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Doppler Global Velocity measurements with overdetermined perspective information using a multi-branch image fiber

Doppler-Global-Geschwindigkeitsmessung mit überbestimmter perspektivischer Information unter Anwendung eines Multi-Arm Bildleiters

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Abstract

The Doppler-Global-Velocimetry (DGV) method, as described by Röhle (1999), has been applied to ducted flows in various configurations. In a novel approach utilizing a multi-branch fiber camera it was possible to capture the flow ROI simultaneously from six different perspectives, utilizing only two physical cameras. With this approach it is possible to selectively mask the valid region for each perspective thus enabling 2D3C measurements even if there are (spurious) reflections or scattered light from surfaces visible in part(s) of the perspectives.

Each of the six branches of the fiber arm camera has its own lens thus transferring the captured light through about 50000 fibers to the sensor of the cameras. The fiber objectives are mounted on magnetic stands, allowing for fast change in perspective. After positioning the fiber-objectives a target images is captured from which the perspective of each camera view is deducted. The image-data for each perspective and camera are mapped on a grid with a spatial resolution of 1mm. The alignment is achieved using the OpenCV toolbox by Bradski (2000). The measuring distance is about 350 mm.

To test the feasibility of the method measurements are conducted in the following test regimes:

- Velocity range ca 30-100 m/s
- straight pipe flow or swirl generator at 0D, 1D and 7D upstream of measuring section
- measuring plane perpendicular to pipe or axial cut of pipe section

A comparison of the obtained velocity results with Laser-Doppler-Velocimetry (LDV) and Filtered Rayleigh-Scattering (FRS) is presented.

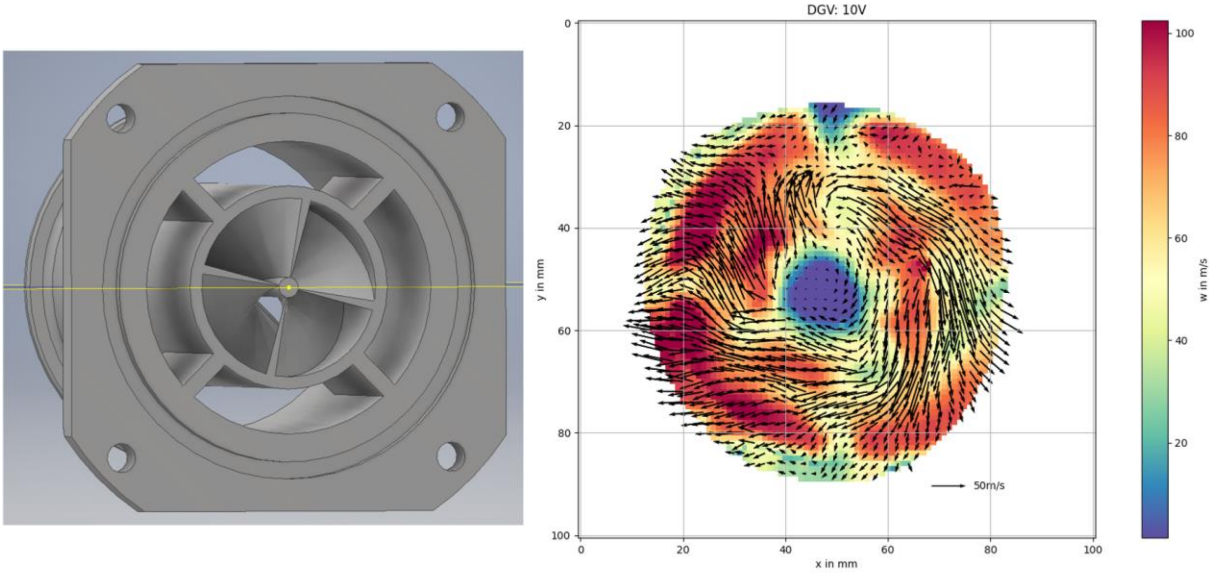

Figure 1: Swirl generator, rotated by 45° around the main flow direction (left). Velocity field captured ca 0.5D after swirl generator, axial velocity component per colormap, the in-plane components are denoted as arrows. Maximum axial velocity ~ 100 m/s (right).

Introduction

In scope of the SINATRA project ILA R&D GmbH developed a new imaging system for multi view Filtered Rayleigh Scattering measurements based on a 6 to 1 image fiber bundle. In this paper the application of the multi view fiber imaging technology is extended to the field of Doppler Global Velocimetry.

DGV measuring principle

For Doppler-Global-Velocimetry measurements small particles hereafter called ‘tracer’ are added to the flow. The Region of interest (ROI) is illuminated with a light source (laser) at a known wavenumber. For evenly illumination a light-sheet generator is applied which spans up a light sheet via an rotating prism. The particle-scattered light is then observed from at least one camera. The Doppler-shift of the back-scattered light depends on the flow velocity (v_x, v_y, v_z) of the particle, the direction of the incident laser light (laser-vector) and the position of the camera (observation-vector).

The governing equation is:

$$\Delta\nu = \nu_0 \frac{\bar{o} - \bar{l}}{c} \bar{v} \qquad (1)$$

where:

- $\Delta\nu$ denotes the Doppler shift in Hz,
- ν_0 is the frequency of the incident laser light in Hz,
- $\bar{o}$ is the observation vector,
- $\bar{l}$ is the laser vector,
- c is the speed of light and
- $\bar{v}$ is the 3C velocity vector (v_x, v_y, v_z) in m/s.

Doppler Global Velocimetry (DGV) utilizes a molecular filter, in our case an iodine cell, to determine the Doppler shift of the back scattered light for each perspective / camera. The iodine cell is integrated in the camera module which splits and distributes the collected light to a reference camera and a signal camera. The reference camera determines the intensity of the back-scattered light while the signal camera gathers the the light intensity after the molecular filtering. The ratio of the signal to the reference image determines the Doppler shift based on a prior determined calibration of the molecular filter.

To determine the three components of the velocity $\overline{v}$ (v_x, v_y, v_z), at least three linear independent combinations of observation vector ($\overline{o}$) and laser-vector ($\bar{l}$) are needed. This can either be established by capturing consecutively different illumination(s) by one camera or by using multiple cameras (perspectives) with the same illumination (light-sheet). In our setup we utilize the latter approach by observing the same light-sheet from different perspectives using image fiber objectives which are combined to be captured by one camera module.

Test rig

A laboratory scale test rig is established for the further development of the fiber imaging technology, compare 2. The overall principle is an open return wind channel. The nominal diameter is DN 80, the feasible mean velocity range is between 30 and 100 m/s.

The inlet section features a bell shaped inlet for mean flow measurement, and a flow straightener section to precondition and homogenize the flow field. The measurement section is composed of an calibrated borosilicate glas pipe of approximately 500 mm length allowing for good optical access to the ducted flow. The illuminating light sheet is introduced into the flow by a bespoke light sheet adapter, which suppresses reflections and stray light in comparison to the easier approach of just illuminating the glass pipe from the outside. The flow is generated by a radial fan, model smp 540 by elektror in suction configuration. The fan speed is set and regulated by an frequency converter. In respect to logging the ambient pressure, temperature and humidity, the pressure drop in the inlet section which is linked to the mean axial flow, the temperature of the iodine cell, and the temperature in the flow are monitored. The auxiliary piping consists of powder coated steel pipes by JACOB with quick-lock flanges for fast assembly and reconfiguration.

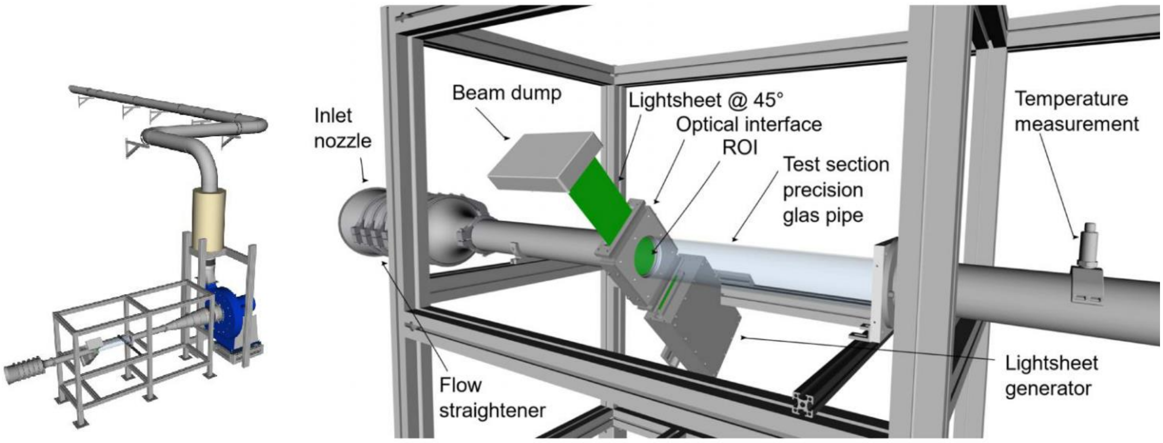

Figure 2: Overview on the laboratory scale testrig for DGV, rendering, the overall length of the piping is 15m (left). Close up on the measuring section, flow direction is left to right, rendering (right).

DGV measuring system

In this section the Doppler Global multibranch fiber arm setup is explained.

The incident laser light is generated by an AzurLight ALS 6W fiber laser at a bandwidth below 200 kHz. The output frequency can be fine tuned via piezo in a range of 10 GHz and adjusted via thermal tuning in a range of 700 GHz. A small portion of the laser beam is coupled out and let to an wavemeter, model WS-8 by HighFinesse.

The laser power is monitored relatively by another small part of the beam which is coupled out and led through a diffusive disc on a photo diode.The remaining laser beam is then guided by a mirror arm to a bespoke light sheet generator which spans up a light sheet of approximately 100 mm height. The light sheet is introduced to the region of interest through an in house developed light sheet interface which reduces reflections and stray light which appear due to the light passing through the optical transparent sections. To further reduce the stray light a beam dump is installed on the adjacent site of the flow region.

The illuminated portion of the flow is observed through the six image fiber arms, the inlet of each equipped with a focusing lens. The active area of each branch is 4 by 4 mm with approximately 50000 fibers for each arm. The output of the multi arm image fiber is combined to an active area of 12 by 8 mm, which can be observed by just one physical camera. For the envisaged DGV setup however, the combined images need to be further processed. A beam splitter diverts the incoming light into two paths: one portion leading directly to the attached reference camera and the other portion through the molecular filter to the signal camera. Signal and reference camera (pco edge 4.2) are capable of capturing 2048 by 2048 pixel at 16 bit resolution. The transmission profile of the temperature controlled iodine cell has been calibrated prior to the measurement.

The perspective and the alignment for each of the six cameras is determined via OpenCV's (compare Bradski (2000)) framework based on a target inserted at the position of the light sheet and a prior determined camera calibration. A GUI has been developed to aid in the determination of the camera perspectives with partially covered or round domains enabling for a good coverage of the ROI.

In the described measurements the working distance of the fiber objectives is in the range of 350 mm.

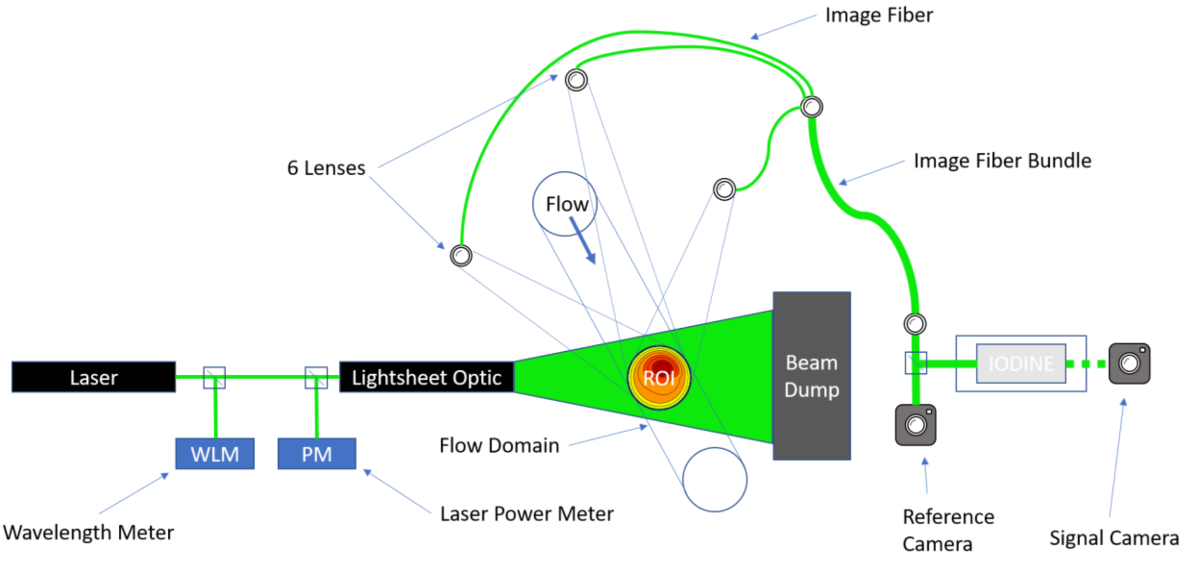

Figure 3: Schematic overview of the DGV system. Note: only three of the six fiber objectives are displayed to keep the image apprehensive.

DGV Evaluation Steps

Prerequisites: Camera Calibration

DGV measurements rely on the absorption properties of a steep molecular filter to translate small frequency shifts into a change in illuminating intensity and vice versa. The transmission profile of each iodine cell is different. Although the transmission profile can – to a certain extend– be modeled with empirical relations (Forkey (1996)) it is still recommended to calibrate the iodine cell for lower uncertainty.

To determine the transmission profile of the iodine cell, the laser is tuned to to different wavenumbers. Once stable conditions are reached in terms of laserpower and wavenumber, the aquisition process starts. Consecutively each wavenumber is set and the transmission determined. Then all recorded transmissions are unified via averaging and filtering. All wavenumbers are measured at least 5 times.

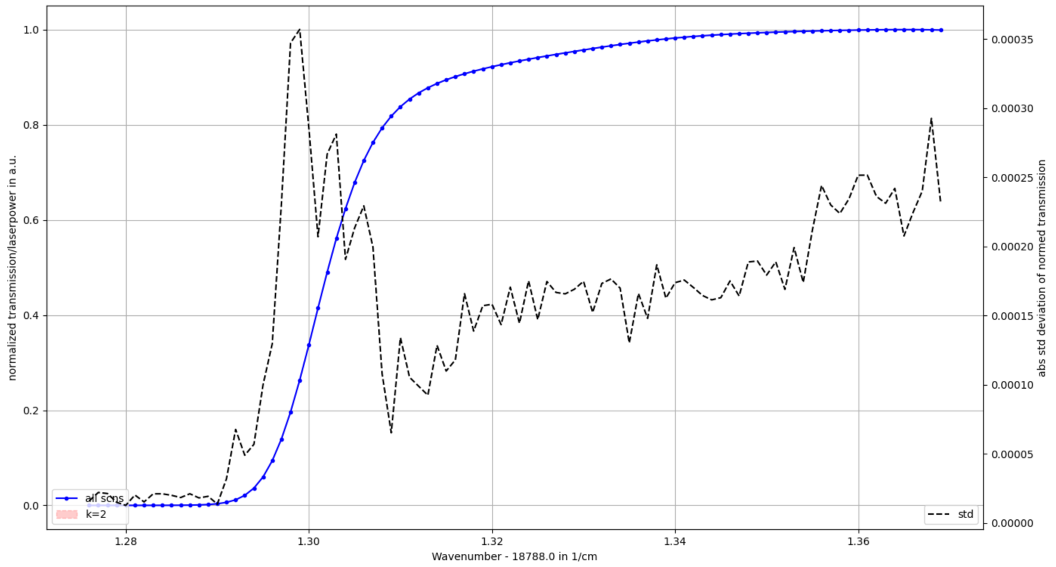

Figure 4: Excerpt from the calibration of the iodine cell: Wavenumber in 1/cm on the horizontal axis, normalized transmission (left vertical axis) in blue, standard deviation of the transmission in black , (right vertical axis).

For the latter detection of the pose (observation vector), the alignment and dewarping of the images from multiple perspectives a camera calibration is needed for each of the fiber objectives. The camera calibration determines the camera intrinsics from a set of target images.

A target stretching for maximal ~ 30% of the ROI is put at the approximate distance of the latter measurement. An image is taken. The target is then moved to a different position within the field of view (FOV) of the camera. Thus multiple images are captured, image by image mapping the whole FOV of the camera. According to the OpenCV Framework at least images are needed, however a reliable performance can be expected from 30+ valid individual images.

Prerequisites: Observation and laser vector determination

Based on the prior aquired camera intrinsics the observation vector (extrinsics) and the homography matrix which is needed for alignment in the computational domain for each fiber objective can be determined from a target image.

The calibration target for pose calibration is aligned with the region of interest and with the lightsheet. It is useful to evenly illuminate the pattern with a torch or by other means. Then one image from every camera / perspective is taken.

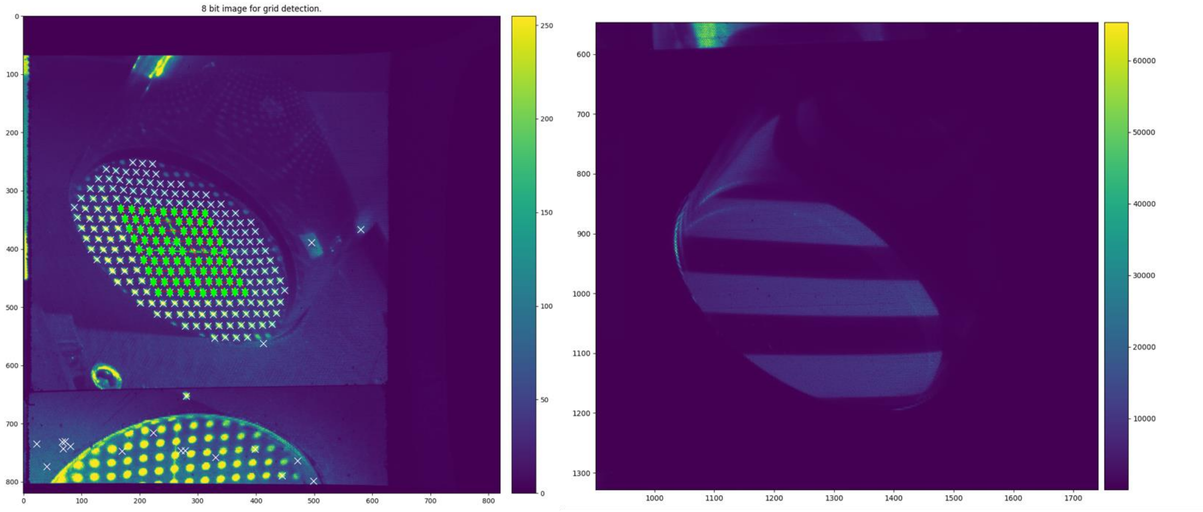

Figure 5: Target image as captured by one fiber objective with detected grid points denoted by white crosses and valid grid points by green diamonds (left). Stripe image (right).

A GUI has been developed to aid in the detection of the camera perspectives. The GUI enables automatic detection of the target markers and validation of the detected points by an user defined adjustable geometric grid pattern and extended validation criteria.

The direction of the incident laser light is determined by inserting a mask into the lightsheet which creates a grid pattern in the roi. The grid image is then dewarped according to the prior determined intrinsics and extrinsics of the camera view. A GUI aids the the user to determine the laser vector: The dewarped stripe image is overlayed with an arrow for the laser vector. The user aligns the arrow per drag and drop with one edge of the laser grid image, various filter and edge detections are available for better detection of the edges.

The steps described above to determine the pose and dewarping information must be concluded for each of the six perspectives and each camera (reference and signal), resulting in 12 perspectives to be determined prior to evaluation.-

Preriquisites: Image alignment and mapping

The captured images from all perspectives and cameras are dewarped on a uniform computational domain. The computational domain is aligned with the coordinate system of the pipe. After alignment each ‘super-pixel’ in the computational domain corresponds to one mm in the ROI.

DGV Evaluation

First background and dark image are subtracted from the aligned images. All images are then normalized by a sensitivity image to eliminate inevitable transmission inconsistencies by the experimental setup. The ratio of the respective normalized signal to reference images denotes the obtained transmission for each pixel in the computational domain. The offset of the the transmission from the expected incident transmission is then converted to a Doppler shift by applying the iodine calibration for each pixel.

The resulting 3C velocity field is reconstructed by inverting equation (1) pixel wise. It is worth noting that each pixel has a unique observation vector. In case of three perspectives the inverse of the equation can be applied directly. In case there are more than three perspectives the inverse of the over determined equation system is determined with a least square procedure.

Experimental Setup

A swirl generator, compare Fig. 1 (left) is placed at approximately 0.25 and 1D upstream of the ROI. Mean flow velocities of roughly 30, 60 and 100 m/s have been realized. DEHS seeding provided by a thermal generator has been applied to the ambient air in front of the inlet section. The measurements are carried out at a wavenumber with nominal 50% transmission, enabling robust detection of reverse flow.

Results

As depicted in Figure 6 the velocity profile downstream of the swirl generator has been captured. At 0.25 D downstream the outflow of the swirl generators' channels are clearly recognizable. The outer wakes due to the struts of of the swirl generator are clearly visible. In the center a small region with back flow is apparent. At 1D downstream the inner wakes of the swirl generator are already less visible and the flow has homogenized in respect to the main introduced swirl. Although the back flow region has vanished the blockage of the swirl generator is still reflected in the lower mean axial velocity at the center.

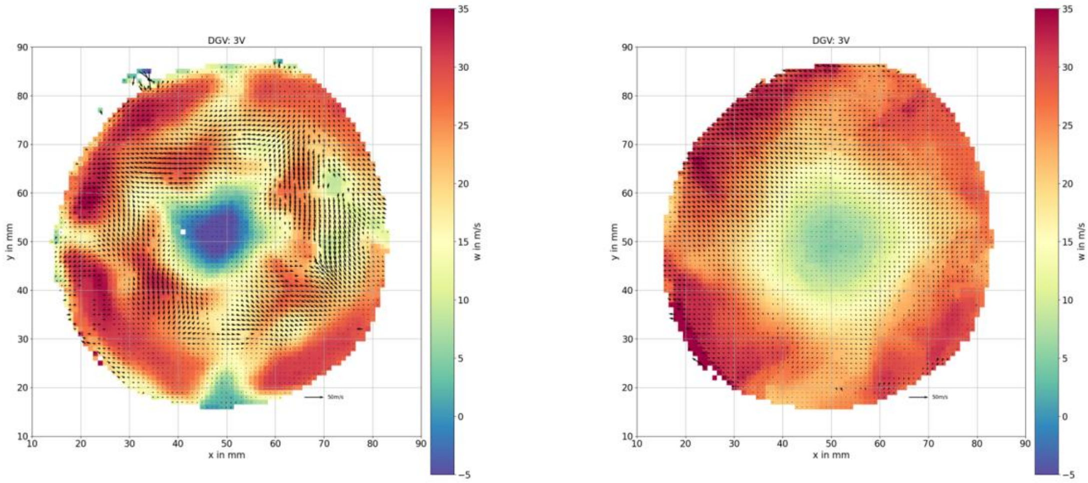

Figure 6: Velocity profile ca 0.25 D (left) and 1D (right) downstream of the swirl generator at a mean axial flow of approximately 30 m/s. The in-plane components are denoted by arrows.

Summary

A multi-view DGV setup has been established utilizing a six to one image fiber bundle in conjunction with one camera module. The utilized solution enables high flexibility in respect to the accessibility of the optical access. Due to the over determined setup robust measurements are possible even in challenging optical configurations. As a benchmark the complex flow situation behind a swirl generator has been successfully captured with a high resolution. The developed processing chain makes it a perfect complementary techniques for multi-view FRS measurements.

Acknowledgements

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