Volumetrische High-Speed-FM-DGV-Messungen mit einer Hochgeschwindigkeitskamera (1 Mfps) zur Analyse instationärer Sprays

Volumetric measurements using High-Speed-FM-DGV with a high-speed camera (1 Mfps) for analyzing unsteady sprays

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Instationäres spray, transiente Strömung, Hochgeschwindigkeitskamera, hohe Messrate
Unsteady spray flow, transiente Strömung, high-speed camera, high measurement rate

Summary

In order to investigate complex unsteady spray flows such as fuel injections, the measurement technique is required to acquire a measurement volume with a high temporal resolution of ≤ 1 ms. For resolving unsteady phenomena in a single spray cycle, a high measurement rate of ≥ 1 kHz is additionally required. For this reason, the Doppler global velocimetry with frequency modulation (FM-DGV) is enhanced towards a volumetric measurement. Thereby, a Mfps high-speed camera with high sensitivity is employed for fast planar measurements in combination with a depth-scanning of the laser light sheet. As scanner, a micro mechanical mirror is used, which provided a scan rate of 1 kHz. As a result, volumetric measurements at an unsteady spray with a volume rate of 1 kHz are performed, which demonstrate the measurement capabilities of the enhanced FM-DGV measurement setup for investigating unsteady phenomena such as transients of injection processes.

1. Introduction

In order to be able to investigate the complex and unsteady flow behavior of sprays, volumetric flow measurement techniques with a high temporal resolution ≤ 1 ms are required, see Kostas et al. 2009 and Müller et al. 2010. Additionally, a high measurement rate ≥ 1 kHz is desired for resolving flow oscillations and flow transients. One approach for achieving high measurement rates is to apply Doppler global velocimetry with laser frequency modulation (FM-DGV). With the current FM-DGV system setup, 25 measurement points can be measured simultaneously along a line (1d) with measurement rates up to 100 kHz as reported e. g. by Fischer et al. 2007, 2009 and 2013a. In principle, cameras can also be employed for photo detection to allow imaging (2d) FM-DGV measurements as shown by Müller et al. 2007. Due to the required high camera sensitivity, only charge coupled device (CCD) cameras were applied yet. This limits the maximal measurement rate to a few ten Hz, which is insufficient. Furthermore, volumetric (3d) measurements currently require a time-consuming traversing of the measurement system or the experiment. As a result, only stationary and quasi-stationary (for instance periodic) flow phenomena can be investigated, see Fischer et al. 2013b, Haufe et al. 2013. In order to allow investigations of unsteady spray flows, the FM-DGV technique has to be enhanced toward volumetric measurements with a repetition rate of ≥ 1 kHz.

The aim of the present article is to report about volumetric FM-DGV measurements at unsteady spray flows with kHz rate. This is achieved by using a combined approach of a 1 Mfps high-speed camera for the lateral resolution and a micro-scanner for depth scanning. The key challenge is to cope with the low signal-to-noise ratio (SNR) due the short integration times and the read-out noise from the CMOS high-speed camera. Here, the measurement uncertainty is shown to be sufficiently low for resolving the unsteady spray flow in time.

2. Our approach: Principle and setup

Volumetric measurements with kHz rate are achieved by using a laser frequency modulated DGV (FM-DGV) system that is extended by a micro scanner and a high-speed camera, see Fig. 1. The fundamentals of the FM-DGV principle are described e. g. in Fischer et al. 2007. Here, a narrow band, single-frequency, fiber-coupled, power amplified diode laser with an output power of up to 600 mW is used as laser light source. The frequency modulated laser with a wavelength of 895 nm is compatible with cesium gas absorption cells, because cesium has an atomic resonance at 895 nm and, thus, can be used for edge demodulation at the respective spectral transmission curve.

For detecting the light scattered by the spray droplets, a new high-speed camera of type Phantom v1610 from Vision Research is applied, which offers high frame rates up to 1 Mfps. Using the camera enhances previous line measurements along one axis to planar measurement capability in lateral direction. A high frame rate is crucial, because the first and second order harmonic of the scattered light signals have to be resolved according to the FM-DGV measurement principle, see Fischer at al. 2007. Due to the maximum camera frame rate of 1 Mfps the maximum laser modulation frequency amounts to 250 kHz, which determines the maximum achievable measurement rate of the high-speed planar FM-DGV system. The chosen camera also offers a relatively high sensitivity for the laser wavelength of 895 nm with a quantum efficiency of about 20 % and a pixel size of 28 µm x 28 µm. For planar illumination, a laser light sheet is created with a cylinder lens optic. As a result, illumination and detection of the setup allows planar measurements in the x-y-plane, cf. Fig. 1.

The micro scanner is employed to realize a depth scanning (in z-direction), see Fig. 1. While slewing the laser beam with an oscillating mirror, planar velocity measurements are continuously performed with a measurement rate higher than the scan rate. The scan position z(t) is monitored using a position sensitive device (PSD), which allows to assign the z-position to each measured velocity image. As a result, the volumetric velocity field is obtained.

As scanning device, a 1d micro scanner from the Fraunhofer Institute for Photonic Microsystems (IPMS) is applied. It is driven by electrostatic forces and 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. The small size of the micro scanners also offers the perspective for embedding scanners in endoscopes for light supply. This is useful when endoscopic measurements inside machines are required, e.g. when investigating the fuel injection in a motor cylinder.

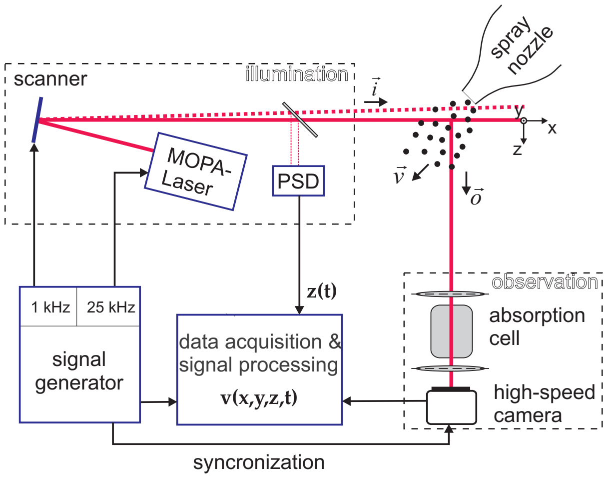

Fig. 1. FM-DGV setup for high-speed volumetric measurements (3d) using a kHz-micro-scanner (from the Fraunhofer Institute for Photonic Microsystems) and a Mfps high-speed camera (Phantom v1610)

The measurement 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- and y-direction is 11 mm and 8 mm, respectively, which is acquired with the measurement setup.

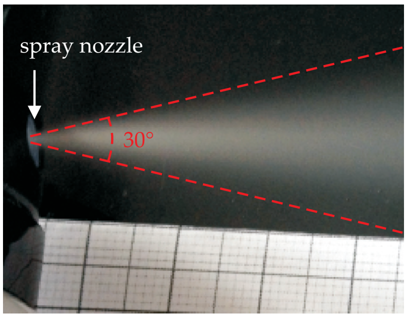

Fig. 2. Visualized spray flow

3. Measurement characteristics

High camera frame rates require a reduced frame size. As compromise between a high measurement rate (modulation frequency) and a sufficiently large field of view, the camera is operated with a frame rate of 250 kHz yielding a frame size of 256 x 128 pixels. An 8 x 8 pixel binning is then applied, which results in images with 32 x 16 superpixels. For having 10 samples per modulation period, the laser modulation frequency is set to 25 kHz. Hence, a maximum planar measurement rate amounts to 25 kHz.

The depth scanning is performed with a rate of 1 kHz. By evaluating the forward and the backward scan, 25 different depth positions are resolved. Hence, a volume of 32 x 16 x 25 superpixels is observed with a measurement rate of 1 kHz.

The laser light sheet is about 8 mm in height, which covers the (lateral) field of view in y-direction of 7.2 mm. The field of view in x-direction amounts to 14.3 mm. The lateral resolution in x- and y-direction is 450 µm. The z-resolution is determined by the light sheet thickness (560 µm) and the light sheet movement during one measurement due to scanning (≤820 µm), which is minimum 560 µm maximum 1100 µm. The scan width along z-direction is about 6.5 mm.

A high signal to noise ratio is important especially when using a camera, because in addition to the short integration times, also the spanning of a light sheet leads to a reduced available light energy per measurement point. Although the camera was chosen because of its relatively high quantum efficiency for the laser wavelength, the reduced available light energy in general contradicts the aim of achieving a low uncertainty. Due to the high-power laser, the moderate light sheet size and the pixel binning, an uncertainty of approximately

$$\sigma_v = \frac{0.03\, m/s}{\sqrt{T/s}} \qquad (1)$$

was achieved in calibration experiments and in experiments at a free jet nozzle. Here, T is the measurement time. Due to scanning, the actual measurement time per measurement point is 1/25-th of the measurement time without scanning. For the volumetric measurements with 1 kHz measurement rate, T amounts to 1/25 ms and, thus, the random error is 4.7 m/s. Despite the decreased light energy, the measurement uncertainty is sufficiently low for investigating unsteady effects in spray flows.

4 Measurement results

The volumetric mean velocity field (average over 500 time steps) and a snapshot (single time step) from the high-speed-3D-FM-DGV measurements at the spray are shown in Fig. 3. The mean spray velocity in the core region decreases rapidly with increasing distance from the nozzle exit. The maximum mean velocity is 45 m/s, which decreases over 8 mm along the spray main flow direction to 30 m/s. In addition, the spray velocity field widens with increasing distance from the nozzle exit as expected. In contrast to the mean velocity field, the snapshots (see example in Fig. 3, right) indicate fluctuations of the measured flow field, which vary strongly in space and time.

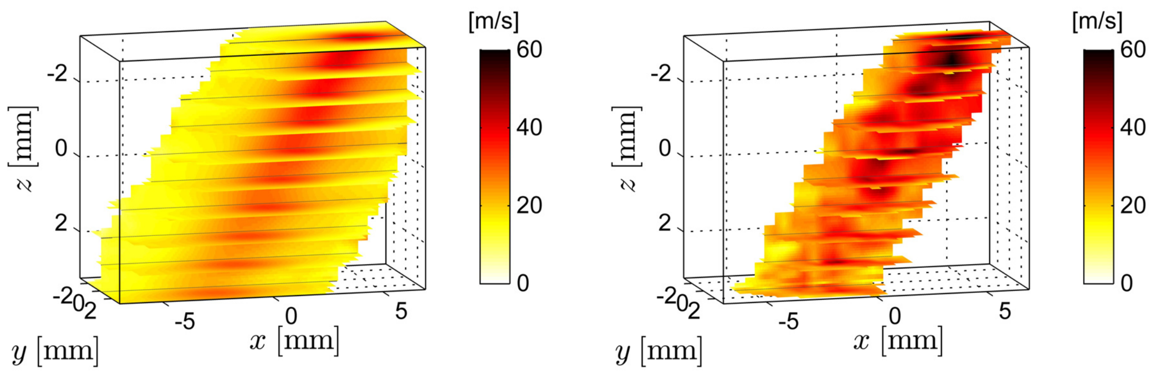

Fig. 3. Mean velocity field (left) and snapshot (right) of a volumetric spray measurement with 1 kHz measurement rate using FM-DGV

As an example of analyzing unsteady flow phenomena, the transient after the spray actuation ended is studied. The respective velocity time series of one single data point from the spray center region is shown in Fig. 4. In addition to the original dataset with 1 kHz measurement rate, the result of averaging over four subsequent samples is given in Fig. 4. Although velocity fluctuations are present, the tendency of the velocity decrease after t = 1.4 s is successfully resolved.

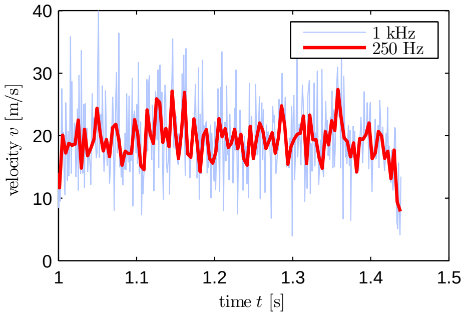

Fig. 4. Time series of a single measurement point at the end of the spray actuation showing the transient spray behavior

5. Summary

A high-speed camera and a micro-mechanical scanner were employed to yield volumetric FM-DGV measurements with a measurement rate of 1 kHz. The measured volume consists of 32 x 16 x 25 data points, while the spatial resolution is 450 µm x 450 µm x 1.1 mm. Although the noise of the CMOS-type high-speed camera is higher than that of formerly used avalanche photo diode arrays, temporal and spatial averaging can be applied to increase the signal-to-noise ratio. With the combined camera and scanner approach, the number of measurement points is increased by a factor of 512. The realized high-speed-3D-FM-DGV system was tested at a free jet and finally applied to an unsteady spray flow.

As a result of the high measurement rate, volumetric spray velocity data was obtained from a single spray actuation cycle. Studying the measured time series, the transient spray behavior at the end of the spray actuation was successfully resolved. The continuous acquisition of measurement data further allows to perform a Fourier analysis e.g. for identifying possible velocity oscillations, which should be considered next. Hence, the high-speed-3D-FM-DGV system is shown to be capable of investigating unsteady spray flow phenomena.

The proposed 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, see Nobes et al. 2004 and Willert et al. 2005. On the other hand, a combined FM-DGV and PIV measurements can be performed with the presented setup, cf. Wernet 2004 and Willert 2006. This would allow simultaneous measurements of all three velocity components with kHz rate for analyzing unsteady flows with limited optical access such as fuel injections in motors.

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