually the case for flow measurements, the velocity standard deviation is approximately indirect proportional to the
scattered light power and coincides well with our estimations. The case of higher scattered light powers is less important for flow applications, but as can be seen needs consideration of further error sources, e.g. laser frequency variations.

The velocity standard deviation w.r.t. time resolution was subsequently investigated and is given in fig. 16. Here, a detector signal from a nozzle flow was sampled with a rate of 2 MHz for a time interval of 2 s. The velocity estimation from subsequent signal parts with different lengths provides the time dependency of the measurement uncertainty. The resulting velocity standard deviations were normalised by the scattered light power according the previously discussed influence of the scattered light power. The measurement uncertainty was found to be approximately indirectly proportional to the square root of the temporal resolution. According to the measurement results, it can be estimated by

$$\sigma_v = \text{std}(v) = \frac{0.012 \text{ m/s}}{P_s/nW \cdot \sqrt{T/s}}$$

with $P_s$ as scattered light power and $T = N \cdot T_a$ as measurement time for one velocity value.

![Fig. 14 FM-DGV velocity field measurement of a nozzle flow](image)

The velocity standard deviation w.r.t. scattered light power $P_s$ at rotating glass disc ($T = 16$ ms) (APD 1: NEP = 260 fW/√Hz, APD2: NEP = 35 fW/√Hz)
This experimental result could be validated in good approximation by a derivation of the Cramér-Rao lower bound [6]. The deviations from this relation are assumed as a result of temporal fluctuations of the scattered light. In contrast to conventional DGV, where spatial intensity gradients can cause large errors due to image misalignment, the FM-DGV technique is sensitive to temporal scattered light fluctuations [4]. However, it can be significantly reduced by increasing the modulation frequency.

After the current FM-DGV system performance concerning temporal resolution and measurement uncertainty was presented, we now describe the array measurement results of a time-varying flow in a wind tunnel experiment. A rod was attached to a chopper as turbulence generator and periodically crossed a laminar flow perpendicular. The measurement took place about 7 cm downstream, the nozzle diameter amounted 10 cm, the free jet mean velocity was 9.6 m/s. The velocity spectra of three channels (linear array arrangement, separated by 3 mm) as well as one Hot-Wire comparison measurement are shown in fig. 17. The FM-DGV sampling rate again was 2 MHz. 4000 samples served for measuring one velocity value, which represents a measurement rate of 500 Hz. The overall measurement duration was 2 s. The periodicity of the flow could be correctly resolved and exactly matched the chopper frequency of 12 Hz. Higher order harmonics up to 150 Hz were identified in good agreement with the Hot-Wire measurement. The remaining deviations of < 0.1 m/s can have different reasons, e.g. the different velocity direction sensitivity of DGV and How-Wire technique. Actually, the measured velocity amplitudes with FM-DGV had the tendency to be smaller than the Hot-Wire results, which supports this thesis. However, the noise level of both techniques is similar, demonstrating the potential of FM-DGV for multi-point velocity measurements with high temporal resolution for e.g. turbulence analysis.

![Fig. 17 a) Measured velocity spectra of turbulent flow with FM-DGV (APD-Array) and Hot-Wire Anemometer (HWA), b) cut-out of the measured velocity spectra (The values represent the real amplitude of an oscillation similar to equation (4).) 6. Conclusions]  
A Doppler Global Velocimeter with sinusoidal laser frequency modulation (FM-DGV) with 5x5 pixels and 100 kHz measurement rate each was presented as a new tool for 3c2d turbulence spectra study, if high seeding concentration is possible. It consists of a diode laser emitting at 852 nm for generating a laser light sheet, caesium absorption cells and a fibre coupled APD array with 25 elements. The velocity dependent Doppler frequency shift of the light scattered on particles in the flow thus can be measured by evaluating the quotient of the first and second harmonic order amplitude of the detector signals. A reference detector unit for measuring the scattered light power is not necessary, since the mean scattered light power is eliminated by the division. Hence, image
misalignment and common beam split errors do not occur. By reducing additionally the light sheet height and the lateral spatial resolution, respectively, high scattered light powers can be achieved. This allows velocity measurements with lower statistical measurement uncertainty and high temporal resolution. The high bandwidth of the APD array in contrast to usually applied CCD cameras is crucial for this purpose.

The maximum measurement rate was found to be equal to the modulation frequency, which is currently 100 kHz. The FM-DGV measurement uncertainty was demonstrated to be indirectly proportional to the scattered light power and the square root of the measurement time. This illustrates the need for high light powers, when a high temporal resolution and a low measurement uncertainty is desired. In a nozzle flow, a minimum standard deviation of 0.04 m/s was achieved with about 20 nW scattered light power and 16 ms temporal resolution. In a wind tunnel experiment about 970 pW scattered light power could be achieved, due to a lower seeding concentration, thus a velocity standard deviation down to 0.28 m/s and a measurement rate of 500 Hz can be currently attained. The velocity spectra of a turbulent flow were finally measured using the linear arrangement of the fibre coupled APD array and successfully validated by comparison measurements with a Hot-Wire anemometer. In summary, for the first time velocity turbulence spectra were measured by DGV. Up to 50 kHz bandwidth was achieved. Hence, new application fields in fluid mechanics can be opened.

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8. References


