Imaging Laser Doppler Velocimetry using a High-Speed Camera

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Abstract Imaging Laser Doppler Velocimetry (ILDV) is a flow measurement technique which facilitates the measurement of one velocity component of a flow field in an imaging plane. It is an evolution of Heterodyne Doppler Global Velocimetry and may be regarded as the planar extension of the classical dual beam LDV by crossing two light sheets in the flow instead of focused laser beams. With different light sheet configurations different velocity components of the flow field can be measured. Seeding particles within the flow are illuminated with two light sheets from two different directions. The light scattered from the moving particles exhibits a frequency shift due to the Doppler effect. The frequency shift depends on the direction of the illumination and the velocity of the particle. With two different illumination directions the scattered light exhibits two different frequency shifts. The superposition of the two different frequency shifted signals creates interference on the detector and leads to an amplitude modulated signal wherein the modulation frequency depends on the velocity of the particle. This signal is detected using a conventional high speed camera and the acquired data is analyzed using an autocorrelation based data analysis technique. To demonstrate the feasibility of the technique the velocity distribution of a fully turbulent jet in water is measured with two different setups. In the first setup the light sheets are arranged such that the in-plane velocity distribution can be measured. This setup facilitates a simultaneous PIV measurement using the same high speed camera and the same image data set, therefore allowing a validation of the technique. The second setup measures the out-of-plane velocity distribution of the jet. Using this out-of-plane velocity measurement in combination with PIV a so called 2D3C measurement could be performed, that is a measurement of all three velocity components of the flow field in a plane.

1. Introduction

The measurement of flow velocity distributions based on optical Doppler shift detection remains an active field of research in flow diagnostics. By measuring the frequency shift of light scattered from moving particles Doppler Global Velocimetry (DGV) avoids some of the restrictions of Particle Image Velocimetry (PIV). Without the need for resolving individual particles, the method may be particularly well suited for large-scale applications. DGV techniques rely on the use of molecular line filters to convert the frequency shift into a change in intensity (Ainsworth et al. 1997; Elliott et al. 1999; Samimy et al. 2000) or phase (Landolt et al. 2009). The technique has been successfully applied in full scale wind tunnels (Beutner et al. 1998), high-speed flows (Smith et al. 1996) and combustion measurements (Roehle et al. 2000). With Heterodyne Doppler Global Velocimetry (HDGV) we proposed a new approach to measure global Doppler frequency shifts (Meier et al. 2009). In HDGV the flow is illuminated using a light sheet. The frequency shift of the light scattered from particles in the flow is demodulated using a reference beam derived from the same coherent light source and detected using a smart pixel detector array (SPDA, Beer et al. 2005). This setup can be seen as the planar extension of the well known reference beam LDV (Yeh et al. 1964). HDGV has demonstrated the feasibility of this concept but the measured velocities were limited to a maximum velocity of 2 mm/s. To extend this limited velocity range Imaging Laser Doppler Velocimetry (ILDV, Meier et al. 2012) uses a setup which represents the planar extension of dual beam LDV (vom Stein et al. 1969). Instead of crossing two focused laser beams from the same source, two light sheets are crossed allowing the measurement of Doppler shifts in a plane. With
two different crossed light sheet configurations either the out-of-plane velocity or one component of the in-plane velocity are measurable. Both HDGV and ILDV required a SPDA to demodulate the high frequency Doppler signal. In a SPDA the pixels of the detector do not only detect the light but also pre-process the data on pixel level. Due to the low overall frame rate and the pixel based pre-processing of the SPDA the measurement techniques were limited to the evaluation of steady (mean) flows only. With the recent development of high speed cameras featuring frame rates and resolutions comparable to the demodulation frequency of the SPDA a simpler technical approach becomes feasible. In contrast to the SPDA a high speed camera just records a stream of images without any pre-processing of the data. This allows recording the data required for a velocity measurement in a shorter time and therefore facilitates the measurement of unsteady flow fields.

2. Method

The frequency $v$ of the light scattered from an illuminated moving particle is shifted according to the Doppler equation (Eq. 1):

$$v - v_0 = v_d \frac{v}{c} (\vec{O} - \vec{I}) \cdot \vec{V}$$

(1)

The Doppler shift $v_d$ depends on the velocity and direction of motion $V$ of the scattering particle, the frequency $v_0$ and the direction the illumination $I$, the direction of observation $O$ and the speed of light $c$. Figure 1 shows the geometry of this scattering process indicating the arrangement of the vectors of Eq.1. As the Doppler shift $v_d$ is a scalar also only one component of the velocity can be measured, namely the component into the direction of $O - I$.

Figure 1: Geometry of the scattering process

In dual beam LDV and ILDV the particle is illuminated from two different directions $I_1$ and $I_2$. The light scattered in the direction of observation $O$ has two different frequency shifts $v_1$ and $v_2$. The interference of those signals on the detector results in the observable Signal $S$:

$$S = A_1^2 + A_2^2 + 2 A_1 A_2 \cos(2\pi(v_1 - v_2)t + \phi)$$

(2)

$A_1$ and $A_2$ denote the intensity of the scattered light of the two illumination directions and $\phi$ a random phase shift which can be assumed constant during the scattering process. The signal $S$ has a constant offset ($A_1^2 + A_2^2$) and is modulated by the difference of the two Doppler shifts. Using Eq. 1 this difference can be written as:

$$v_1 - v_2 = \frac{v_0}{c} (\vec{I}_2 - \vec{I}_1) \cdot \vec{V}$$

(3)

The modulation frequency of the signal $S$ does not depend on the observation direction but only on the arrangement between the two illumination directions and the velocity of the particle.
Eq. 3 can be further simplified, by using the crossing angle $\theta$ between $I_1$ and $I_2$ and the velocity component $v_p$ to

$$v_1 - v_2 = \frac{2 \sin(\theta/2)}{\lambda_0} v_p = \vec{\Sigma} \cdot \vec{V}.$$  \hspace{1cm} (4)

$\lambda_0$ denotes the wavelength of the illumination light source and $v_p$ is the component of the velocity $V$ into the direction of $I_2 - I_1$. The dependencies on the optical arrangement can also be collected into the sensitivity vector $\Sigma$. Its direction describes the sensitive direction of the technique and its length the conversion factor from the measured signal frequency to the flow velocity.

This demodulation technique is commonly used in dual beam LDV as a point measurement technique. It can be extended into a planar imaging measurement technique where the velocity distribution in a plane is measured using different light-sheet configurations and suitable cameras to detect the distributed signal. To extend this point measurement technique into a planar one, a measurement plane has to be generated, where each point is illuminated from two directions. This can be accomplished by crossing two light sheets. However, the cross section between two planes is usually only a line. To obtain a planar measurement volume special care has to be taken in the geometrical alignment between the two planes. Crossing two light sheets to form a measurement plane where each point is illuminated from two directions can be accomplished in many different ways. They all can be seen as combinations of two basic configurations: The co-planar light sheet configuration, shown in Fig. 2(a) and the crossed light sheet configuration, shown in Fig. 2(b). In the co-planar light sheet configuration both light sheets illuminate the same plane but from two different directions. With both $I_1$ and $I_2$ within the same illuminated plane, $\Sigma$ lies within the illuminated plane as well. This configuration therefore allows to measure one of the in-plane components of the velocity. In the crossed light sheets configuration the two light sheets are oriented such that $I_1$ and $I_2$ are again in the same plane, but the plane of the light sheets is perpendicular to this plane. Usually the cross section between two such planes is a line. But the intersection between the two planes can be expanded from a line into a volume when very shallow crossing angles $\theta$ and light sheets with a thickness of several millimeters are used. With this setup, the out-of-plane component of the velocity can be measured.

Using crossing angles $\theta$ of approx. 0.25° the modulation frequencies of the signal are in the range of 10 kHz/(m/s). These frequencies can be resolved using the latest high-speed cameras (HSC) which offer frame rates typically ranging from 7500 frames per second (fps) at a resolution of 1280 x 800 pixels up to 1 million fps (1 Mfps) at reduced resolutions of around 128 x 16 pixels. The Doppler signal S described by Eq. 2 lacks the sense of the direction of $V$ along the sensitivity vector $\Sigma$. Moreover particles that do not move do not generate a signal at all. In a classical dual beam LDV this directional ambiguity of the Doppler measurement is eliminated using a Bragg cell.

![Figure 2: Different light-sheet geometries. (a) co-planar light-sheets, (b) crossed light-sheets](image-url)
which shifts the frequency of one illumination beam by 30 to 40MHz. This shift results in an additional frequency offset in the signal S. Therefore particles that do not move will generate a signal S with a frequency at the shift frequency of the Bragg cell, and the direction of the particle motion is resolved by frequencies higher or lower than that shift frequency. For the sampling frequencies provided by high speed cameras the large shifts generated by a Bragg cell are not suitable. Instead, an electro optical modulator (EOM) is used to shift the frequency of one light sheet. In addition to the ability of generating frequency shifts in the kHz range the EOM also allows tuning of the shift frequency in a wide range.

Analyzing the data recorded with the high speed camera is straightforward. The signal of each pixel of the camera is analyzed individually as a single point time series. Therefore the signal frequency can be extracted using a wide range of frequency detection algorithms as it is done in single point LDV. For the results in Sec. 3 an autocorrelation based approach is used as presented by Meier et al. (2012). This algorithm was developed for the use with a SPDA, but it can also be applied to the data from the HSC. The main advantage of this data analysis technique is that it does not require many consecutive frames as they are required for a Fourier analysis. The frequency is estimated by using 8 consecutive frames and many independent repetitions to calculate the autocorrelation. The need for only 8 consecutive frames drastically reduces the requirements for the camera system. Moreover, the independent measurements used to calculate the autocorrelation do not necessarily have to be from independent measurements taken over time, neighboring pixels can also be used. By using neighboring pixels the spatial resolution will be reduced in exchange for a higher temporal resolution as will be shown in the next section.

### 3. Experiments

To demonstrate the feasibility of measuring instantaneous turbulent flow fields, the velocity distribution of a turbulent jet in a water tank is measured. Two different setups were tested. For the first setup the co-planar light sheet configuration (Fig. 2(a)) was chosen to measure one of the in-plane velocity components of the jet. This setup facilitated a simultaneous PIV measurement using the same high speed camera and the same image data set, therefore allowing a validation of the technique. Figure 3 shows the setup used for the in-plane velocity measurement. The laser beam
A CW-laser (Coherent, Verdi V5, $\lambda_0=532$ nm, 5.5 W) is first passed into a telescope (T) to reduce the beam diameter. Then the beam is split up into two beams using a 50:50 beam splitter (BS). One part of the beam is fed into the EOM (EOM: Conoptics Model 350-50, Driver: Model 302A) to shift the frequency of the laser beam. The two beams are then redirected using several mirrors (M) to a cylindrical lens (CL, $f=-25$ mm) which expands the laser beams into light sheets and crosses them. The two light sheets are directed below the water tank where a large front surface mirror redirects them upwards, such that the flow is illuminated by a vertical light sheet. The HSC (Photron Fastcam Ultima 512, Lens: Schneider Kreuznach 25mm f/0.95) is placed in front of the water tank at right angle with respect to the light sheets and images an area of approx. $100 \times 200$ mm$^2$. A close up of the water tank is shown in Fig. 4.

The water is seeded with polyamide particles with a diameter of 200 $\mu$m. The seeding density is adjusted to allow for the comparative PIV measurement. For the ILDV measurement alone a higher seeding density would be preferable to obtain a more continuous signal. The jet with a velocity of approx. 10 cm/s is generated using a small water pump and a nozzle with a diameter of 5 mm. With a Reynolds number of 500 the jet is fully turbulent. The two light sheets enter the tank from the bottom and are crossed such that the $x$-component of the velocity can be measured. The crossing angle is 0.25° at the bottom of the tank. At the top of the tank an anodized aluminum plate is suspended below the water surface to suppress the reflections of the laser at the water surface.

For the measurements the camera was set to a frame rate of 4000 fps. At that frame rate the camera recorded 4096 consecutive images at a resolution of 512 x 256 pixels. The EOM was set to a shift frequency of 1000 Hz, therefore particles that are not moving will generate a signal with a frequency of 1000 Hz. To measure the instantaneous and the mean flow velocities, the camera recorded 32 independent realizations with a time delay of 0.6 s. In each of the independent realizations 128 consecutive images were recorded. The total signal acquisition time was approx. 20 s.

The ILDV data was analyzed using the autocorrelation based data analysis technique presented in detail in Meier et al. (2012). The 128 consecutive images were used to calculate the autocorrelation to estimate the signal frequency of each independent realization. To account for the spatial variations in the crossing angle between the illumination directions across the y-direction in the tank, a linear model was used to calculate the local crossing angle for each pixel. This local crossing angle was then used to convert the measured signal frequency to the velocity. Each of these 32 independent measurements will give an "instantaneous" velocity distribution. To calculate the mean flow field the velocities of 32 independent measurements were averaged.

![Figure 4: Close up on the water tank set up for the in-plane velocity measurement](image-url)
The results of the ILDV measurement are displayed in Fig. 5 (left) for the mean flow field and in Fig. 5 (right) for the instantaneous flow field. In the mean flow field the shape of the jet in the center of the tank is clearly visible. Due to the walls on the side and at the end of the water tank the jet does not show any spreading. Instead a drop of the velocity towards the end of the water tank and the back flow at the bottom and at the top can be seen. In the instantaneous flow field the shape of the jet is not as clearly visible any more. Due to the turbulence, the shape of the jet is not as sharply defined as in the mean flow, instead elongated turbulent structures can be identified.

To validate the ILDV velocity measurement the recorded images were also used to compute the flow velocity using PIV. From each of the 32 sets of 128 consecutive images the first 8 images and the last 8 images were averaged to obtain the image pairs for the PIV analysis. This averaging is necessary to eliminate the fluctuating Doppler signal component which otherwise disturbs the PIV analysis. The image pairs were then analyzed using the commercial software PIVView (PIVTec, Germany). The mean and the instantaneous velocity distributions obtained by the PIV analysis are shown in Fig. 6.

Comparing the results from PIV with ILDV one can identify the same structures. Especially in the instantaneous velocity distribution the turbulent structures are visible in both measurements. Compared to the PIV measurements the ILDV measurements have a much higher resolution, as PIV uses spatial cross correlations to determine the velocity. The size of the windows used for the cross correlation limits the spatial resolution of the measurement. In contrast ILDV uses the time signal.

![Figure 5: Measured x-component of the in-plane velocity distributions using ILDV. Left: Mean flow field, right: Instantaneous flow field.](image)

![Figure 6: Measured x-component of the in-plane velocity distributions using PIV. Left: Mean flow field, right: Instantaneous flow field](image)
of each pixel to determine the velocity, thus each pixel gives an independent velocity measurement. For a more quantitative comparison between the measurement techniques, the mean and instantaneous velocity profiles along a line at \( x = 27 \) mm obtained with PIV and ILDV are displayed in Fig. 7. The ILDV measurements show a very good agreement with the PIV measurement for both the mean flow and the instantaneous flow measurements, and again the higher resolution of the ILDV measurement is visible.

For the second experiment the crossed light sheet configuration (Fig. 2(b)) was chosen to measure the out-of-plane velocity component. Figure 8 shows the setup used for the measurement. The flow is now illuminated from the side at approx. 20mm away from the end wall of the tank. The camera is again located at a 90° observation angle and images the area inside the red rectangle of 120x250mm². The crossing angle, the camera settings and the data analysis technique for the ILDV measurement were the same as for the in-plane velocity measurement.

The measured mean and instantaneous out-of-plane velocity distributions are shown in Fig. 9. The jet in the center is clearly visible in both measurements. At the left and the right side of the tank the areas with the back flow are visible as well. The instantaneous measurement again shows the turbulent structures of the jet. A validation of this data using PIV would only be possible using a stereo PIV setup. Nevertheless PIV can be used to analyze this data as well: With PIV the in-plane velocity profiles along a line at \( x = 27 \) mm obtained with PIV and ILDV are displayed in Fig. 7.
motion of the particles can be analyzed. A combined ILDV-PIV will then give all three velocity components in the measurement plane. The result of this combined analysis for the mean velocity distribution is shown in Fig. 10. The ILDV measurement shows the main structure of the flow and the PIV measurement the secondary flow structures inside the jet.

With this data set the possibility to calculate the autocorrelations in space can also be tested. Instead of calculating the autocorrelation with the 128 consecutive images it is calculated on a 16x16 pixel neighborhood using only 8 consecutive images. The resulting velocity distribution of this analysis is shown in Fig. 11. The spatial resolution is now the same as in the PIV analysis. The different flow structures can be identified as well. For a better comparison the velocity profiles along a line at \( x = 27 \text{ mm} \) are plotted in Fig. 12. The green line shows the velocity calculated using 128 consecutive images and the red line the result using the spatial autocorrelation. The curves do not give the same results. This could be expected as the turbulent flow changes over time. Thus the two techniques average the flow over different times. To compare the techniques the average of the calculated velocities using the spatial autocorrelation over all 128 images is shown as well. The averaged result is very close to the result of the calculation using 128 consecutive images. Only the spatial resolution is lost due to the spatial averaging.

![Figure 9: Measured out-of-plane velocity distribution using ILDV. Left: Mean flow field, right: instantaneous flow field](image)

![Figure 10: Combined ILDV-PIV measurement](image)
4. Conclusions

The presented experiments demonstrate the feasibility of demodulating the Doppler shift of scattered light in a planar observation volume using crossed light sheets and detecting the signal using a conventional high speed camera. The ILDV measurements of the turbulent jet in water show the benefit of using a conventional high speed camera instead of the earlier used smart pixel detector array. Not only could the mean flow velocity distribution be measured but also the instantaneous flow field. The comparative PIV measurements show a very good agreement for the in-plane velocity measurements. Moreover, an out-of-plane velocity measurement could also be performed using the crossed light sheets configuration. Both the mean and the instantaneous flow velocity distribution could be measured. The combination of ILDV and PIV allowed to measure all three velocity components in the illuminated plane. In these experiments the crossing angle could be reduced to a very small value of only 0.25° which allowed to measure a velocity range of 16 cm/s with the high speed camera operating at only 4000 fps.

The measurements also allowed to assess the feasibility of using spatial autocorrelations instead of the temporal autocorrelations. This showed that as little as 8 consecutively recorded images are enough to estimate the flow velocity if a sufficient number of independent measurements is available. It could be shown that these independent measurements can either be consecutive measurements of the flow in time but also neighboring pixels of the camera. This relaxes the requirements on the camera systems significantly. Framing cameras that can record only 8 consecutive images at up to 100 Mfps with a high resolution can be used as well as conventional high speed cameras that can record hundreds of consecutive images at comparatively low resolutions. Dependent on the camera used and the spatial resolution required, this allows to measure either mean or instantaneous flow velocity distributions. Especially the instantaneous velocity distributions can be measured in a very short time if spatial autocorrelations are used. The measurable velocity range is only limited by the frame rate of the camera and the power of the illumination light source. From the present measurement it can be extrapolated that with a camera recording at 1 Mfps a measurement range of 25 m/s can be achieved. This makes this technique interesting to be applied in larger facilities e.g. low speed wind tunnels especially to measure the out-of-plane velocity component which is otherwise difficult to obtain. This concept should be further expandable if a larger measurement area is examined utilizing another promising property of the technique: Since the particles do not need to be resolved as in the displacement based
techniques, ILDV should be readily scaled up. Additionally the frequencies that have to be detected can be reduced as well. This should simplify the measurement on larger areas even more.

5. References


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