Planar velocity measurements of unsteady spray flows with kHz rate using a micro scanner and a high speed camera

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Abstract In order to optimize fuel injection processes, the fuel spray velocity field has to be resolved in time with a high temporal resolution of at least 1 ms. For analyzing the unsteady behavior of each single fuel injection cycle, a high measurement rate is additionally required. While current measurement system usually only meet the first requirement of a high temporal resolution, time-resolved particle image velocimetry (PIV) systems are capable of achieving sufficiently high measurement rates. However, Doppler global velocimetry (DGV) systems are either too slow or is restricted to velocity profile (1d) measurements. Since DGV is considered to be a useful alternative or complement to PIV due to its high optical robustness, a DGV system based on laser frequency modulation (FM-DGV) capable of achieving line rates up to 100 kHz is enhanced by a micro scanner and a high-speed camera to yield planar (2d) measurements with measurement rates of ≥1 kHz. As a result, respective spray flow measurement are presented to analyze the unsteady spray behavior. The flow fields are visualized in time, the transient behavior at the end of the spray actuation is resolved and characteristic spray oscillations at 320 Hz - 340 Hz are identified by a short-time Fourier analysis. Hence, the enhancements of the FM-DGV technique allow analyzing unsteady spray phenomena.

1. Introduction

1.1 Motivation, state-of-the art and aim

The optimization of spray flows is highly relevant for industrial applications. For instance in order to improve the combustion of liquid fuels, the fuel injection process has to be understood more detailed. For this purpose, measurement techniques are required to measure the fuel spray velocity field with a high temporal resolution below one millisecond [1,2]. It is common to synchronize the measurement with the injection start time and, due to a low measurement rate, to measure only once per injection cycle [3]. By repeating the measurements over many injection cycles while varying the time delay between the injection trigger and the measurement, the mean temporal behavior of the spray flow field can be reconstructed. However, possibly occurring unsteady effects during a single injection remain hidden. In order to resolve unsteady spray flow effects, a measurement technique with a high temporal resolution ≤ 1 ms and a high measurement rate ≥ 1 kHz is required.

While time-resolved particle imaging velocimetry (PIV) is capable of achieving sufficiently high measurement rates [4,5], current Doppler global velocimetry (DGV) systems are either too slow [6,7] or are essentially restricted to velocity profile (1d) measurements [8,9]. However, DGV is considered to be a useful alternative technique or complement to PIV, because of its higher optical robustness with respect to image distortions and its capability to resolve the out-of-plane velocity component with a single observation direction [10,11,12,13,14]. For these reasons, a DGV measurement system is desired providing planar (2d) measurements with a measurement rate ≥ 1 kHz.
1.2 Our approach

Planar measurements with kHz rate can be achieved by using a laser frequency modulated DGV (FM-DGV) system that is extended by a micro scanner or a high-speed camera.

The first approach of using a micro scanner is possible, because the FM-DGV system is capable of achieving an extraordinary measurement rate up to 100 kHz [9]. Due to the high measurement rate, FM-DGV was recently applied to investigate the tip leakage flow in turbines [15], to comprehend the sound-turbulence interaction that causes acoustic damping [16,17] and to study flow oscillations in a swirl-stabilized flame [18] using a linear detection array. Now applying a depth scanning with 1 kHz, planar measurements with a rate of 1 kHz will be obtained without moving the linear detector array. This approach is especially useful for applications with limited optical access such as in high-pressure combustion chambers, motors and turbomachines. The size of the micro scanner unit is only about 10 mm squared, so that it can be applied in endoscopes.

The second approach is to use a high speed-camera, because new cameras with increased sensitivity and high frame rates up to 1 MHz are available. For, the current FM-DGV setup a frame rate of 400 kHz is required according to the measurement principle and the Nyquist sampling theorem. This requirement is met by new high-speed cameras.

After briefly recapitulating the FM-DGV measurement principle and the 1d setup below, both 2d approaches are described subsequently. For each approach, the working principle, the realized setup, the measurement characteristics and the obtained measurement results at a spray flow are described. Finally, an outlook of the measurement technique and a summary of the achieved progress are given.

2. FM-DGV principle and 1d measurement setup

The general DGV measurement principle is based on illuminating seeding particles in the flow with a narrow bandwidth laser, whose center frequency is stabilized, and detecting the Doppler frequency shift of the scattered light [6]. In order to measure the velocity dependent Doppler frequency

$$f_D = \frac{(\bar{v} - \overrightarrow{d}) \cdot \overrightarrow{v}}{\lambda}$$  

(1)

Where $\bar{v}$ is the particle velocity, $\lambda$ the laser wavelength, $\overrightarrow{d}$ the observation direction and $\overrightarrow{v}$ the illumination direction, a molecular filter is used as a frequency-to-intensity converter and a photo detector array or camera for light intensity detection. Since the transmitted light intensity through the molecular filter depends also on the scattered light intensity, a reference measurement is performed either directly by using a beam splitter and a second photo detection unit [6] or indirectly from consecutive measurements with laser frequency modulation [8,19,20]. Note that according to Eq. (1), the velocity component along the direction of the sensitivity vector ($\bar{v} - \overrightarrow{d}$) is measured. Three component measurements require three different illumination or observation directions. In the present article, only one component measurements are performed with the FM-DGV setup.

Using sinusoidal laser frequency modulation (FM) with the modulation frequency $f_{mod}$, the laser center frequency is stabilized to the resonance frequency of the molecular absorption filter. From the time signals of the photo detection unit, the amplitudes $A_1, A_2$ of the first (frequency $f_{mod}$) and second (frequency $2f_{mod}$) order harmonics are determined. Since both amplitudes are directly proportional to the mean scattered light intensity, the latter is canceled out when evaluating the...
amplitude ratio \( q = A_1/A_2 \). Since \( q \) only depends on the desired Doppler frequency, it is used as measurand. The relation between \( q \) and the measured velocity component is finally established by a calibration, for instance by using a rotating glass disk with a rough surface and with known rotation frequency as scattering calibration object.

The arrangement of an FM-DGV system setup with beam illumination for the 1d spray flow measurement is depicted in Fig. 1. The illumination direction \( \vec{i} \) and the observation direction \( \vec{o} \) are aligned perpendicular. The sensitivity direction, i.e. the bisecting line between the vectors \( \vec{o} \) and \(-\vec{i}\), coincides with the main spray flow direction. Since the applied FM-DGV system is equal to the one described in [17], only the main features of the setup are briefly summarized: As laser light source, a power amplified diode laser from the company Toptica Photonics is used. The modulation frequency \( f_{\text{mod}} \) of the laser is 100 kHz, which gives the maximum measurement rate. The laser wavelength amounts to 895 nm, which corresponds to the cesium D1 absorption line. Consequently, cesium vapour is used as absorber in the molecular filters. One filter is used for stabilizing the laser center frequency and one filter is located in the detection unit for measuring the frequency of the scattered light, which contains the Doppler frequency. For multiple channel photo detection, an array of 25 avalanche photo diodes is used having low noise (minimum noise equivalent power of 39 fW/Hz\(^{1/2}\)) and a sufficiently high bandwidth of 450 kHz. The latter allows to detect the first and second order harmonics of the scattered light signals transmitted through the absorption cell. According to [8], the amplitude of the sinusoidal laser frequency modulation was chosen to be about 55 % of the full width at half maximum of the spectral transmission profile of the molecular filter, which provides minimum uncertainty.

![Fig. 1 FM-DGV setup for high-speed profile measurements (1d)](image1)

![Fig. 2 Visualized spray flow](image2)

The measurement test object is a commercially available deodorant spray with a measured nozzle exit diameter of about 400 µm. Based on a visualization of the spray flow, the full opening angle of the spray flow is roughly estimated to be 30°, see Fig. 2. The measurement region in case of no scanning is located 15 mm off the nozzle exit. The respective z-position is defined as \( z=0 \). The center of the spray in the plane \( z=0 \) is further defined as \( x=0, y=0 \). At \( z=0 \), the extent of the spray in x-direction is 11 mm along the measurement line and is completely acquired with the measurement setup.
3. High-speed planar FM-DGV using a micro scanner

3.1 Working principle and setup

The key idea is to realize a depth scanning (in z-direction) by slewing the laser beam with an oscillating mirror while continuously performing velocity profile measurements (along x-direction) with a measurement rate higher than the scan rate. The principle and the respective setup is depicted in Fig. 3. The scan position $z(t)$ is monitored using a position sensitive device (PSD), which allows to assign the z-position to each measured velocity profile. As a result, the velocity field in the x-z-plane is measured.

As scanning device, a 1d micro scanner from the Fraunhofer Institute for Photonic Microsystems (IPMS) is applied and shown in Fig. 4 [21]. The chosen scanner has a relatively large aperture of 3 mm for easy optical alignment and is driven by electrostatic forces. As perspective, such micro mechanical scanning mirrors offer high scan frequencies up to 50 kHz, a high degree of miniaturization and the potential for low cost manufacturing at high volumes. Furthermore, the single crystalline material shows nearly ideal elastic behavior, excellent long-time stability without any fatigue and high mechanical fracture strength. These features allow applications in harsh industrial environment, where vibrations and shocks can occur. The small size of the micro scanners also offers the perspective for embedding scanners in endoscopes for light supply. This is useful when measurements inside machines are required, e.g. when investigating the fuel injection in a motor cylinder.

3.2 Characteristics

The micro scanner is operated at a scan rate of 1 kHz yielding the required imaging rate. Since the 1d velocity measurement is performed with 100 kHz, 50 z-positions are resolved during each forward and backward scan. Currently, only the data from the forward scan is processed. Having 25 elements of the linear detector array in x-direction, the resulting velocity images consists of 25 x 50 pixel. Due to the geometrical arrangement of the setup and the tilting amplitude of the scanner mirror of 0.6° at 1 kHz, the total field of view is 25 mm x 12 mm. The spatial resolution is x- and y-direction amounts to 1 mm, while the spatial resolution in z-direction is approximately 240 µm.
Since the scanned depth range is smaller than the depth of focus of the observation unit, no degradation of the spatial resolution or the signal power occurs during the scanning. However, the illumination direction varies over the field of view, which can cause errors up to 2% (calculation see [17]). Since these errors are systematic, they are corrected by taking the different illumination directions into account.

The random error is the same as for the non-scanning FM-DGV except for the different temporal resolution or exposure time. Assuming high scattered light powers over 1 nW, the random error amounts to [17]  
\[ \sigma_v = \frac{3 \, \text{mm/s}}{\sqrt{T}} \]  
with \( T \) as exposure time. Experimental results of the velocity standard deviation vs. the exposure time are shown in Fig. 5, left. These measurements were performed at a free jet flow (< 2% turbulence intensity) using seeding particles. As a result, the random error for scanning and non-scanning FM-DGV can be approximated by Eq. (2). The deviation from the estimation for higher exposure times is due to the unsteadiness of the jet flow and the longer measurement time, respectively, that is required for the scanning operation to yield exposure times equal to non-scanning operation. In Fig. 5, right, the velocity standard deviation curves are plotted w.r.t. the measurement time. Due to scanning, the cumulative exposure time is 100 times lower than with non-scanning FM-DGV when considering equal measurement times. For this reason, the random error is increased by about one order of magnitude yielding a random error of about 1 m/s for the imaging rate of 1 kHz.

![Fig. 5 Random error of FM-DGV vs. exposure time (left) and vs. measurement time (right) measured in a free jet flow with and without scanning](image)

3.3 Planar spray flow measurements with kHz rate

Despite the decreased exposure time, the measurement uncertainty is sufficiently low for investigating unsteady effects in spray flows. For visualization, two arbitrarily chosen images from the planar FM-DGV measurements at the spray with 1 kHz measurement rate are shown in Fig. 7. The spray velocity at the center is about 25 m/s in time and varies strongly in time.

![Fig. 6 Example images of the measured spray flow with scanning FM-DGV (1 kHz rate)](image)
In order to demonstrate the capability of resolving transient flow phenomena, the velocity time series at the end of spray actuation is shown in Fig. 7, left, from the spray center \((x = 0, z = 0)\) as an example. For comparison, a repeated measurement without scanning is additionally shown in Fig. 8, left. Of course the results are not identical, because two different spray actuation cycles were measured and the spray was manually actuated. Also note the different measurement rates for scanning (1 kHz) and non-scanning (100 kHz) operation. However, both data sets agree qualitatively very well, indicating strong velocity oscillations during the spray actuation and a rapid velocity decrease when the spray actuation button is released. Hence, the transient spray behavior is resolved.

In order to determine characteristic frequencies of the velocity fluctuations, a local Fourier analysis during the spray actuation over a time segment of 0.5 s is performed. The results are shown in Fig. 7, right, and Fig. 8, right, respectively. Both spectra agree qualitatively very well indicating a maximum oscillation at 340 Hz. To summarize, planar spray flow measurements with kHz rate are possible with scanning FM-DGV allowing spray flow visualization, investigation of transient phenomena and studying local flow oscillations.

![Fig. 7 Example time series (left) measured with scanning FM-DGV (1 kHz measurement rate) at the end of the spray actuation and short time Fourier analysis over 0.5 s during spray actuation (right)](image)

![Fig. 8 Example time series (left) measured with non-scanning FM-DGV (100 kHz measurement rate) at the end of spray actuation and short time Fourier analysis over first 0.5 s during spray actuation (right)](image)

4. High-speed planar FM-DGV using a high-speed camera

4.1 Working principle and setup

The second key idea is to use a new high-speed camera, which offers high frame rates up to 1 Mfps. A high frame rate is important to resolve the first and second order harmonic according to the FM-DGV measurement principle. With 1 Mfps the maximum laser modulation frequency amounts to 250 kHz, which is also the maximum in principle achievable measurement rate of the high-speed planar FM-DGV system. In order to finally obtain planar measurements, a laser light sheet instead of a laser beam is used. For this purpose, a cylinder lens optic is applied, see Fig. 9. As a result, illumination and detection of the setup is extended from 1d to 2d allowing planar measurements in the x-y-plane.
4.2 Characteristics

In order to achieve a frame size of 256 x 128 pixels (pixel size 28 µm x 28 µm), the camera is operated with a frame rate of 250 kHz. For having 10 samples per modulation period, the laser modulation frequency is set to 25 kHz. Hence, a maximum measurement rate of 25 kHz exists, but due to averaging only 1 kHz or 5 kHz is used.

The (lateral) field of view amounts to 16.7 mm x 8.4 mm. Since an 8 x 8 pixel binning is applied, the velocity image consists of 32 x 16 superpixel and the lateral resolution in x- and y-direction is 520 µm. The z-resolution is determined by the light sheet thickness, which is 1 mm.

Similar to the scanning FM-DGV, where the depth scanning of the laser beam lead to different illumination angles, the expansion of the laser beam to a laser light sheet results in different illumination directions over the entire field of view. The beam focus is at x = -100 mm and the light sheet is about 8 mm high in the field of view finally yielding a systematic error below 0.3 % (calculation see [17]), which is considered to be negligible here.

A high signal to noise ratio is important especially when using a camera, because in addition to the desired temporal resolution of \( \leq 1 \text{ ms} \) also the increase in the number of channels/pixels leads to a reduced available light energy per measurement point. Although the camera was chosen because of its relatively high quantum efficiency of about 20 % for the laser wavelength of 895 nm, the reduced available light energy in general contradicts the aim of achieving a low uncertainty. For the applied frame rate and the applied signal threshold (amplitude \( |A_2| \) must be greater than 7.5 % of the full well capacity of one superpixel), a maximum random error of \( 1.7 \text{ mm/s} \cdot (T / 1 \text{ s})^{-1/2} \) is calculated when considering read-out noise only. Neglecting shot noise in comparison to read-out noise and including the further random error described by Eq. (2) yields in total

\[
\sigma_v = \frac{3.5 \text{ mm/s}}{\sqrt{T \cdot t^2}}.
\]

As a result, the random error of the FM-DGV system with the high-speed camera is almost equal to the random error of the FM-DGV system operated with the linear detector array.
4.3 Spray flow measurements with kHz rate

Two arbitrarily chosen samples of the measured flow field are shown in Fig. 11 for visualizing a cross-section of the spray flow field. The measured flow field appears to be elliptical, which is mainly due to the fact that the angle between the spray nozzle and the z-axis amounts to 45 °, cf. Fig. 9. A maximum velocity occurs at the spray center, which is approximately at \( x = 0, y > 1 \text{ mm} \). As a result, the measurements with the scanning FM-DGV were performed at \( x = 0, y = 0 \) below the maximum, which explains the lower maximum velocities in comparison to the camera measurement. Here, a maximum velocity of 40 m/s and a large velocity gradient of approximately 8 m/s per mm are visible.

![Fig. 11 Example images of the measured spray flow with high-speed camera FM-DGV (1 kHz rate)](image)

In order to demonstrate, that the analysis of unsteady flow phenomena is also possible with the planar FM-DGV with high-speed camera, the velocity time series and the local amplitude spectrum from 0.5 s during the spray actuation are given for the signal at \( x = 0, y = 0 \) in Fig. 12, left and right, respectively. The results of the spray actuation cycle are not directly comparable with Fig. 7 and 8, because it is a different spray actuation and was performed after the experiments with the scanning FM-DGV, i.e. the spray was less full (less pressure). However, the velocity decrease at the end of the spray actuation is well resolved as is (amongst others) an oscillation frequency at 320 Hz. The slightly lower oscillation frequency and the lower oscillation amplitude compared to the previous experiments agrees with the decreased spray pressure because of its sequential actuation. As a result, the FM-DGV technique can be combined with a high-speed camera to yield planar spray flow measurements with kHz rate for investigating unsteady phenomena.

![Fig. 12 Example time series (left) measured with non-scanning FM-DGV (5 kHz measurement rate) at the center of the spray at the end of spray actuation and short time Fourier analysis over first 0.5 s (right)](image)

5. Outlook: High-speed volumetric FM-DGV measurements

The proposed camera technique is especially attractive for endoscopic measurements e.g. in motors or inlets where imaging fiber bundles have to be applied. DGV techniques are robust with respect to the degradation of image resolution when using imaging fiber bundles [12,22,23]. Furthermore, it seems feasible to combine both presented approaches of depth scanning and planar detection with the high-speed camera to obtain volumetric (3d) FM-DGV measurements. Thereby, the measurement rate is determined by the scan rate, which is currently 1 kHz.
When using the high-speed camera, the FM-DGV signal evaluation can also be combined with a PIV algorithm to measure the in-plane velocity components [10,11]. This would allow to extend the system capabilities from simultaneously measuring one component (1c) to all three velocity components (3c).

However, some challenges must be considered in future work. In order to achieve a low uncertainty for planar or even volumetric measurements with 1 kHz measurement rate, a high scattered light power (high laser power per voxel, high numerical aperture, high number of scattering particles per voxel, high scattering efficiency) is necessary. For the spray flow measurements the spray droplets were assumed to be larger than 10 µm, because of the nozzle diameter of 400 µm, so that a high scattering cross section exists. The application of the proposed technique to other sprays or with other scattering particles have to be studied further. Attention should also be given to the fact, that fluctuations of the scattered light signal which are faster than the laser frequency modulation can lead to an increased measurement uncertainty [24]. Especially with respect to analyzing fast unsteady phenomena, thus, reducing the laser modulation frequency for increasing the number of pixels per frame has to be balanced by respecting the need for a fast laser frequency modulation.

### 6. Summary

Both measurement setups (micro-scanner and high-speed camera) successfully provided time-resolved velocity field measurements in a spray flow without repetition of the spray cycle. During each single run, the same characteristic oscillations with 320 Hz – 340 Hz were identified and the decrease of the velocity at the ending of the spray injection was resolved. Hence, the technique is applicable for analyzing unsteady spray phenomena.

Using the micro scanner, 25 x 50 pixels are resolved with a measurement rate of 1 kHz in the plane along the detection axis (depth scanning). With the high-speed camera, a maximum measurement rate of 5 kHz is demonstrated for an image of 32 x 16 pixels in the plane perpendicular to the detection axis (lateral imaging). The random error of the velocity for the 2d measurements is about one order of magnitude higher than for 1d measurements when considering equal measurement rates, because the light is either distributed in time (scanning beam) or in space (light sheet). A typical value of the velocity standard deviation is about 1-2 m/s for a measurement rate of 1 kHz.

Using a high-speed camera allows combined FM-DGV and PIV measurements to obtain all three velocity components in the measurement plane at once with kHz rate. As outlook, a three component volumetric measurement (3d3c) seems feasible when combining the high-speed imaging and the depth scanning technique.

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