Fachtagung "Lasermethoden in der Strömungsmesstechnik"
4. - 6. September 2007, Rostock

Application of laser Doppler Velocity Profile Sensor to Turbulent Flows: Measurement of Water Channel Flow and Two-Point Correlation

K. Shirai†, C. Bayer†, H. Nobach‡, C. Klaucke†, A. Voigt†, L. Büttner†, J. Czarske†

†Technische Universtität Dresden, Fakultät Elektrotechnik und Informationstechnik,
Professur Mess- und Prüftechnik, Helmholtzstraße 18, 01069 Dresden

‡Max-Planck-Institut für Dynamik und Selbstorganisation
Am Fassberg 11, Turm 2, SOG, 37077 Göttingen

Keywords: velocity profile sensor, near-wall, turbulence, two-point correlation

Abstract

We report on the new applications of laser-Doppler velocity profile sensor. The first one is a measurement of the near-wall turbulence statistics in a water channel flow. The measurement is to be conducted in a fully developed condition with a new velocity profile sensor dedicated to this application. The sensor is specially designed for the near-wall measurement with which long time stability is required. The measurement is under preparation and they will be compared with available data of direct numerical simulation at a moderate Reynolds number. The second application is the measurement of lateral two-point correlation in a turbulent free jet. Velocity profile sensor has an advantage over conventional methods for the measurement of two-point velocity correlation. It does not need adjustment of multiple measurement and detection volumes, which is known as a main source of the measurement uncertainty in conventional two-point laser Doppler measurement. Here we describe the basic principle of the two-point correlation measurement with velocity profile sensor.

Water channel flow

Background

Universality and the dependence of turbulence statistics in a high Reynolds number flow have been discussed based on many experiments. The difficulty of this discussion arises mainly from the lack of spatial resolution in conventional measurement techniques at high Reynolds numbers. Velocity profile sensor is one of the most promising techniques for overcoming this limitation. The feasibility to turbulent boundary layer has already been reported in the last conference (e.g., Shirai et al. 2006b). The measured turbulence statistics showed good agreement with available data from direct numerical simulations (DNSs). The new measurement in the water channel has several important aspects. First of all, the application of the profile sensor has been reported only to an air flow but not to a liquid flow. The higher viscosity of water contains relatively large scales compared to those of air flow. The large turbulence scale of water advantageously increases the effective spatial resolution of the sensor compared to the measurement in an air flow. Though the attainable Reynolds number range is relatively limited for a water flow compared to an air flow, the new water channel constructed in Technische Universität Bergakademie Freiberg is capable of attaining moderate Reynolds number at which DNS data is available. The change of the flow medium also necessitates a complete new robust sensor system which can be flush-mounted directly to the wall of the water channel. It would reduce the influence from the vibration of the channel wall, which was found problematic to provide statistics with full capability of the spatial resolution of velocity profile sensor (Shirai et al. 2006a). A dedicated special calibration system has to be built in order to calibrate the profile sensor in the same fluid as the measurement.

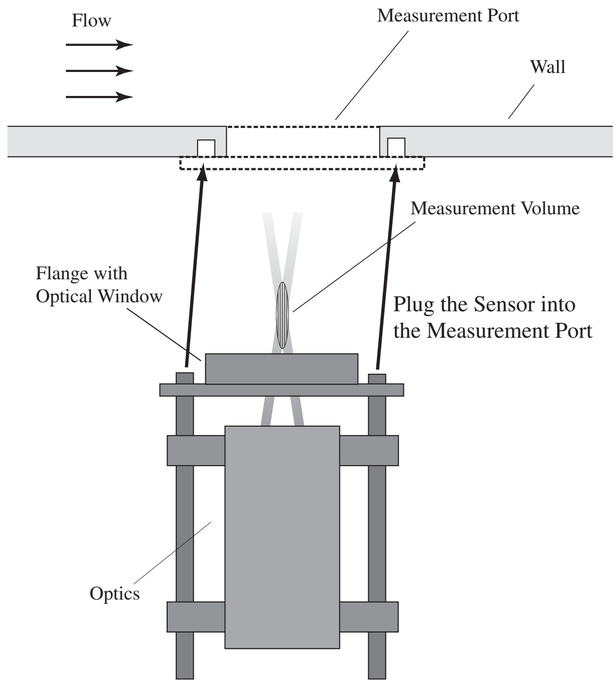

Fig. 1: The concept of “plug-in” type profile sensor. The profile sensor integrated with a flange directly plugged into the measurement port on the wall. In the flange there is an optical window for the measurement. The direct attachment of the sensor to the wall requires good stability of a sensor but could reduce the influence of the flow channel vibration.

Plug-in Sensor

This new system called ”plug-in” sensor is under development. The plug-in sensor is attached directly to the wall where near-wall velocity to be measured as shown in Fig. 1. This is a clear advantage over a conventional laser Doppler anemometer (LDA) applied to the near-wall velocity measurement. With a conventional LDA, the optical access from the side is required to have match the axis of the high spatial resolution to the wall-normal direction (see Fig. 1 (a) in Shirai et al. 2005). This is because a steep mean velocity gradient exists in the direction normal to the wall. The spatial resolution of a conventional LDA used in the near-wall measurement is determined roughly by the beam waist diameter of laser beams. On the other hand, the velocity profile sensor has a spatial resolution in the direction of optical axis inside the measurement volume. Therefore, it should be applied with its optical axis perpendicular to the wall (see Fig. 1 (b) in Shirai et al. 2005). With this configuration, the measurement of velocity profile with a high spatial resolution is enabled without reducing the size of the measurement volume causing lower data rate. The plug-in type sensor has a further advantage that there is no need to have an optical access from the side, which is not always available for realistic applications. Besides, less adjustment effort is needed to position the probe for a near-wall velocity measurement when a back-scatter detection is used together. The plug-in sensor would open several new applications which has been expected for a long time. For example, it is suitable for *in situ* calibration of other types of shear stress sensors. Near-wall measurement of a flow with an adverse pressure gradient may also be possible as long as the tracer follows the flow, since the profile sensor does not require any analogy like other near-wall and wall-mounted sensors for near-wall measurements.

Measurement

The measurements are planned in a two dimensional water channel flow from relatively low to moderate Reynolds numbers. The results will be compared with currently available DNS data. The statistical behavior of near-wall turbulence statistics will be discussed especially on possible Reynolds number effects. In low Reynolds number regime, "low-Reynolds number effect" reported in past discussions would be observed. This effect should be carefully excluded from the Reynolds number effect to be discussed afterward. One of the challenges of the plug-in sensor is focused on how close to the wall the velocity profile can be measured. In the last measurement of near-wall velocity statistics, a high peak of third order moment seen in DNS data was not able to be detected with a velocity profile measurement. The new plug-in sensor is expected to yield some insights on this issue.

Two-point correlation

Background

Two-point correlation of fluctuating velocity is closely related to the important scales of turbulence. Measurement of two-point correlation yields the integral and Taylor length scale (λ shown in Fig.2), from which the basic features of turbulence is characterized. Furthermore, the Taylor length scale can be used for deducing the dissipation rate of turbulent kinetic energy in the case of isotropic turbulence (Hinze 1975, Pope 2000).

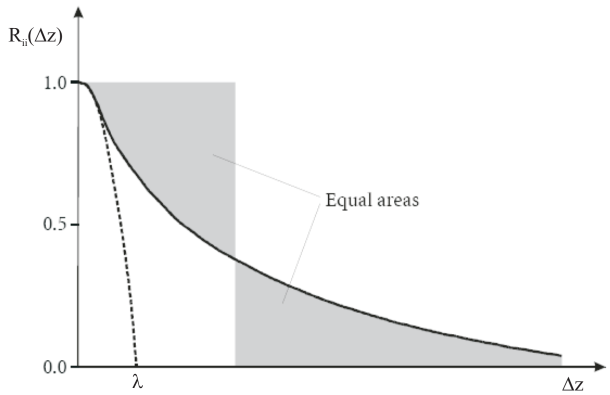

Fig. 2: Taylor micro scale estimated from the two-point spatial correlation. (from Albrecht et al. 2003)

Conventionally, measurement of spatial correlation has been carried out using arrays of hot-wire anemometers (HWAs). However, the use of HWAs is not suitable for the measurement of longitudinal spatial resolution and their intrusiveness is not preferable in certain cases. In the case of hot-wire array, the minimum physical separation exists between the wires to avoid the mutual thermal influence of the two wires, which in turn influences the accuracy of the scale estimation. Since the use of LDA can solve these two difficulties, researchers started to use LDA for the measurements of two-point velocity correlations. Even though several measurements have been carried out based on LDA (e.g., Absil et al. 1990, Benedict and Gould 1999, Ducci and Yanneskis, 2005), these methods are known to suffer from inherent difficulties. In the case of laser Doppler anemometry, high adjustment effort is required to place the measurement volume pair with a sufficient accuracy. The overlapping of the two measurement volumes or detection volumes becomes one of the main sources of error when the Taylor micro scale is deduced from the measured two-point correlation (Ducci and Yanneskis, 2005).

Velocity profile sensor would be suitable for this task, since it has a high spatial resolution inside the measurement volume (see Fig. 3). There is no need to overlap two measurement volumes and hence the measurement result would be free from the positional ambiguity of the two measurement volumes. Similar to velocity profile sensor, LDA with an elongated measurement volume has been applied by Absil et al. (1990) using two independent detection optics. However, their measurement suffered from the overlapping of the detection volumes. On the other hand, the profile sensor is capable of providing velocity and positional information using a single measurement volume and a single photo detector. The obtained position-velocity information is not influenced by location of the detection volume since they are calculated from the Doppler frequency pair. This is an advantage over the system reported by Absil et al. (1990). Besides, the detection area is broad compared to other two-point LDA techniques in which the data rate and the spatial resolution are trade-off relation.

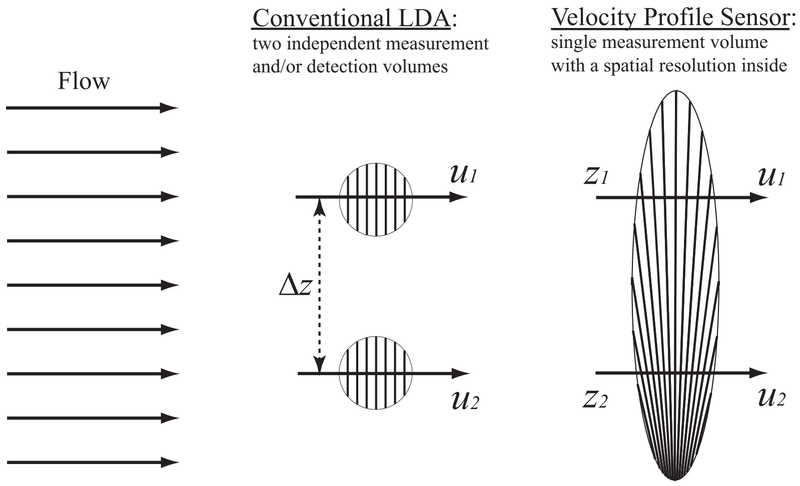

Fig. 3: The comparison of conventional LDA and profile sensor for the measurement of two-point correlation. In the case of conventional LDA, two independent measurement and/or detection volumes are necessary. In the case of profile sensor, the Doppler signals themselves have the information of position and velocity in a single measurement volume. Hence, it reduces the difficulty arising from the use of two independent measurement and/or detection volumes.

Principle

The two-point correlation of fluctuating velocity u_i at the location x_j is generally defined as

$$R_{ij}(\Delta x_j) \equiv \frac{\overline{u_i(x_j,t)u_i(x_j+\Delta x_j,t)}}{\sqrt{\overline{u_i(x_j,t)^2}}\sqrt{\overline{u_i(x_j+\Delta x_j,t)^2}}}, \quad (1)$$

with the separation distance Δx_j. Since the velocity profile sensor has a spatial resolution in the direction of optical axis z, the correlation in the lateral direction can be measured (g-type correlation defined in Hinze 1959). For simplicity, the main velocity direction is assumed to be u and if the lateral coordinate is adapted to the optical axis of the profile sensor, the equation can be rewritten as

$$R_z(\Delta z) \equiv \frac{\overline{u(z,t)u(z+\Delta z,t)}}{\sqrt{\overline{u(z,t)^2}}\sqrt{\overline{u(z+\Delta z,t)^2}}}. \quad (2)$$

The correlation is calculated from a pair of Doppler burst signals occurring at the same time. Ideally a burst pair used for the calculation has to be from at the same arrival time, but it is not possible in practice due to the finite time duration of the burst signals. The signal pairs also has to be taken with their time difference within a certain interval. Otherwise, the obtained two-point correlation becomes spatio-temporal correlation. The maximum allowable time interval for calculating the two-point correlation will be investigated. This is closely related to the question how close particle pairs can be resolved at the same time. Another point to be investigated is an effective method of signal processing. Normally, dual bursts (Doppler bursts overlapping each other in time domain) are discarded because of processing difficulty. However, it is possible to process such dual bursts as described in Nobach (2002) and necessary for the measurement of two-point correlation with a velocity profile sensor. It is possible to separate the frequency range of Doppler signal pairs by carefully setting up the profile sensor. In the present study, a data acquisition card with a large memory capacity is going to be used for recording a series of Doppler burst signals (Fig. 4). An offline signal processing is to be used for extracting the position-velocity information from the recorded signals.

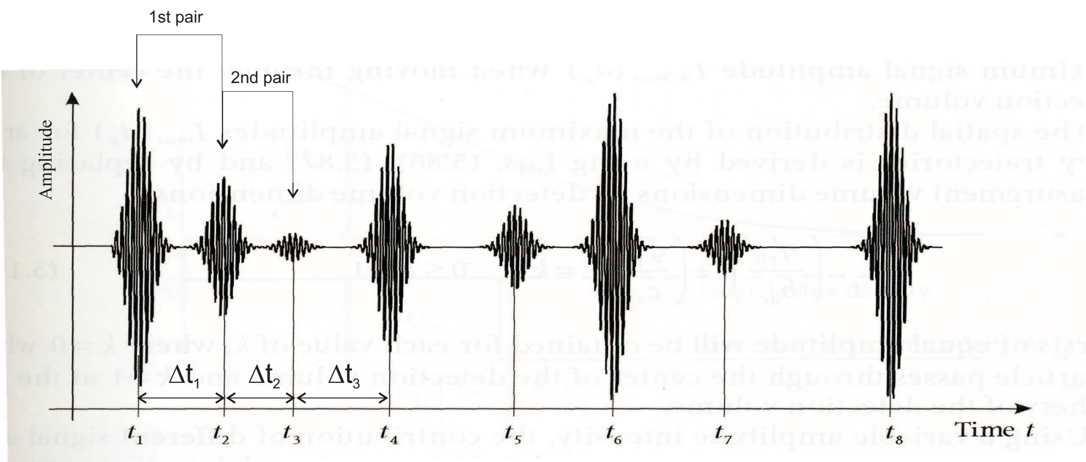

Fig. 4: Time series of Doppler burst signals. The two-point correlation is calculated from a pair of Doppler bursts occurring close together (from Albrecht et al. 2003).

Measurement

We are going to investigate the feasibility of lateral two-point correlation with a velocity profile sensor. The first measurement is going to be carried out in a free jet from a contraction nozzle. From the measured two-point correlation, the Taylor micro scale will be estimated and compared with available experimental data. Preliminary results in the flow will be presented in the conference.

Summary

We report on our ongoing two applications of velocity profile sensor to turbulent flow investigation. The first one is the measurement of near-wall turbulence statistics in a two dimensional water channel flow. The measurement is going to be conducted at moderate Reynolds numbers, at which some DNS data is available. The second application is the measurement of two-point correlation. The profile sensor has a potential to overcome the difficulty which arose in the past measurement techniques for lateral two-point correlation of velocity using conventional techniques. Preliminary results for those two applications will be presented in the conference.

Acknowledgement

The support (CZ55/20-1) from the Deutsche Forschungsgemeinschaft is greatly acknowledged.

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