Highly precise correlation estimates of turbulent shear flows using a LASER Doppler profile sensor and array detection

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Abstract In order to determine characteristic flow structures in turbulent flows, correlation techniques can be used whose precision is based on the resolution and uncertainty of the applied measurement system which is, most of the time, a severe limitation. In this paper a novel sensor system for highly precise correlation estimation is presented, consisting of a laser Doppler velocity profile sensor in conjunction with an array detector. The elongated measurement volume is divided into two detection volumes which are observed independently while maintaining the high spatial resolution of the profile sensor which is in the range of 10 µm. The achieved resolution is approximately 10 times higher compared to systems used in the past, e.g. laser Doppler anemometers or hot-wire anemometers. Parallel processing of the detection volumes is used which increases the data rate and, furthermore, enables the sensor system to evaluate spatial correlation with minimum interarrival times in the range of a few microseconds. Additionally, a new evaluation technique is presented which combines temporal as well as spatial particle separations for the correlation calculation in order to achieve higher data rates in addition to more precise correlation estimations. To prove the applicability, measurements have been performed in the turbulent flow of a free jet as well as in grid generated turbulence. On the basis of correlation functions measured with the laser Doppler velocity profile sensor the Taylor microscale \( \lambda_g \) of the grid turbulence could be determined to 370 µm. The results agree with theory and other experimental data.

1. Introduction

In order to understand the complex flow structures in turbulence, information of instantaneous flow velocities at spatially distinct positions are of significant importance. For the estimation of correlation functions and instantaneous velocity gradients, simultaneous velocity measurements at two spatially separated points in the flow have to be performed. Based on correlation functions, spatial length scales of turbulence such as integral lengthscale and Taylor microscale can be derived. Ideally, the measurement positions have to be located very close to each other, that is why the measurements of local flow velocities at spatially independent points still remain a challenging task. In most cases the spatial resolution of the sensor system is a severe limitation especially with regard to the evaluation of fluctuating flow velocity correlation at small distances which is of outstanding importance for the determination of the mentioned length scales in turbulence research. In the past, different techniques such as laser Doppler anemometry (LDA), particle image velocimetry (PIV) and hot-wire anemometry (HWA) have been used for numerous experimental attempts to evaluate two-point spatial correlations. Due to the physical size of the HWA and the temperature influence of two probes positioned side by side, measurements at small spatial separation distances can hardly be achieved. Moreover, HWA is intrusive and, therefore, disturbs the flow. Hence, it is not an ideal tool for precise correlation estimations. On the other hand, PIV suffers from relatively high velocity measurement uncertainties larger than 3 % [1] which are strong limitations for the mentioned applications. That is a reason why most of the two-point spatial correlation measurements in the past have been undertaken employing several different approaches using LDA systems. Chehrroudi and Simpson [2, 3] applied a scanning mirror device to shift the measurement volume dynamically at different positions in the flow. Another technique that has
been applied quite often in the past is based on a two-point LDA system with an elongated measurement volume [4-6]. This technique utilizes a single very long measurement volume and two independent detection volumes. A further technique uses two completely independent LDA systems, i.e. two measurement and detection volumes [7-9] (see Fig. 1 - left). However, the study by Benedict and Gould [9] revealed that an overlapping of the measurement and/or detection volumes was found to set a severe limitation on the evaluation of two point correlations. This is consistent with the earlier results by Eriksson and Karlsson [7] who stated that the spatial resolution should be in the range of the Kolmogorov length scale, which is often in the micrometer range, in order to estimate correlation functions in turbulent flows properly. Thus, in case of high Reynolds numbers or small geometric sizes, where the Kolmogorov scale becomes very small, the spatial resolution required can hardly be achieved by conventional LDA systems since it is determined by the size of its measurement and/or detection volumes.

The application of the novel laser Doppler velocity profile (LDP) sensor which offers a spatial resolution inside the measurement volume is a promising approach to overcome the drawbacks mentioned above. The sensor utilizes a pair of fan-like fringe systems inside the measurement volume and hence the spatially resolved velocity information is obtained without depending on the position and the size of the measurement/detection volume (see Fig. 1 - middle). That means that the axial position as well as the velocity of a particle passing the elongated measurement volume can be evaluated simultaneously. This approach allows determining the correlation of the velocity fluctuation of two consecutive particles, passing at different positions, and consequently yields the spatio-temporal correlation function. A spatial resolution in the range of a few micrometers was demonstrated already [10] and the applicability of the LDP sensor for two-point spatio-temporal correlation measurements has been shown [11]. Nevertheless, the LDP sensor utilized was not able to measure the flow velocity at two different positions simultaneously since single burst signals are required. This is caused by the fact that two tracer particles passing the measurement volume coincidentally cause interference of the scattered light which cannot be evaluated. To eliminate this problem, a detection array is utilized which separates the measurement volume into two detection volumes (see Fig. 1 - right). With this approach, a significant increase of the effective data rate is possible and even parallel processing of burst signals is enabled.

In this paper, we report about the LDP measurement system which has been applied during measurements in a turbulent free jet and a grid flow.

2. Measurement System

The applied laser Doppler velocity profile sensor consists of two fringe systems which are superposed in the measurement volume [12]. In contrast to conventional LDA systems, the fringe spacing $d$ is not constant but purposely misaligned in order to achieve a diverging and a converging
fringe system, respectively (see Fig. 2). That is why, a burst signal of a tracer particle passing the measurement volume consists of two characteristic Doppler frequencies $f_i$ ($i = 1, 2$), belonging to each fringe system, which are used to determine not only the velocity $v$ but also the position of the particle along the optical axis $z$. In order to distinguish between the two fringe systems, a frequency division multiplexing (FDM) technique has been applied [13] (see Fig. 3). The formed measurement volume has a length along the optical axis of about 400 µm and a diameter of around 40 µm.

For the calibration, a pinhole mounted in a rotating wheel with the constant velocity $v$ is used to determine the quotient $q(z)$ out of the two Doppler frequencies $f_1$ and $f_2$ as follows

$$ q(z) = \frac{f_2(v,z)}{f_1(v,z)} = \frac{v/d_1(z)}{v/d_2(z)} = \frac{d_1(z)}{d_2(z)} $$

(1)

With the known velocity during the calibration the fringe spacing functions follow as

$$ d_i(z) = \frac{v}{f_i(v,z)}. $$

(2)

Afterwards, the velocity $v$ of a particle can be calculated during measurements with the help of the known fringe spacing $d_i$ ($i = 1, 2$) by

$$ v = f_1(v,z) \cdot d_1(z) = f_2(v,z) \cdot d_2(z). $$

(3)

The detection array consists of two fibres, with a core diameter of 400 µm, positioned side by side. Each half of the measurement volume with approximately 200 µm diameter is projected through a 1:2 Keplerian telescope into one of the fibre cores. The whole optical setup is depicted in Fig. 3. Thus, two detection volumes are created while maintaining the high spatial resolution of the profile sensor which could be determined from the calibration data to be lower than 10 µm.

Furthermore, the measurement system consists of two A/D converter cards (2 channels, 8-bit, 1 GS/s, 500 MHz bandwidth, 256 MS memory depth) which record the detected signals of the avalanche photo detectors (APDs), each observing one of the two detection volumes. The converter cards are configured to work independently and can be controlled via a proprietary software which is responsible for the card setup, data acquisition and signal evaluation. Since the two detection volumes are observed independently from each other, the software also includes parallel processing algorithms for each detection volume resulting in an efficient data processing in conjunction with the used multi-core computer system.

One difficulty resulting from the detection array is the handling of the two detection volumes. The focusing of the fibre images causes that the two detection areas do not overlap because of the fibre cladding which means that a certain region in the middle of the measurement volume is not covered
(see Fig. 4 - grey area in the left sketch). Since this is the important region for correlation measurements where particles with a very small spatial separation can be detected simultaneously by the two APDs, this unobserved region is a serious problem. We solved this problem by defocusing the optics slightly hence enlarging the detection areas in such a way that they overlap (see Fig. 4 - grey area in the middle sketch). For future experiments a special aperture with a high aspect ratio forming rectangular detection areas shall be applied (see Fig. 4 - right). This will help to eliminate any unobserved regions while creating almost no overlap of the detection volumes. Another problem is the measurement cards which are working independently and, therefore, not absolutely synchronously. A variable initialization time difference of around 8 µs could be determined during tests with a function generator.

A further crucial point is that, due to measurement uncertainties, the system cannot distinguish between two separate particles passing the overlapping region and one particle being detected twice which is called double detection. Further details concerning the temporal and spatial resolution of such critical bursts can be found in the following section.

3. Data Evaluation and Uncertainty Discussion

In order to estimate the measurement uncertainty of the sensor, a test measurement has been performed in order to determine the characteristics of the system. Within the overlapping region, the occurring double detections should ideally cause the same results when evaluated by both detectors. Due to additive noise (e.g. shot noise of the photo detectors and quantization noise) as well as the different initialization time of the A/D converter cards the measurement results differ. In Fig 5 the results of the double detections in a small region around $\Delta z = 0$ and $\Delta t = 0$ is shown. Due to the error propagation the standard deviations of this concentration is $2^{0.5}$ times the standard deviations of the whole array measurement system stated in Table 1.

![Fig. 5: Double-detection distribution in the overlapping region around $\Delta z = 0$ and $\Delta t = 0$.](image)

Another crucial point is the achievable burst pair data rate $f_{\text{measure}}$, which represents the amount of evaluated burst pairs allowing the maximum interarrival time $\Delta t$. With a mean data rate of $f_{\text{particle}}$ for each detector of around 10 kHz, an evaluation probability $p_{\text{eval}}$ of around 2% and the relation of recording time $T_{\text{rec}}$ and processing time $T_{\text{proc}}$ it can be estimated by the following formula (in case of $f_{\text{particle}} \ll 1/(2 \cdot \Delta t \cdot p_{\text{eval}}^2)$)

$$f_{\text{measure}} = f_{\text{particle}} \cdot 2 \cdot \Delta t \cdot p_{\text{eval}}^2 \cdot \frac{T_{\text{rec}}}{T_{\text{rec}} + T_{\text{proc}}}.$$  \hspace{1cm} (4)

As a result, a burst pair data rate $f_{\text{measure}}$ of around 2.3 Hz was achieved and measurements lasting more then 6 hours have been performed per position in order to achieve an adequate amount of data for the correlation estimations. In order to determine the stability of the experimental flow setup
long-term HWA measurements have been performed beforehand in order to determine the stability of the windtunnel. The turbulence degree was determined to 0.2 %. Drift effects can be neglected since repetitive measurements have been performed and each dataset has been evaluated separately.

Table 1: Spatial, temporal and velocity uncertainty of the whole measurement system.

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>spatial uncertainty $\sigma_z$</td>
<td>15 $\mu$m</td>
</tr>
<tr>
<td>temporal uncertainty $\sigma_t$</td>
<td>10 $\mu$s</td>
</tr>
<tr>
<td>rel. velocity uncertainty $\sigma_v/v$</td>
<td>0.5 %</td>
</tr>
</tbody>
</table>

4. Correlation Estimation

In general, correlation estimations are based on precise and simultaneous measurements of the flow velocity $v_i$ at different, spatially separated positions. The measured flow velocities $v_i$ are separated (Reynolds decomposition) into a mean flow velocity $\bar{v}_i = 1/M \sum_{n=1}^{M} v_{i,n}$ and a fluctuating velocity component $v_i'$ as follows

$$v_i = \bar{v}_i + v_i'$$

from which the velocity fluctuations $v_i'$, caused by vortices, are of importance. The aim is to investigate the relations of the fluctuating velocity $v_i'$ which can be done with the help of the normalized spatio-temporal correlation function $\rho_{ij} = (\Delta r_k, \Delta t)$, where $i,j,k$ are the directions of interest, which reads as follows

$$\rho_{i,j}(\Delta r_k, \Delta t) = \frac{v_i'(r_0,t) \cdot v_j'(r_0 + \Delta r_k, t + \Delta t)}{\sqrt{(v_i'(r_0,t))^2 \cdot (v_j'(r_0 + \Delta r_k, t + \Delta t))^2}}$$

(6)

On basis of this formula pure temporal as well as pure spatial correlation can be estimated in case of allowing no separation either in a spatial ($\Delta r = 0$) or a temporal ($\Delta t = 0$) sense, respectively. Nevertheless, due to spatial and temporal uncertainties of the measurement system (see Sec. 3) the detected particle pairs occurring within the $\pm 2\sigma$ uncertainty limits (see Fig. 6 - red dashed box around $|\Delta z| = 0, \Delta t = 0$) are erased before estimating the correlation functions. Moreover, pure spatial correlation is practically impossible since the probability of two particles passing the two detection volumes at exactly the same time is very low. This is the reason for a very small interarrival time to be allowed in general, resulting in spatio-temporal correlation estimations. The main aim is to reduce this interarrival time as much as possible in order to minimize the bias of the correlation function which is caused by the different measurement times.

The characteristic Taylor microscale $\lambda$, which represents the average size of the intermediate eddies, is defined on basis of the correlation functions as follows [14]

$$\lambda = \frac{1}{\sqrt{-0.5 \cdot \rho_{i,i}''(\Delta r_k = 0, \Delta t = 0)}}.$$  

(7)

A parabola $p(\Delta r_k)$ fitted to the correlation function in the region around $\Delta r_k = 0$ can be used to determine the Taylor microscale on basis of the correlation results. This means the parabola has to fulfill the following criteria $p(0) = \rho_{i,i}(0,0), p'(0) = \rho_{i,i}'(0,0)$ and $p''(0) = \rho_{i,i}''(0,0)$ which means that

$$p(\Delta r_k) = 1 + 0.5 \cdot \rho_{i,i}'(\Delta r_k = 0, \Delta t = 0) \cdot \Delta r_k$$

$$= 1 - \frac{\Delta r_k^2}{\lambda^2}.$$  

(8)

Thus, the intersection of the parabola $p(\Delta r_k)$ with the abscissa represents the size of the Taylor
microscale.

Taylor's frozen-flow hypothesis, if fulfilled, can be used to convert temporal information into spatial ones. The hypothesis states that the turbulent flow field appears frozen and its characteristics are transported only by the advection velocity [14]. Due to the low turbulence degree, the local mean streamwise velocity is assumed to be the advection velocity for the conversion. Comparing the temporal and spatial correlation functions the temporal ones show less scattering due to the larger amount of samples. Hence, it would be of advantage to incorporate the temporal correlation function data for the estimation of the spatial ones using Taylor's hypothesis.

The transformation includes two steps. At first, the transformation from temporal into spatial, longitudinal correlation (f-type) and, secondly, the transformation into spatial, transversal correlation (g-type) according to Fig. 7. In general, this technique can be used if the turbulence intensity is low \( \left( \frac{v_x}{\overline{v_x}} \ll 1 \right) \) [15] and the temporal to spatial transformation follows as

\[
\Delta x = v_x \cdot \Delta t = \frac{\Delta x}{u} \cdot \Delta t
\]

\[
f(\Delta x) = \rho_{x,x}(\Delta x,0) = \rho_{x,x}(0,\Delta t = \frac{\Delta x}{u}) = f(\frac{\Delta x}{u}).
\] (9)

The second step demands isotropic turbulence, i.e. independence of the products and squares of all velocity components and their derivatives from the direction. In this case, there exists a relation between f- and g-type correlations according to [16]

\[
g(\Delta z) = \rho_{x,x}(\Delta x,0) = f(\Delta x) + \frac{\Delta x}{2} \left( \frac{df(\Delta x)}{d\Delta x} \right)_{\Delta x=\Delta z}.
\] (10)

with \( \Delta x = \frac{v_x}{u} \cdot \Delta t \) according to equation 9. Using Taylor’s frozen flow assumption, the right side can be calculated on basis of the temporal correlation measurements. It is of advantage to use a model function for the f-type correlation when calculating the derivatives (see Fig. 9). A fitting function has been adapted to the measurement data in a least square sense and the following model has been used

\[
m = \alpha^{-\Delta t} \quad (\alpha > 1).
\] (11)

In case Taylor's hypothesis is fulfilled and isotropic turbulence is present, it is even possible to go one step further and determine a total spatial-temporal distance \( \Delta r \) for each detected burst pair as follows

\[
\Delta r = (\overline{u} \cdot \Delta t, \overline{y}, \Delta z)^T
\]

\[
\Delta r = \sqrt{(\overline{u} \cdot \Delta t)^2 + \overline{y}^2 + \Delta z^2}.
\] (12)

Here \( \overline{u} \) represents the measured mean velocity of each particle pair and \( \overline{y} \) is the mean distance in
y-direction which can be estimated on basis of the measurement volume height and was determined to be \( y = 17 \mu m \).

Moreover, the correlation coefficients \( \rho(\Delta r,0) \) can be obtained in case of isotropic turbulence as follows [16]

\[
\rho_{i,j}(\Delta r,0) = \frac{f(\Delta r) - g(\Delta r)}{\Delta r^2} \Delta r_i \Delta r_j + g(\Delta r) \delta_{i,j}
\]

with \( \delta_{i,j} \) being the Kronecker-delta. The values for \( f(\Delta r) - g(\Delta r) \) can be derived directly from equation 10 and setting \( i=j=x \) it follows that

\[
g(\Delta r) = \rho_{x,x}(\Delta r,0) + \frac{1}{2\Delta r} \frac{df(\Delta r)}{d\Delta r} \langle u \cdot \Delta r \rangle^2.
\]

The result is a transversal, spatial correlation that should be equal to \( g(\Delta z) \). The unique point of this method is the possibility to include much more burst pairs, even with very high temporal distances, and thus to compensate the low data rate (see Fig. 6). In case of clearly spatial or temporal correlations only burst pairs from the two solid boxes contribute to the mean value of one slot. But in case of combined spatio-temporal correlations all burst pairs within the two dashed semi circles can be used for the determination of the value of \( \rho(\Delta r,0) \). Nevertheless, this technique is only applicable under the assumption of isotropic turbulence and Taylor’s frozen flow hypothesis.

5. Measurement Results

The flow apparatus used for the first experiments is an axisymmetric free jet from a contoured nozzle. The jet is created using a small blowing type wind tunnel with air at room temperature as working fluid. The whole setup including the wind tunnel and the fibre-optic sensor equipment were placed on an optical table covered by a chamber which can be closed hermetically. DEHS tracer particles with a mean particle diameter 0.9 \( \mu m \) were seeded inside the chamber to avoid seeding bias and to maintain a high seeding level without damaging sensitive devices which stayed outside. In the present experiment, the wind tunnel was traversed using a two-dimensional translation stage while the sensor and the detection optics were kept fix (see Fig. 8).

A series of measurements of the two-point correlations with the new system was carried out at 13 different locations in total including the jet centreline and the shear layer in both self-similar and near-field regions at two different Reynolds numbers. The Reynolds number Re = \( D \cdot \langle u_c \rangle / \nu \) was defined with the nozzle diameter \( D = 4.5 \) mm and the exit centreline velocity \( u_c \). The measurement conditions are summarized in Table 2 and have been kept as close as possible to those of Wygnanski and Fiedler [17] in order to achieve comparable results.

**Table 2:** List of measurement conditions (see Fig. 8 for coordinate information).

<table>
<thead>
<tr>
<th>Position</th>
<th>Re</th>
<th>x/D</th>
<th>z/x</th>
<th>y/x</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5 \cdot 10^3</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>5 \cdot 10^3</td>
<td>10</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>5 \cdot 10^3</td>
<td>10</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>10 \cdot 10^3</td>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>10 \cdot 10^3</td>
<td>30</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>5 \cdot 10^3</td>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>5 \cdot 10^3</td>
<td>30</td>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>
Temporal as well as spatial correlations have been calculated based on measurements at different position in the shear layer and agree very well with comparable results [17] (see Fig. 10 and Fig. 11). The maximum allowed interarrival time for the spatial correlation estimations has been set to 100 µs in order to include an adequate number of particle pairs for each separation distance.

The temporal as well as the spatial correlation results in the shear layer and on the centreline agree well with the reference data [17]. The spatial correlation function decreases slightly faster than the measured one of Wygnanski and Fiedler [17] which is reasonable since the Reynolds number of their experiment was about 1 magnitude higher compared to our experiment.

Another measurement was performed in the turbulent wake of a grid which was mounted at the exit of a wind tunnel. Again, air was used as working fluid in conjunction with DEHS seeding particles with a mean size of approximately 0.9 µm. In order to limit the largest scales occurring in the grid turbulence, a very fine grid was employed. In that way, it was planned to observe the whole interesting correlation profile even with the very small maximum spatial distance of about 400 µm, the system is capable of detecting without traversing. It is suggested that the correlation coefficient strives for zero within a range of twice the grid size [18]. Thus, a grid with a mesh size M= 200 µm was selected and measurements have been carried out in a distance of x= 9 mm in front of the grid. The mean velocity was set to $u = 2.6 \text{ m/s}$ which was the highest value possible without deforming the small mesh too strongly. The first step was to test the isotropic character of the flow and the energy dissipation rate of the grid turbulence. Based on HWA measurements a spectrum analysis of the turbulent kinetic energy (see Fig. 12) has been done which suggests that the energy cascade is not fully developed, since there is no frequency region showing the characteristic -5/3 slope [14].
Since the spectrum also exhibits a characteristic frequency at about 1 kHz which hints at a wake flow and could represent the characteristic vortex shedding frequency. The Strouhal number $S_f = f M / u \bar{u}$ equals about 0.08, which is consistent with the Reynolds number $Re_M = 37$.

Zhonglei et al. [15] suggest an equation, derived from Taylor’s law of turbulent energy, to determine the Taylor microscale from the dissipation rate of the turbulent kinetic energy, where $\nu$ is the kinematic viscosity and $\lambda_g$ is the transverse Taylor microscale, which follows as

$$\frac{d\overline{u'^2}}{dt} - \frac{d\overline{u'^2}}{dx} - u = -10\nu \frac{\overline{u'^2}}{\lambda_g^2}. \quad (15)$$

According to this equation, the Taylor microscale $\lambda_g$ should equal approximately 500 µm, based on HWA measurements, but since the turbulent energy cascade is not developed, this value may not be very reliable. Nevertheless, it can be taken as a rough estimate which can be compared to the results from the correlation measurements using the LDP sensor.

Afterwards, measurements with the LDP array sensor system have been performed in order to estimate the spatial as well as temporal correlation function of the flow. According to equation 14 the temporal correlation was transformed into a spatial, transversal one and compared to the measured spatial correlation which is depicted in Fig. 13. Since both correlations are in good agreement, local isotropy as well as the Taylor hypothesis seems to be satisfied. Therefore, it was possible to determine a combined spatio-temporal correlation as described in section 3. At small total correlation distances $\Delta r$ the adjustment of the correlation values according to equation 10 has a very small share. Thus, the error created by the uncertainty of this adjustment is relatively small, even if the assumptions are not completely satisfied.

![Fig. 14: spatial correlation incl. linear function for Taylor microscale determination.](image1)

In order to extrapolate the Taylor microscale, Belmabrouk et al. [8] suggested fitting a linear function $h(\Delta r^2)$ in a least-square sense to the coefficients of the correlation function $\rho$ versus traversing distance squared. This is a slightly modified technique equal to the theory presented in equations 7 and 8. This technique has been applied to the pure spatial correlation function as well as to the combined spatio-temporal correlation data which is depicted in Fig. 14 and Fig. 15 respectively. The fitted linear function $h(\Delta r^2)$ depicted is used to extrapolate the transverse Taylor microscale $\lambda_g$ as follows

$$h(\Delta r^2) = 0 \iff \lambda_g = \sqrt{\Delta r^2}. \quad (16)$$

Consequently, the Taylor microscale could be determined to $\lambda_g = 330$ µm on basis on the spatial correlation and to $\lambda_g = 370$ µm based on the combined spatio-temporal correlation data which is in good agreement to the value derived from the turbulent energy dissipation yielding a Taylor
microscale of around 500 µm.

6. Conclusion

A new measurement system was presented for the evaluation of flow velocities at two closely independent locations, aiming at the small scale studies of turbulence. The system is based on the laser Doppler velocity profile sensor with a high spatial resolution in the micrometer range. Furthermore, a special detection system forming two detection volumes are implemented for evaluating instantaneous flow velocities inside the two locations with almost no interarrival time allowed. The new system offers velocity measurements at two independent locations with a lateral separation distance in the range of 30…400 µm. The advantage is the measurement capability with minimum spatial distance down to 30 µm maintaining an exceptionally high spatial resolution in the micrometer range. Measurements of velocities at such small distances could never be achieved with conventional techniques because of their large spatial ambiguities. The new system was examined concerning its fundamental features including limitations. It was further applied to a turbulent free jet and grid turbulence. Temporal and spatial correlation functions of the streamwise velocities were measured at different positions with variable Reynolds numbers. The results are comparable to those reported in literature. The new system offers an advanced diagnostic tool for investigating small scale structures of turbulence such as correlations and spatial derivatives.

7. Outlook

Though achieving results which are more precise compared to conventional correlation measurement systems, the necessity of eliminating all detected particle pairs in the uncertainty region around \( \Delta z = 0 \) and \( \Delta t = 0 \) is unfortunate. This is especially problematic since the particles with a small spatial as well as temporal distance are very important for the correlation function in order to determine the Taylor microscale. That is why one main future development aspect is the synchronisation of the A/D converter cards in order to reduce the temporal uncertainty or, alternatively, to determine the exact time difference before each measurement. Moreover, new signal processing algorithms are investigated which shall help to decide whether a double detection occurred or two independent particles have been measured.

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References


