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LDV-bias corrections for flow rate prediction in turbulent pipe flow

LDV-Bias-Korrekturverfahren zur Volumenstrombestimmung in turbulenten Rohrströmungen

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Abstract

Laser-optical measurement techniques in pipes are commonly applied for flow diagnostics. More recently they are also used to determine the flow rate. Therefore uncertainties must be sufficiently low to be competitive with conventional flow meters. In this contribution the implication of the bias effect on flow rate prediction in turbulent pipe flow is investigated. LDV data sets from two different test rigs are evaluated and compared to reference flow rate measurements. An overestimation of the flow rate of 1 % for fully developed and 1.8 % in disturbed flow conditions is stated. Furthermore 3 bias correction methods are applied. The combined method of inverse velocity magnitude and trapezoidal time weighting exhibits the best results for fully developed conditions as it eliminates the bias effect almost completely. In disturbed flow conditions this method is over correcting the bias effect. Overall the inverse velocity magnitude weighting exhibits the lowest absolute errors. All bias correction methods provide lower absolute errors then the arithmetic average. Therefore the application of a bias correction is recommended.

Introduction

Laser-Doppler-velocimetry (LDV) is used to measure fluid velocities in various fluid mechanical applications. In pipe flow it is mostly used to determine the velocity profile in a cross section to estimate errors of flow meters (Halttunen (1990); Wendt et al. (1996)) or to characterize test rigs (Müller et al. (2006)). More recently the LDV-technique is also used to determine the flow rate, see Guntermann et al. (2011), Juling et al. (2016), and Mickan and Strunck (2014).

In the project “EnEff:Wärme: On-site calibration of flow meters in district heating“ LDV measurements are used for calibration of flow meters. Therefore the accuracy of the measured velocities is critical. A reduction of the bias effect is an important aspect in order to reduce the measurement uncertainty.

With LDV the velocity of small particles inside the fluid is measured, rather then the velocity of the fluid itself. At test rigs sufficiently small particles are added, which have a very similar density as the fluid. Assuming that the particles are equally distributed and follow the flow without a slip, the particle’s velocity is equal to the fluid’s velocity. Considering turbulent flow, the velocities are fluctuating over time. To obtain representative quantities the measured velocities must be averaged. The most commonly applied method is the arithmetic average.

Mainly two effects cause the so called bias to overlay the arithmetic average: turbulent irregular fluctuations in time and strong velocity gradients inside the measurement volume. Both effects are difficult to separate, as the velocity gradient in the measurement volume creates a virtual turbulence in the detected time sequence. Particles with higher velocities are more likely to pass the measurement volume. In fact there are several more effects causing the arithmetic average to be defective. For example a filter bias and an angle bias are described in Edwards (1987). For measurements near the wall also a wall bias (or wall effect) occur, see Steinbock et al. (2017).

The LDV bias effect was firstly recognized in McLaughlin and Tiederman (1973), where a correlation to the square of the turbulence intensity was shown. Different methods to eliminate the velocity bias were proposed and applied in literature, with partly conflicting recommendations, e.g. see J. L. Herrin (1993); Adrian and Yao (1987); McDougall (1980) and Edwards (1987). The best choice of an correction method depends on the type of application and apparatus.

In this contribution the bias effect with implication for flow rate prediction is studied for fully developed and disturbed turbulent pipe flow. An overview of common methods is given and discussed, additionally a new method is proposed. Selected bias correction methods are applied to a measurement data set consisting more than 30000 single LDV measurements from two pipe flow test rigs and compared with reference flow rates.

Averaging techniques of burst signals

In the following an overview of the existing bias correction methods is given. The first class of correction methods can be labeled as **time averaging methods**. As they interpret the measured velocities as sample points of a continuous function over time t. Therefore any numerical integration scheme could be applied to approximate the mean value

$$\bar{u}_t = \frac{1}{T}\int\limits_0^T u(t)\,\mathrm{d}t \tag{1}$$

by a weighted sum

$$\tilde{u}_t = \frac{1}{\sum_0^{N-1} w_i}\sum_0^{N-1} w_i u_i. \tag{2}$$

The total measurement time at a location is denoted T. For weights $w_i = 1$ the arithmetic average is obtained.

Controlled processors/saturable detectors were firstly proposed in Edwards and Jensen (1983) and describe sampling techniques. The goal of the methods is to eliminate the bias by sampling in equally spaced time intervals. Any LDV system can be seen as a saturable detector if the present data rates are higher than the data processing speed. The success of the methods depends of the time scales of the flow, LDV system and sampling, for details see J. L. Herrin (1993); Edwards (1987) and the references within. However these methods usually induce data loss, which is critical for low data rates. Thus those methods are not considered in this contribution.

Sample and hold weighting / interarrival time weighting has been proposed in Barnett and Bentley (1974). For the sample and hold weighting the weights according to Equation 2 are set to $w_i = t_{i+1} - t_i$, whereas for the interarrival time weighting $w_i = t_i - t_{i-1}$. With both weights only constant functions can be exactly approximated. Here a variation of the methods is considered: the **trapezoidal rule (trpz)**. It is defined by

$$\tilde{u}_{trpz} = \frac{1}{2T} \sum_{i=1}^{N-2} (t_{i+1} - t_i)(u_{i+1} + u_i). \tag{3}$$

It can be applied with the same effort as the previous method, but inherits first order accuracy.

Other classes of correction methods are based on correlations of the bias effect with other quantities. In contrast to the time averaging methods it is not tried to reconstruct the time series itself.

Inverse velocity magnitude weighting (ivmw) was already proposed by McLaughlin and Tiederman (1973). It takes into account that fast particles pass the measurement volume more often then slow ones. The weights according to Equation 2 are set to $w_i = 1/|u_i|$, whereas the absolute value $|u_i| = \sqrt{u_{ix}^2 + u_{iy}^2 + u_{iz}^2}$. This method assumes the burst number to be proportional to the velocity. Therefore equally distributed particles in the fluid are an important requirement. Some authors do not recommend this method, e.g. Edwards (1987) and J. L. Herrin (1993). However the method seem promising to decrease the gradient bias. Here the procedure is used with a simplification that for the calculation of the weights w_i only the axial velocity is taken into account i.e. $|u_i| = |u_{iz}|$. For high flow rates or fully developed pipe flow this simplification seems appropriate.

The methods **velocity-data rate correlation** and **particle residence time weighting** are not considered in this work as informations about the residence time of a particle within the measurement volume are necessary but not available in the present data sets, e.g. see Meyers and Clemmons (1978).

Square turbulence intensity weighting is denoted as $\bar{u}_{tu} = \frac{\bar{u}_b}{1+\mathrm{Tu}^2}$, whereas the turbulence intensity is defined as the relative standard deviation Tu$= \sigma/\bar{u}$. This method was firstly proposed in McLaughlin and Tiederman (1973). It has been demonstrated theoretically as valid for turbulence intensities Tu < 0.5 in Zhang (2002). However this method is only recommended for an estimation of the bias error and is not suitable for a correction.

A combined method is proposed in order to compensate the velocity bias and additionally the gradient bias. Therefore the inverse velocity magnitude and the trapezoidal time weighting are combined. It approximates the integral

$$\bar{u}_{wtrpz} = \frac{1}{\int_0^T 1/|u|} \int\limits_0^T \frac{u}{|u|} \,\mathrm{d}t \tag{4}$$

with the trapezoidal rule

$$\tilde{u}_{wtrpz} = \frac{1}{2\sum_{i=1}^{N-2}(t_{i+1} - t_i)(\frac{1}{|u_{i+1}|} + \frac{1}{|u_i|})} \sum_{i=1}^{N-2} (t_{i+1} - t_i)(\frac{u_{i+1}}{|u_{i+1}|} + \frac{u_i}{|u_i|}), \tag{5}$$

and will be referred to as **weighted trapezoidal rule (wtrpz)**.

Measurement Setup

The first data set is obtained at the heat meter test section, the so called "Wärmezählerprüfstrecke" (WZP) at the Berlin Institute of the Physikalisch-Technische Bundesanstalt (PTB). The WZP is a gravimetrically traceable flow measurement facility. The reference flow rate is determined via the mass, the density and time. Volume rates from $5\,\mathrm{m^3\,h^{-1}}$ to 1000 $\mathrm{m^3}$/h and temperatures from $3\,^\circ\mathrm{C}$ to $90\,^\circ\mathrm{C}$ can be provided. The expanded relative uncertainty of the volume realization amounts to $U = 0.04\,\%$ (k=2), compare Mathies (2005). For the measurements presented here, the test facility is set to the following parameters: In pump operation, a volumetric flow velocity of 0.24 m/s and 1.45 m/s is generated. This corresponds to a flow of 29.52 $\mathrm{m^3}$/h and 177.14 $\mathrm{m^3}$/h and to a Reynolds number of $5 \cdot 10^4$ and $3 \cdot 10^5$. Approximately 50 g of tracer particles, each with a diameter of 15 μm, were added to the approximately 100 t of water held in reserve in the test facility. The test rig has two measurement sections, both of them have a free installation length of approximately 25 m. The investigations take place in the dimension DN 200, with special tubes supplied by the SEIKO company. Due to a special design, these tubes have a maximum flange offset of 50 μm. This makes a reproducible setup of the section possible, without any mismatch or edges which might influence the flow. The tubes have a wall roughness of less than 0.5 μm and a waviness smaller then 1 mm / 25 m. LDV measurements were carried out at distances of 20 D, 40 D, 50 D, 60 D and 85 D from the inlet section, where a flow conditioner package is installed. Those measurements are referred to as fully developed. Additionally different flow disturbers were installed 50 D behind the inlet section: A 1/3-segment orifice, a swirl generator (see Figure 1, top right) and a ball valve with three different closing angles (15°, 30°, 70°). The LDV measurements were obtained 6 and 11 D behind each flow disturber. Those measurements are referred as disturbed flow conditions.

The second experimental data set were obtained on a test rig at the department of fluid system dynamics of the Technical University (TU) in Berlin[1]. The test rig contains plastic pipes with a smooth surface and a nominal diameter D of DN50. For the most measurements the fluid temperature was about $25\,^\circ\mathrm{C}$. Two electro magnetic flow meters are installed. To ensure low uncertainties in flow measurement they have been calibrated with their respective inlet configuration at the WZP. However the mean value of both meters is taken as reference flow rate in this work. LDV measurements were carried out at distances of about 100 D from the inlet section, where a flow conditioner package is installed. Those measurements are referred to as fully developed. They were performed at 7 different Reynolds numbers ranging from $1.7 \cdot 10^4$ to $4 \cdot 10^5$. Additionally different flow disturbers were installed 100 D behind the inlet section: A 1/3-segment orifice, a swirl generator and a ball valve with three different closing angles (15°, 30°, 70°). Additionally combinations of pipe elbows were installed, two closely coupled 90° elbows in-plane and 6 closely coupled elbows out-of-plane with different distances to each other, see Figure 1 right bottom. Those measurements are referred to as disturbed flow conditions. The Reynolds numbers and measurement positions of the disturbed measurements correspond to those conducted at the PTB.

At the PTB the LDV probe is a commercial system with a Nd:YAG laser having a wavelength of λ = 532 nm. The transmission lens has a focussing length of 250 mm. The interference fringe distance determined thereby amounts to $\Delta x = 2.96\mu$m. The length of the measurement volume is approximately 1 mm. At the TU Berlin the LDV apparatus is a fp50 shifted LDV-System from the company ILA R&D GmbH. It consists of a Nd:YAG laser with a wavelength of 532 nm, a

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[1] Measurement data obtained by F. Neuer and A. Swienty

focus length of 120 mm, a Beam Distance of 45 mm, an actual fringe distance of 1.44 μm. The length of the measurement volume is approximately 0.5 mm. Both probes have been calibrated on a velocity standard with an uncertainty of $U(u) < 0.018\%(k = 2)$. The sample rate of the system is 50 MHz, whereas the maximal possible realization of measurement data rate is 10 kHz.

On both test rigs the measurement volume is positioned on a grid consisting of 25 radial and 20 angular locations in concentric circles, see Figure 1.

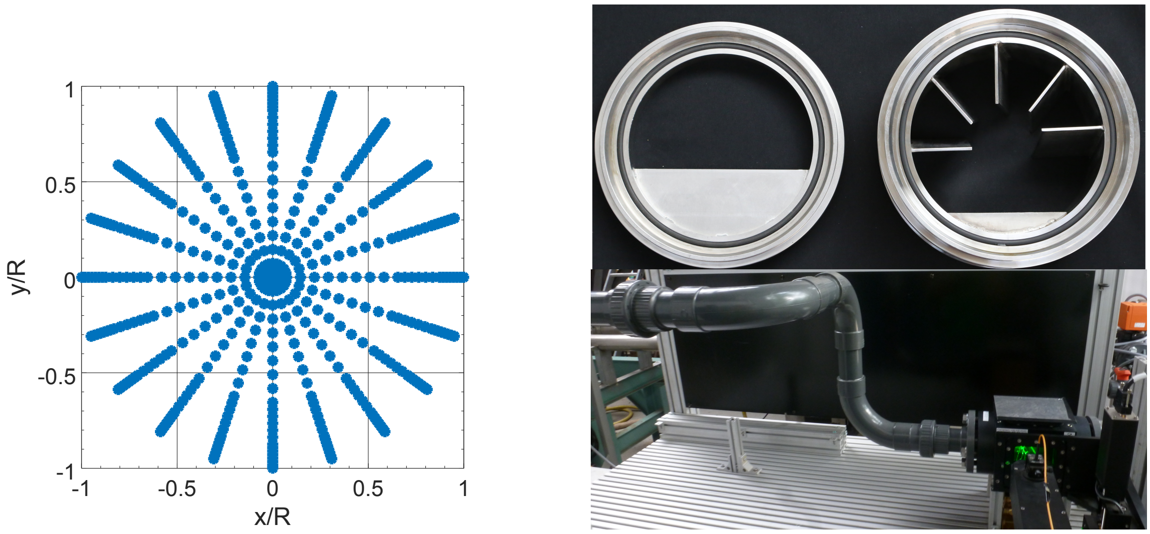

Figure 1: Left: the LDV measurement grid on a pipe cross section for normalized spatial coordinates. Right: two flow disturber in DN200 and three elbows out-of-plane in DN50.

Flow rate prediction with LDV measurements

The flow rate Q is calculated by the integral in polar coordinates of the axial velocity field over the cross section

$$Q = \int_0^R \int_0^{2\pi} \bar{u}(\varphi, r) r \, \mathrm{d}\varphi \, \mathrm{d}r. \tag{6}$$

Note: here u is always used as the axial velocity that have been in z-direction for all measurements. An LDV data set consists of discrete points, therefore a numerical integration scheme is necessary. Here piecewise linear functions between the measurement points in radial direction and a midpoint rule in angular direction is used to obtain $\tilde{Q}$. A special aspect of the integration of velocity profiles is the steep gradient near the wall. To approximate the integral accurately with piecewise linear functions, many measurement points close to the wall would be necessary. Because of reflections, the wall effect (see Steinbock et al. (2017)) and low data rates this is not feasible. Hence a wall function according to the theoretic velocity profile from Gersten (2005) is connecting the last measured point to the wall. The wall distance of the out most measuring point is chosen such that the measurement volume is not affected by the wall. Additionally measurement points with high standard uncertainty $U_{stat} = 2\mathrm{Tu}/\sqrt{N_{bursts}} < 5$ or less than 5 bursts are removed and interpolated (piecewise linear or with the wall function). With these integration methods the flow rate is slightly underestimated less than 0.1 % for a theoretical profile. The velocities at positions with increasing radius have a greater influence to the flow rate $\tilde{Q}$. At the same time the bias effect is increasing because of the steep gradient and the increased turbulence.

Results

As discribed before, the following averaging methods are applied:

- arithmetic average (aa),
- inverse velocity magnitude weighting (ivmw),
- trapezoidal time averaging (trpz),
- weighted trapezoidal time averaging (wtrpz).

The different integrated velocity profiles are compared to the reference flow meters from the test rigs. The error is defined by

$$\text{error} = \frac{\tilde{Q} - Q}{Q} 100\%, \tag{7}$$

whereas $\tilde{Q}$ is the predicted flow rate from the LDV measurements and Q the reference flow rate. The data set is divided in fully developed and disturbed flow conditions.

For the fully developed case 14 profile measurements are evaluated (7 from each test rig). The average errors of the flow rate prediction of the methods is shown in Table 1 and Figure 2 on the left side. With the arithmetic mean velocities the flow rate is over predicted by 1 % on average with an standard deviation of 0.84 %. All applied methods reduce the bias effect. With the trapezoidal rule the flow rate is still over predicted by 0.8 %, with the inverse velocity magnitude weighting by 0.17 %. The weighted trapezoidal rule shows the best results, it eliminates the bias error almost completely. The standard deviation is slightly increased for the bias correction methods, but does not change significantly for all methods.

For the disturbed pipe flows 55 profile measurements are evaluated. The average errors of the flow rate prediction of the methods is shown in Table 1 and Figure 2 on the right side. As expected higher turbulence intensities enhance the bias error compared to those in fully developed conditions. The flow rate is over predicted by 1.84 % with a standard deviation of 1.32 %. Here again all bias correction method reduce the error. With the trapezoidal time averaging the flow is still over predicted by 1.28 %, the inverse velocity magnitude weighting and the weighted trapezoidal time averaging under predict the flow rate by 0.14 % respectively 0.71 %. The standard deviation is reduced for inverse velocity magnitude weighting and the trapezoidal rule and is slightly enhaunced for the weighted trapezoidal rule.

	fully developed flow conditions				disturbed flow conditions			
	aa	ivmw	trpz	wtrpz	aa	ivmw	trpz	wtrpz
mean error	1.01	0.17	0.82	-0.03	1.84	-0.14	1.28	-0.71
st. dev.	0.84	0.88	0.87	0.92	1.32	0.86	0.88	1.38

Tabelle 1: Mean error and standard deviation of flow rate prediction from LDA data $\tilde{Q}$ in % with different averaging methods for fully (left) and disturbed (right) pipe flow.

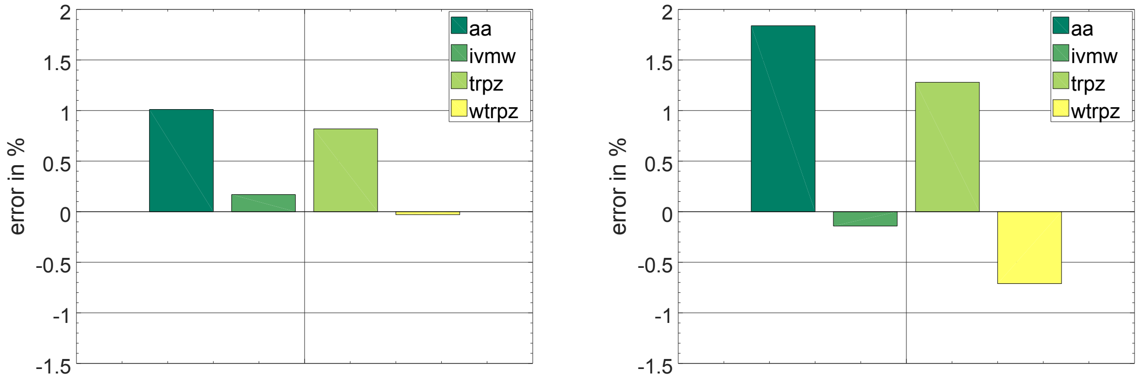

Figure 2: Mean error of the flow rate prediction from LDV data $\tilde{Q}$ with different averaging methods for fully (left) and disturbed (right) pipe flow.

Conclusion

The implication of the bias effect on flow rate prediction in turbulent pipe flow was quantified. For fully developed flow conditions the bias error is lower (1 %) then for disturbed pipe flows (1.8 %). This is due the enhanced turbulence. A conservative bias correction method is the trapezoidal time averaging, it weakens the bias error for all cases (0.8 %, 1.28 %), but is not capable of eliminating the whole bias effect. The inverse velocity magnitude weighting does eliminate more of the bias effect, but for high turbulence intensities it is slightly over correcting the velocity values (0.17 %, -0.14 %). The weighted trapezoidal time averaging can be recommended for fully developed conditions as it eliminates the bias almost completely (-0.03 %), on the other hand it over corrects the velocity values in disturbed flow conditions (-0.7 %). All bias correction methods provide lower absolute errors then the arithmetic average. Therefore the application of a bias correction methods is recommended for flow rate prediction. Further work will focus on finding a correlation of specific flow properties and a best suited method for correction.

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