Application of Phase-Averaging Doppler Global Velocimetry to Engine Exhaust Flows

by

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ABSTRACT

The aim of this application of Doppler global velocimetry (DGV) was to provide three-component, phase-averaged velocity data of the engine exhaust flow with a resolution of 5-10° for direct comparison with numerical simulations, ultimately providing a means of validating numerical simulations used in the industrial design process. The test object chosen for this application was an unfired, externally driven four cylinder, turbo-charged engine driven at 2000 rpm (partial power) and 6000 rpm (maximum power). Phase-averaged DGV measurements were made possible by adding an acousto-optic modulator (Bragg cell) to an existing DGV system that was previously optimized for the measurement of time-averaged velocities. CCD cameras with a high signal-to-noise ratio and low dark current (background signal) allowed for integration times up to one minute thereby obtaining velocity averages of more than 1000 cycles. The DGV measurements were performed at the exit plane of the exhaust manifold for cylinders 3 and 4.

The presented DGV results provided the data base for a validation study of the pulsating flow in an exhaust manifold. Complementary numerical simulations of the pulsating flow were performed using a computational grid of 635,000 cells. The code solved for the compressible Navier-Stokes equations using a standard k-ε model with the boundary conditions for the calculation (pressure ratio and initial temperature) matched to the experiment. The comparison between measured and calculated data showed a reasonable agreement in flow topology, cyclic behaviour and integral quantities. The remaining discrepancies between measured and calculated data for the maximum power operating condition (6000 rpm) mainly concerned the level of the magnitude of the flow velocity and the location and strength of secondary flow vortices. The encouraging study enables the assessment of different concepts in an early stage of the design process.

Figure: Phase-averaged, three-component velocity data obtained by DGV at the exit plane of an exhaust manifold after the junction of cylinders 3 and 4. The data on the left was obtained for an engine speed of 2000 rpm (partial load) and 6000 rpm (full load) on the right. The crank angles in both cases are identical. The averaging interval covers 5° of the cam-shaft’s rotation.
1. INTRODUCTION

The intended further reduction of both the fuel consumption as well as emissions will lead to the development of new engine concepts (see e.g. Holy et al., 1998). Computational Fluid Dynamics (CFD) is used as a design tool in order to visualize the processes as well as to analyze the mechanism of different engine parameters. The proof of the quality of the numerical results is a major prerequisite for achieving such a goal.

The calculation of the transient flow in the exhaust manifold is the basis for the numerical analysis of phenomena observed during cold-start of the engine or for the analysis of the performance of a closed-coupled catalytic converter at partial load. A short outline of the application used to validate the numerical method is given in section 4 in which a comparison between measured and calculated data will be described.

The basis for validation of the numerical simulations are phase-resolved, three-component velocity data obtained by Doppler global velocimetry, a planar, laser-based, non-intrusive flow velocity measurement technique. This paper focuses on the description of the DGV-system and the results obtained with it. Descriptions of the physical principles behind the DGV-method can be found in other recent publications (Elliot & Beutner, 1999; McKenzie, 1996; Meyers, 1995; Röhle, 1996, 1998). Aside from its non-intrusive operation, one of the major advantages of DGV lies in the rather straightforward data-retrieval from the acquired images making it a predestined tool for rapid flow analysis and feedback into the design process. Although the method is generally more suitable for high-speed flows (\( U > 50-100 \ \text{m/s} \)), it can be optimized for the recovery of time-averaged velocity data with a resolution on the order of \( \pm 1 \ \text{m/s} \) or better (Röhle, 1999; Röhle et al., 1998, 2000).

2. EXPERIMENTAL METHOD AND PROCEDURES

2.1. The Doppler Global Velocimeter

Based on experiences collected with a first prototype imaging DGV system developed in 1995 (Röhle, 1996, 1998, Willert et al. 1998), a second Doppler global velocimeter was built with increased emphasis on operability, portability and reliability. Like its predecessor the system follows the general principle of frequency selective filtering by means of an iodine cell as put forward by Komine (1991) and Komine et al. (1991). Unlike many other DGV-systems relying on pulsed laser light sheet illumination as presented elsewhere, this system is optimized for the measurement of time-averaged, planar velocity fields in three components. This is accomplished by illuminating the plane of interest with light from a frequency-stabilized, continuous-wave laser (Ar+ at \( \lambda = 514 \ \text{nm} \) and 1-2 Watts of single-mode power) from three different directions in succession thus providing three separate Doppler-shifted images (see Fig. 1). Given the viewing and illumination geometry the three Doppler-shifted images can then be converted to Cartesian velocity components.

Even though Fig. 1 suggests orthogonal viewing of parallel light sheets, the hardware and dedicated software allow oblique viewing arrangements with diverging or converging light sheets. Image de-warping techniques common also in stereo particle image velocimetry are used to reconstruct the light sheet plane. Optimum measurement uncertainty is achieved when the light sheets are arranged with 120° angular separation which is not always possible for practical reasons. Since the light scattered by the seeding particles typically has a strong angular dependence (Mie scattering), that is, forward scattered light is generally more intense than backward scattering, an orthogonal view of the three light sheets will provide similar image intensities. For oblique viewing arrangements the image integration times have to be adapted accordingly to achieve optimum dynamic range in each image.

The camera system which is shown schematically in Fig. 2 uses a single lens to image the region of interest. The intermediate image formed by the collection lens is projected onto two CCD sensors by a relay lens pair and adjoining polarization-independent beam splitter. One of the two optical paths passes through the iodine absorption cell thereby providing a signal image. Another image is projected onto the reference CCD sensor which is necessary to normalize the image recorded by the signal CCD. After initial coarse alignment of the CCDs with respect to each other, automated image de-warping by software is used to not only account for the residual CCD misalignment but also to reconstruct the object coordinates in the case of oblique viewing. The light sensitivity of the camera system is roughly \# 2.8. However the presence of the beam splitter reduces the effective sensitivity by a factor of two. Further, a 50% neutral density filter in front of the reference CCD compensates for the non-resonant absorption within the iodine cell. In effect, only one fourth of the collected light reaches each CCD sensor. Ideally, a beam splitter with a 30%/70% or 25%/75% splitting ratio could improve the camera system’s sensitivity. However, essentially polarization-free beam splitters are not commonly available.
An important aspect of a DGV-system is the choice of recording cameras. Contrary to particle image velocimetry, DGV does not image single particles over an otherwise dark background, but rather records an image intensity field in which all pixels locally have similar intensity levels. This implies that DGV inherently requires a combination of higher seeding intensity and cameras with increased sensitivity. Furthermore, the DGV-method relies on the calculation image intensity quotient between the iodine filtered (signal) and reference images which requires a high dynamic range and good signal-to-noise ratio of the cameras to achieve an adequate measurement accuracy.

The DGV image recording system of the present setup is comprised of two high-resolution, thermoelectrically cooled (-15°C) CCD camera systems with a dynamic range of 12 bit. A high sensor resolution was chosen not on the basis of increasing the spatial resolution; in fact, the relay imaging configuration shown in Fig. 2 only has a resolution limit of approximately 8 pixels at F#4. Rather, “pixel-binning”, that is, the merging of square clusters of pixels into one (typ. 2×2, 3×3, 4×4 px), is applied to the recorded image in order to increase the signal-to-noise ratio. This effect is illustrated in Fig. 3 which shows the signal-to-noise ratio (SNR) of the camera as a function of the CCD exposure level. The SNR is roughly proportional to the square root of the exposure, indicating that photon shot noise dominates (Holst, 1998). Thus, pixel binning can be used to improve the SNR proportional to
the square root of the number of binning pixels, also shown in Fig. 3 for data obtained by experiment. For the DGV-measurements presented herein 4×4 pixel binning increased the camera SNR from 170:1 (45 dB) to 680:1 (57 dB) at 90% saturation. At the same time the spatial resolution is decreased from 1280×1024 pixel to 320×256 pixel which is still beyond the spatial resolution provided in typical PIV applications. (Note: The DGV vector maps presented in this paper were de-sampled by another factor of four.)

A second important factor in the choice of CCD cameras for time- and phase-averaging DGV is their characteristic during long integration times, especially with regard to the accumulated dark current and associated dark current noise. The dark current is strongly reduced by cooling the sensor (approx. halved for each 6-7°C temperature reduction, Holst, 1998). Fig. 4 shows the accumulated average image intensity without incident light for integration times between 1 and 60 seconds and represents the charge accumulated only by the dark current which is less than 10 counts per minute over a block of 4×4 pixels (or less than 1 count min⁻¹ px⁻¹). This performance allows the CCDs to collect the DGV signal for rather long integration periods without any significant side effect. However, to take full advantage of this feature, good light shielding of the CCDs and imaged area from parasitic light (e.g. daylight, light from laboratory instruments) is mandatory. Since complete darkness generally can not be achieved in practice, recordings of the background signal prior to the actual measurements account for this light as well as the constant dark current and A/D-converter offset. The highly linear response of the CCDs allow the subtraction of these background images from the images of the seeded flow to provide the net-images from which the signal-to-reference intensity ratio can be computed.

Another requirement for making time-averaged measurement possible is to guarantee a frequency-stable operation of the laser during the time of data acquisition. This is achieved by stabilizing the laser on the absorption profile of a second iodine cell. As shown in Fig. 5, a continuous measurement of the frequency-dependent cell transmission, by means of two photo-diodes, is used in a feed-back stabilization circuit to adjust both the etalon temperature and the resonator length. While the intra-cavity etalon ensures a single-mode operation of the laser by selecting one of the 70 modes within the gain profile of the laser, a DC-offset on the piezo-mounted front cavity mirror shifts the laser frequency to the appropriate transmission of the iodine cell. An additional modulation of the resonator length by wobbling the cavity mirror in conjunction with a lock-in amplifier adjusts the etalon temperature to the mode maximum. At the same time this mode-lock avoids the occurrence of etalon mode ‘hops’, which are frequency jumps on the order of the laser free spectral range (typically 150 MHz). The dynamic range of the piezo and temperature control were chosen such that the laser can be tuned within a 1 GHz range such that the entire iodine cell transmission profile can be scanned for calibration purposes. The stabilization concept was realized in the form of a self-contained microcontroller-based system which can be monitored and configured from a PC via a serial line.
2.2 Extension of the DGV-system to phase-averaged measurements

Phase-averaging DGV measurements can be accomplished in a variety of ways. One approach would be to use a frequency-stabilized pulsed laser which is synchronized to the cyclic events of the experiment while the camera either integrates the image continuously, is shuttered synchronously with the laser, or records a sequence of images which are then integrated by software. An alternative approach to phase-averaged DGV utilizes a frequency-stabilized CW-laser where phase-synchronous exposure of the CCD sensors can be achieved by an electronic camera shutter or by modulation of the CW-light while the sensor stays active. The latter approach was chosen for this application, mainly because of its rather simple implementation – it only required the addition of a Bragg cell as shown in Fig.5. Due to its short response time (< 1µs), synchronization with external events, such as the periodic trigger of the cam-shaft, is straight-forward. This would not have been the case for pulsed lasers which generally operate at fixed frequencies with a fixed lead-time for stimulating the laser medium prior to emission (typ. 200µs for Nd:YAG). In principle, a Bragg cell triggered CW-laser could be triggered by stochastically recurring events which would not be possible with standard Nd:YAG systems.

A positive side effect of utilizing a Bragg cell is that it serves as an optical isolator: Typically, any back-reflection of the stabilized laser light into the resonator by lenses, fiber ends, etc. can stimulate multi-mode operation of the laser which destroys its single-frequency behavior and ‘confuses’ the stabilization system. Generally, Faraday optical isolators are used to avoid this problem. In this case, the frequency-shifting nature of the Bragg cell operated at 40 MHz causes the back-reflected light to be shifted by a total of 80 MHz which is approximately half the free spectral range of the laser (e.g. etalon mode spacing, 150 MHz). Since the laser frequency stabilization system ensures that the laser operates at a mode’s maximum, the back-reflected light will be close the minimum between two etalon modes and hence is not amplified within the resonator.

2.3 The Engine Test Rig

The DGV measurements described in this paper were performed on an externally driven engine as diagrammed in Fig. 6. To simplify the experimental procedure and adjoining numerical simulation, a cylinder head without any pistons and sealed inlet ports was placed on a pressure vessel. Only the cam-shaft was driven by a high-torque variable speed DC-engine. A straight pipe connected upstream of the pressure vessel contained an orifice-plate flow meter and temperature and pressure sensors for acquisition of the standard operational parameters. A ferromagnetic sensor placed on the cam-shaft gear provided a precise trigger for the phase-averaged measurements. This trigger was fed into a PC-based, digital phase-shifter that operated on the basis of frequency counters. Given a fixed angular phase resolution (up to 65536 steps), the phase shifter uses the preceding phase to calculate the position of the output trigger in the current phase with respect to the input trigger. The exposure period of typically 5° was set manually for each engine speed using an analog delay generator. The resulting top-hat trigger pulse was then applied to the Bragg cell which in turn generated phase-synchronous laser light pulses for the DGV measurements.

2.4 DGV Setup on the Engine Test Rig

The measurements on the engine’s exhaust manifold were conducted under atmospheric conditions such that the introduction of the light sheets into the measurement plane was straight forward, that is, there was no need for a pressure-sealed light sheet access modules that is commonly used for the measurement of confined flows (see for
instance Fig. 12). A nearly orthogonal viewing arrangement was chosen (Fig. 6). A collection lens with f=105mm at f#2.8 allowed the camera to be placed in sufficient distance from the plane of interest to minimize the contamination by occasional oil droplets expelled from the engine. Because back reflections and scattered light increase the measurement error by biasing the Doppler-shifted signal, beam dumps were placed beyond the measurement plane to capture the light sheet. Flow seeding on the basis of ethylene glycol (a liquid) was provided by means of several atomizer generators equipped with impactors that delivered droplets in the sub-micron range (< 0.5µm). Although the scattering cross-section of these particles is rather small, this seeding material was chosen because it showed the least amount of coagulation and contamination during its long passage through the engine ducts and valves. The seeding was introduced several meters upstream of the orifice flow meter in the pressurized air supply line which guaranteed a proper measurement of the mass flow rate as well as ensured optimum distribution of the seeding to all of the four active engine exhaust valves.

3. DGV MEASUREMENT RESULTS

Figures 7 and 8 show examples of the phase-averaged velocity data obtained for the exhaust manifold as shown in Figure 6 at engine speeds of 2000 rpm and 6000 rpm, respectively. In the velocity plots color coding is used to map the out-of-plane velocity component (primary flow) while vectors indicate the in-plane (secondary) flow. These results were obtained with a phase resolution of 5° and a spatial resolution of 0.8 x 0.8 mm². For clarity reasons only one half of the vectors are shown. Given a camera integration time of 30 seconds, the phase-averaged velocity represents the average of 500 single-shot measurements for 2000 rpm (1500 shots at 6000 rpm).

The dramatic changes in the flow topology at different phase-angles are due to the exhaust flow of the two different cylinders which open at different times with a phase shift of 90° on the cam-shaft. A vortex pair near the right edge of the oval measurement plane can be attributed to flow separation in the sharply turning flow issuing from cylinder 3. In contrast, the secondary flow formed by cylinder 4 exhibits a more uniform structure with less vortical structures in the in-plane (secondary) flow. At the higher engine speed of 6000 rpm (Fig. 8) compressibility effects such as mass-flow oscillations with a frequency higher than the fundamental can be observed, especially in animated sequences of the data or the mean flow data presented in Fig. 9. For the lower engine speed of 2000 rpm the mean exit velocity exhibits nearly constant mass flows around the maximum valve opening which is not the case at 6000 rpm. This can be explained by the increased influence of inertia effects at higher engine speeds, that is, the acceleration and deceleration of the air column in the manifold influence the time history of the mass flow at the exit plane. Figure 9 demonstrates this in form of an angular lag of the mean exit velocity at 6000 rpm with respect to 2000 rpm. Also, after the valves of cylinder 4 have fully closed (≈ 220°) a strong back-flow into the manifold can be observed.
Fig. 7: DGV-Measurements at four different cam-shaft angles at an engine speed of 2000 rpm. Color coding represents the out-of-plane (normal) velocity component, vectors indicate the in-plane (secondary) flow.

Fig. 8: DGV-Measurements at four different cam-shaft angles at an engine speed of 6000 rpm. Color coding represents the out-of-plane (normal) velocity component, vectors indicate the in-plane (secondary) flow.
Fig. 9: Average exit velocity at 2000 rpm (left) and 6000 rpm (right). The solid line in the right plot indicates the result obtained by the numerical simulation.

4. NUMERICAL SIMULATION

4.1 Computational Model

The goal of the presented application was the validation of the transient flow calculation in an exhaust manifold. The major issues to look for were not only the proof of the quality of the numerical results but also the required level of the complexity of the physical modeling and the required extensions of the calculation domain. The mesh presented in Fig. 10 contains about 635,000 cells. As long as the exhaust valves of cylinder 3 or 4 were open the computational domain was extended to a portion of the cylinders as well, that is, the impact of the valve motion on the flow pattern was fully resolved. Each cylinder part was modeled using about 80,000 cells, the two siamese exhaust ports each contained about 150,000 cells, the exhaust manifold was built up with another 160,000 cells. The mesh motion was done using the preprocessor of STAR-CD which was interactively called by the solver. Using a highly parallel version of the code STAR-CD the CPU time could be reduced to about 8 days on a SGI Origin R12000. The computational domain was decomposed into 4 parts which results in a calculation speed-up factor of about 3. The code solved for the compressible Navier-Stokes equations. The presented results were achieved using the standard $k$-$\varepsilon$ model.

The transient flow was simulated for an engine rpm of 6000. Equivalent to the test rig conditions a constant pressure of 1.1 bar was set at the border of the calculation domain below the exhaust valves. This boundary was placed about 20 mm below the cylinder head. At the exit plane of the exhaust manifold the pressure history was taken from a discharge motion program. Initial values for pressure and temperature were also taken from the discharge motion program.

Fig 10: Finite volume mesh of the Audi 5-valve gasoline engine featuring two cylinders, exhaust ports and a part of the exhaust manifold.
4.2 Comparison between simulation and experiment

Figure 11 shows the comparison of measured and calculated data of the unsteady flow field during the exhaust stroke of cylinder 3 shortly before the exhaust valves of cylinder 4 will open. On the left hand side the measured data for the normal velocity distribution (upper row) as well as of the secondary air motion (velocity vectors in the lower row) are presented. The corresponding calculated results are presented on the right. The maximum velocity observed in the numerical results is lower by about 20%. The flow patterns are very similar. The position and strength of the vortices of the secondary air motion differs compared to the measured data. The use of nonlinear, two-equation turbulence models mostly influences the secondary flow. Preliminary results using nonlinear $k$-$\varepsilon$ models showed only small differences compared to those results of the standard turbulence model. Nevertheless, a very striking agreement can be observed for integral quantities such as the mean exit velocity as plotted in Fig. 9. This comparison to the experimental data proves that the numerical model not only matched the velocity magnitude but also was able to reproduce the compressibility effects (i.e. higher order fluctuations) already observed in the experimental data.

The above shown quality of the numerical predictions could be demonstrated over a wide range of the full cycle. Taking into account the time-dependent, three-dimensional nature of the highly pulsating flow, the achieved agreement between measurement and calculation was judged to be sufficient in order to assess different concepts in an early stage of the development process.

Fig.11: Comparison of measured and calculated data of the unsteady flow field during the exhaust stroke of cylinder 3. Measured data is shown on the left, calculated data on the right. Upper row: normal velocity distribution, lower row: secondary air motion.

5. CONCLUSIONS AND OUTLOOK

At Audi the development of new concepts have been supported by computational fluid dynamics (CFD) calculations. The proof of the quality of the numerical results is a major prerequisite for achieving such a goal. The presented DGV results provided the data base for the validation study of the pulsating flow in an exhaust manifold. The comparison between measured and calculated data showed an encouraging agreement in flow topology and cyclic behavior. Very good agreement was achieved for integral quantities such as the mean
manifold exit velocity. Based on these results the numerical application fulfills the requirements of Audi, which will allow to assess different design concepts in an early stage of the engine development process.

Aside from the presented application, further DGV measurements were performed on the confined flow downstream of the turbo-charger and upstream of the catalytic converter. Optical access for the three light sheets was made possible by means of sealed windows placed around the circumference of the measurement plane (Fig. 12). A fiber-bundle endoscope attached to the camera placed downstream of the measurement plane transmitted to the image to the camera system. The successful application of DGV to the engine test rig was the result of a number of iterative modifications especially with respect to flow seeding and suppression of scattered light. To reduce the particle fall-out, seeding based on sub-micron ethylene glycol droplets, typically used for laser-2-focus velocimetry, was chosen. In addition, purging air on the endoscope and light sheet windows reduced their contamination. (Due to confidentiality reasons, data from this application can not be shown herein.)

Numerical simulations generally require averaged velocity data as a data base for validation. The inherent feature of the presented DGV system of providing time- or phase-averaged velocity data by simple integration of the scattered light, makes the method predestined to provide this type of data with a short turn-over time. At the same time DGV serves as a flow diagnostic tool complementary to unsteady measurement techniques such as PIV. Although stereoscopic PIV can provide the equivalent three-component velocity data, the vast number of required samples, typically more than 50-100 images per phase angle, makes this approach impractical for this type of application. In addition PIV is not as well suited for the measurement of flows with a primary velocity component normal to the imaged plane.

In the presented application the DGV measurements were performed in a cold, that is, unfired, environment. The current DGV development efforts at DLR are directed toward making these type of measurements possible in hot or combusting flows using a specially designed, long-pulse Nd:YAG laser (Fischer et al., 2000). The aim there is to utilize the higher light intensity provided by a pulsed laser in conjunction with shuttered CCD cameras to overcome the background radiation of the flame during the DGV measurement. Although flow measurements in flames have been demonstrated in numerous recent publications using both LDA and PIV, the increased refractive distortions due to strong density gradients (e.g. beam steering) at higher pressures and longer optical penetration depths makes the use of these diffraction-limited imaging techniques practically impossible. In contrast DGV merely records the Mie-scattered light as an intensity field and does not need to resolve individual particles. Therefore DGV is predestined to provide velocity data in environments with strong refractive distortions (e.g. in combustion chambers) and/or environments poor optical access.

Fig. 12: Optical arrangement for DGV measurements downstream of a turbo-charger and waste-gate.
REFERENCES


