Self Calibrating FSK-Doppler Global Velocimetry for Three-Componential Time Resolved and Phase Averaged Flow Field Measurements

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Abstract

By applying frequency shift keying (FSK) to the Doppler Global Velocimetry, it is possible to omit the reference camera which usually is required in conventionally used DGV systems. Additionally frequency shift keying realized by well defined frequency steps of the laser used for the light sheet generation in the measuring plane allows an absolute online calibration of the Doppler shift evaluation in the over-all DGV set-up for the velocity field analysis. Thus the uncertainty of velocity field measurements can be reduced and the absolute velocity measurement accuracy increases.

Based on the application of frequency shift keying to the emission frequency of the lightsheet generating laser, the Doppler shift of the scattered light is evaluated by analyzing image sequences. The well defined frequency steps allow an online calibration including seeding density and absorption cell influences as well as the camera characteristics for each individual pixel. Furthermore it is possible to perform time resolved velocity field measurements with a spatial and temporal resolution depending on the resolution and frame rate of the CCD camera and the available laser power in the laser light sheet.

Applying the self-calibrating FSK technique to time resolved velocity measurements on a spinning disc, standard deviations down to 0.25 m/s and absolute deviations below 0.21 m/s were achieved for velocities up to approximately 30 m/s considering only single CCD camera pixels. Time resolved measurements of a steady flow field show a standard deviation of about 0.6 m/s, while the standard deviation in 100 temporally binned measurement cycles is reduced down to about 0.06 m/s. Phase resolved measurements in the wake of a finite cylinder demonstrate the capability of this technique to suppress systematic influences in long-term measurements.

1. Introduction

Doppler Global Velocimetry (DGV) has successfully been applied especially for the investigation of high speed flow fields. 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 error of 1.75 % 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 described 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 852.36 nm and already 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. First velocity field measurements were demonstrated by Müller et al. in 2004 and 2006. Fischer et al. presented time-resolved measurements of flow profiles using an avalanche photodetector array in 2007. This paper describes the further development of the DGV techniques based on frequency shift keying (FSK), especially regarding online calibration for measuring Doppler frequency shifts absolutely.

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 including continuous sinusoidal modulation (FM-DGV) as well as frequency shift keying (FSK-DGV) to the Doppler Global Velocimetry it is possible to omit the reference detector unit and to reduce the uncertainty of the velocity measurement.

3. Self-Calibrating Doppler Global Velocimetry based on FSK-techniques

In contrast to conventional DGV systems requiring an additional reference camera and a laser for the light sheet generation which is frequency stabilized at a single working point on a calibrated absorption line edge, the described FSK technique is able to omit the reference camera by evaluating a sequence of the images taken for two working points with a well defined frequency difference at both edges of the absorption line allowing an on-line calibration.
As shown in figure 2, the laser frequency is alternately stabilized to each of both edges of the absorption line. Consequently, the Doppler shifted light intensities of each pixel will change according to the Doppler shift \( f_D \) and the gradients of the edges, \((dg/df)_F\) given on the falling and \((dg/df)_R\) given on the rising edge. Taking two images per absorption line edge, while the laser is stabilized to frequencies with a well defined difference \( f_\Delta \), the gradients can be determined simultaneously. Presuming

\[
\begin{bmatrix}
g_0 + g_1 
\end{bmatrix}_{f_D = 0} = \begin{bmatrix}
g_2 + g_3 
\end{bmatrix}_{f_D = 0}
\]

for unshifted laser light, a Doppler shift will result in an intensity difference

\[
\begin{bmatrix}
g_2 + g_3 
\end{bmatrix} - \begin{bmatrix}
g_0 + g_1 
\end{bmatrix} = f_D \left[ (dg/df)_R - (dg/df)_F \right].
\]

Within the linear range of the absorption line edges. Since the slopes are given by

\[
(dg/df)_F = \frac{g_1 - g_0}{f_\Delta} \quad \text{and} \quad (dg/df)_R = \frac{g_3 - g_2}{f_\Delta}
\]

the Doppler frequency can be directly calculated by

\[
f_D = f_\Delta \frac{-g_0 - g_1 + g_2 + g_3}{g_0 - g_1 - g_2 + g_3}
\]

as far as the edges can be assumed as linear.

This method gives the possibility to trace back the measured velocities directly to a well defined laser modulation frequency step \( f_\Delta \), while the scattered light intensity, the absorption line slope and the camera sensitivity are automatically included for each pixel, as long as they affect all four images in the same way. Furthermore, extraneous light and dark image intensities of the camera will have no influence on the evaluation, since only differences in intensities of the same pixels in consecutive images are considered.
A small amount of light from the lightsheet generating laser focused through the absorption cell to the camera, can be used as reference to eliminate laser frequency variations. Also, a nonlinear calibration function can be derived from sampling the absorption line edges at well known laser frequencies using this superimposed reference spot (Eggert et al. 2008). By application of the nonlinearity calibration before and the self-calibration during the measurement, uncertainties caused by temperature variations of the absorption cell and different angles of the scattered light passing through the cell are reduced by one order of magnitude compared to a fixed calibration.

4. System setup

The FSK-DGV system has been realized by using a fiber coupled DFB-MOPA laser system that allows fast frequency switching by keeping the (lightsheet) output power of about 170 mW constant. According to the wavelength of 852 nm a caesium absorption cell (50 mm diameter, 50 mm length) is used for frequency-to-intensity conversion.

![System electronics diagram]

Fig. 3: System electronics

In order to generate well defined, reproducible frequency steps, the lightsheet laser is locked to a second, frequency stabilized laser using a phase locked loop (PLL) circuit. In order to avoid changes of the laser system output power when modulating the laser diode current, the output power is controlled adjusting the optical amplifier current. A microcontroller is used to generate the frequency sequences by internal or external synchronization with the camera and also drives a fiberoptic switch to toggle lightsheets needed to measure three velocity components of the flow field. The reference spot needed for the nonlinearity calibration as well as for the detection of laser frequency variations is generated within the receiving optics.
5. Measurements

5.1 Characterization of the self calibrating system

The described FSK-DGV system has been verified by measuring the well defined velocity field on a rotating scattering disc, including self-calibration, nonlinearity calibration and automatic correction of the laser frequency offset $f_{\text{offset}}$ in respect to the absorption line by monitoring the reference spot scattering light directly from the lightsheet without Doppler shift.

Time resolved measurements, accomplished with our camera’s image rate of 10 Hz leading to a measurement cycle rate of 2.5 Hz and a frequency step $\Delta f = 15$ MHz on both absorption line edges show a standard deviation down to 0.25 m/s (figure 4), depending on the mean velocity. It is dominated by the quantum noise, dark image noise and the read out noise of the camera.

![Figure 4](image-url)  
**Fig. 4:** Standard deviation of time resolved, single pixel velocity measurements on the rotating disc

![Figure 5](image-url)  
**Fig. 5:** Absolute, total deviation of velocity profiles measured at different rotation speeds
The velocity profiles measured at different rotation speeds have also been compared to the true velocity, calculated by the rotation speed and the radius, derived by use of a test pattern (figure 5). For velocities up to 30 m/s, 95% of all measured velocities show a total, absolute deviation of below 0.21 m/s.

To demonstrate the advantages of the self calibrating technique, both the cold finger and body temperatures of the absorption cell have been increased by 1 K during a measurement. The derived image data have been analyzed according to the self calibrating technique, as well as evaluating only the intensities derived at one frequency per absorption line slope, according to the 2ν-DGV technique described by Ford et al. While there is no major difference in the absolute velocity deviation derived from both techniques without temperature change (figure 6a), the self calibrating technique shows a significantly lower temperature dependency than the 2ν-DGV technique with a static calibration (figure 6b).

![Figure 6a: Absolute, total deviation of velocity profiles before the applied temperature change](image1)

![Figure 6b: Absolute, total deviation of velocity profiles after the applied temperature change](image2)
5.2 Measurements of a steady flow field

Using the self-calibrating DGV technique, the flow field in a 20 cm diameter pipe 4 m behind a double elbow has been measured at different flow rates. After recording patterns for image restitution and determination of the lightsheet directions needed for the vector evaluations, 300 measurement cycles comprising 12 images (4 frequencies, 3 lightsheets), 100 ms exposure time each, have been taken (Eggert et al. 2008). The figures 7a,b and 8a,b show the position of the swirl center and the asymmetrical axial velocity profile caused by the double elbow changing with the flow rate, while velocities down to 0.1 m/s are resolved. The measured velocities close to the pipe wall are falsified by indirectly scattered light.

![Fig. 7a,b: Velocity components at a flow rate of 1028 m³/h](image1)

![Fig. 8a,b: Velocity components at a flow rate of 2062 m³/h](image2)
The axial component, calculated for single pixels without binning, shows a standard deviation of about 0.5 m/s calculated from single measurement cycles, while the standard deviation in 100 temporal binned cycles is reduced down to about 0.05 m/s (figure 8). This continuity implies that there is only uncorrelated noise affecting the measurements, easily to be averaged out in numerous cycles, so the velocity resolution is directly linked to the temporal resolution. Averaging 300 cycles, a velocity resolution below 0.03 m/s was achieved in the central (x = 0) velocity profile (figure 9).

As there is no significant difference between the standard deviation derived from single pixels and 10 by 10 binned pixels, the uncertainty is obviously not dominated by pixel noise, as might be expected from the laser power of only 160 mW, but from influences affecting regions of pixels the same way. Considering that the deviation caused by laser frequency variation is also remarkably lower (measured using the reference spot), the standard deviation of this flow measurement seems to be dominated by seeding variations or the flow itself.

Fig. 8: Effect of temporal and spatial averaging on the standard deviation, flow rate 1028 m³/h

Fig. 9: Temporally averaged profile (single pixel column) of the axial velocity vₓ at 1028 m³/h
5.3 Phase resolved measurements of an unsteady flow

By taking interleaved images, also phase averaging measurements are possible: As long as an unsteady flow incorporates periodical elements, the acquisition can be synchronized to take one or more images at dedicated flow phase steps, followed by a frequency step after every flow period and a lightsheet changeover after every frequency cycle. As long as changes in velocity and scattered light intensity are uncorrelated with the frequency step cycles, the velocity evaluation calculated from enough images will just result in the constant and periodical elements of the flow. The more images cycles are summed, the less will the sums be affected by arbitrary velocity and scattered light intensity changes.

Phase-averaged measurements in the wake of a finite wall-mounted cylinder with a diameter \( D = 120 \) mm and height \( H = 2D \), at a flow speed of \( U_\infty = 26 \) m/s \( (Re = 2 \times 10^5) \), have been accomplished in a plane 2.5 \( D \) behind the cylinder axis. Triggered by a hot-wire probe, each vortex transit was captured in 15 images (phase steps), 2 ms exposure time each. For averaging, 3000 image cycles for each phase step, laser frequency and lightsheet have been recorded.

Fig. 9: Time-averaged in-plane velocity components (vectors) and vorticity (color) of the flow field behind the cylinder, in a 250 mm by 288 mm measuring plane

Fig. 10: Phase-averaged 3C velocity (in-plane: vectors, axial: color) 10 ms and 24 ms after trigger
Due to the low power of 170 mW irradiated to the lightsheet, 3% quantum efficiency of the used highspeed CMOS camera at a wavelength of 852 nm and the short exposure time, a velocity of 1 m/s caused an intensity change of only 0.01 digit in the acquired images. So only averaging the intensities, benefiting from sensor noise as a native dithering before quantization, allowed an evaluation. Figure 9 shows the measured flow field behind the cylinder, including a reduction of the axial velocity component and two horse shoe vortices. The phase-averaged results (figure 10) show the effect of separated wake vortices on the horizontal in-plane velocity component.

These results underline the capability of the self-calibrating FSK-DGV to even measure velocities inducing intensity changes far below quantization errors and noise in the single images, unaffected from systematic errors caused by long-term absorption cell temperature deviations and dark image or scattered light intensity changes.

6. Conclusions

The application of frequency shift keying allowed to build a DGV system without reference camera. On the rotating disc, single pixel based, time resolved measurements (10 ms exposure time) have shown a standard deviation down to 0.25 m/s. An absolute, total deviation of less than 0.21 m/s has been achieved for velocities up to 30 m/s, even when the cold finger and body temperatures of the absorption cell changes by 1 K during the measurement. As only the ratio of differences in the intensities of consecutively taken images are evaluated by the self calibrating technique, the measured velocity is also not affected by changes of the scattered light intensity or extraneous light and the camera dark image.

The novel frequency shift keying technique which has been verified for different experimental conditions establishes the use of the Doppler Global Velocimetry for new applications requiring three component flow field measurements with high temporal resolutions and low systematic deviations at even low scattered light intensities. So temporally averaged, as well as phase resolved measurements of steady and unsteady flow fields have been accomplished, even based on intensities according to a single digit of the camera, being exceeded by dark image variations by far. Such measurements will help to analyse and understand the behaviour of turbulent and complex flows.

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8. References


