THREE SENSOR HOT WIRE MEASUREMENTS OF THREE DIMENSIONAL TWO POINT CORRELATIONS IN THE BOUNDARY LAYER OF A FLAT PLATE AT $Re = 50 \cdot 10^6$

R. Abstiens, W. Schröder, and W. Limberg
RWTH Aachen, Aerodynamisches Institut, D-52062 Aachen, Germany

Introduction

Conferences and research programs from the last two decades show that the physical fundamentals of turbulent boundary layer flows are not yet sufficiently analysed at very large Reynolds numbers [1-6]. High-Reynolds-number flow research, particularly in low-speed aerodynamics is mandatory from the point of view of basic considerations, but difficult to conduct for many reasons. This discrepancy has led to numerous disasters, reported in the literature, the major cause being that it is almost impossible to forecast flow behavior at high Reynolds number from experimental data, that were measured at much lower values. Similar problems exist for numerical predictions. For three-dimensional flows, the Reynolds stresses are, in general, not known and their modeling is difficult [7, 8].

An experimental range, where very large Reynolds numbers are obtained, covers atmospheric flow processes within the range of the atmospheric boundary layer. This area represents however a special case, with which thermal convection and the different roughness of the surface ensure that the boundary conditions cannot be defined clearly [10-12]. In this scope are e.g. the investigations of Metzger et al. [12] in the desert of Utah on the large salt lake. For the scientific evaluation cannot be neglected however the thermal influences and the turbulent structures existing in the atmosphere as well as the unknown history of the boundary layer.

Since an easy solution for three-dimensional flows and their modeling is not in sight, high-Reynolds number experiments were designed and carried out in recent years in exceptional cases, despite the high costs. With such experiments, it is expected to acquire sets of reliable experimental data with which numerical predictions can be compared in the future. Two of such experiments, were carried out in 1994 [1, 9]. In one experiment, H. H. Fernholz, M. Nockemann, M. Schober, and the first author, measured mean velocity and Reynolds-stress profiles in the incompressible turbulent boundary layer with zero pressure gradient on the aerodynamically smooth side wall of the German-Dutch wind tunnel in the Netherlands [1]. The measurements provided a complete set of data of the turbulent stresses for Reynolds numbers, based on the momentum thickness, up to $Re_\theta = 6 \times 10^4$. The accuracy of the measurements was secured by employing two different hot-wire probes, placed side by side in the experimental set up. Different experimental investigations were accomplished by Oesterlund and Johansson at the KTH in Stockholm with Reynolds numbers of $Re_\theta = 27300$, $\theta$ represents the momentum thickness, [13]. The turbulence generation in a turbulent boundary layer for $Re_\theta = 9700$ was examined on the basis of two-point-correlations of the velocity components in mean flow direction and wall shear stresses with consideration of hot film and hot wire data [14].

Because of the undefined boundary conditions in further experiments the test setup for the high Reynolds number experiment, described in this paper, was designed to get a large database with exact boundary conditions. In the experiments a zero pressure gradient turbulent boundary layer with a maximum thickness of 150 mm along a flat plate was generated for the measurements of two-point-correlations in the $8 \times 6$ m² test section of the low-speed German-Dutch-Wind tunnel at Reynolds numbers up to $Re = 50 \times 10^6$. An elliptical profile at the leading
edge guaranteed an attached flow at the nose, the distance to the measurement position on the absolutely smooth surface of the plate was 13.4 m (Fig. 1).

In the following sections the details of the boundary-layer investigations will be reported. They include a brief description of the experimental facility and the model, the measurements of the two-point correlations with hot-wire anemometry at 80 points in six different levels in the boundary layer and the PIV measurements at the same position downstream (x = 13.4 m).

**Test Facility and test setup**

Measurements of two-point correlations were performed in the $8 \times 6$ m$^2$ test section of the low-speed German-Dutch-Wind tunnel at Reynolds numbers up to $Re = 50 \times 10^6$. During the tests, the velocity could be varied between 15 m/s and 100 m/s. The temperature in the test section was kept constant within 0.5° C during the measuring period. Other characteristics of the tunnel were described by H.U. Meier, U. Michel, and H.P. Kreplin in [13]. For example, the maximum deviation of the static pressure in the stream wise direction was reported to be $cp = 0.002$ over a distance of about 12 m, and the free-stream turbulence level was measured at 40 m/s to be $Tu = 0.027$ % within a frequency range of 0.15 Hz to 10 kHz.

In the experiments a zero pressure gradient turbulent boundary layer with a maximum thickness of 150 mm along a flat plate was generated. An elliptical profile at the leading edge guaranteed an attached flow at the nose, the distance to the measurement position on the absolutely smooth surface of the plate was 13.4 m (Fig. 1). The two-point correlations were measured at free stream velocities of 40 and 60 m/s with two triple hot-wire probes in a cubic zone ($300 \times 300 \times 300$ mm$^3$) above the surface of the flat plate (Fig. 2).

**Experimental techniques**

The triple-hot-wire probes were built in the Aerodynamisches Institut Aachen. The probe dimensions were as follows: The probe diameter $d = 5.0$ mm, the sensor diameter $5 \mu$m, the length of each wire $l = 3.2$ mm and the effective length $l_{act.} = 1.0$ mm. All wires were gold plated at the ends. The probe was calibrated in situ on the basis of King’s law with three calibration points. One probe was mounted on a traverse mechanism, specially designed for the experiment. It could be moved from a minimum distance of 3.5 mm from the surface of the flat plate up to 300 mm normal to the surface, in span wise and in flow direction. The other probe was fixed at a defined position normal to the surface. The hot-wire instrumentation consisted of two TSI IFA 100 hot-wire bridges, the signals were digitized with an A/D-card using and
processed by an IBM compatible PC. At each point 32000 up to 128000 samples were taken with a frequency of 10 – 50 kHz.

Additionally to the measurements with two three-sensor hot wire probes the 2D-PIV and the Stereo PIV were used. They should supply data over the flow structure and two-point-correlations in flow direction, which could not be measured with the hot wire measuring technique, in a vertical plane.

**Discussion of Experimental Results**

The two-point correlations were measured at free stream velocities of 40 and 60 m/s with two triple hot-wire probes in a cubic zone (300 × 300 × 300 mm³) above the surface of the flat plate (Fig. 2). The three sensor hot-wire measuring technique was developed at the Aerodynamisches Institut and tested further in experiments in the DNW [1]. While one probe was fixed in a defined position, the second hot-wire probe was moved to measure at 450 points in six different levels. With this setup it was possible to collect data for the normal and shear stresses in the normal and in the span wise direction for all levels. Additionally, velocity profiles of the boundary layer were measured and two-point correlations in the vertical symmetry plane of the cube where measured to compare them with PIV (Particle-Image-Velocimetry) data taken in the same plane. The comparison of the data should show the quality of the two-point correlations in the boundary layer attained from highly resolved PIV data (up to 5000 pictures) when they are contrasted with the hot-wire findings.

The six levels of the hot-wire measurements are located in the logarithmic and in the outer layer, to experimentally verify the new exponential law in the external area [2]. Besides the validation of this new law in the external boundary layer it is the objective of this investigation to obtain a database for turbulent boundary layers at large Reynolds numbers with exact boundary conditions that can be used on the one hand, by the CFD community to validate sub grid scale models in large-eddy simulations and on the other hand, to investigate the dependence of, e.g., the integral length scale on the normal distance from the wall and its behavior as a function of the recording frequency.

Figures 5 and 6 show the boundary layer profiles for 40 and 60 m/s, scaled with the shear stress velocity and the turbulence intensity determined using the hot-wire data. Because of the
zero pressure gradient on the flat plate, the semi-empirical relation of H.H. Fernholz was used [18] to calculate the shear stress velocity for the data in Fig. 5.

The two-point correlations from the hot-wire data for the stream wise, normal and the span wise velocity component are presented in Fig. 7 for one fixed probe position. The correlations of the stream wise velocity possess approx. twice the level of the v- and w-component, which show a sharp drop in the vicinity of the wall. Only the w-components have positive values in the inner and negative values in the outer part. Furthermore, the findings will be juxtaposed with PIV data in the vertical plane (Fig. 8). The PIV measurements will also be used to determine two-point correlations and integral length scales in the stream wise direction.

**Conclusions**

The boundary-layer on the flat plate was investigated experimentally in the $8 \times 6 \text{ m}^2$ low-speed German-Dutch-Windtunnel at Reynolds numbers up to $Re = 50 \times 10^6$. Two-point correlations were measured at free stream velocities of 40 and 60 m/s with two triple hot-wire probes in a cubic zone ($300 \times 300 \times 300 \text{ mm}^3$) above the surface of the flat plate. Additionally, velocity profiles of the boundary layer were measured and two-point correlations in the vertical
symmetry plane of the cube were measured to compare them with PIV data taken in the same plane. The comparison of the data show the quality of the two-point correlations in the boundary layer attained from highly resolved PIV when they are contrasted with the hot-wire findings.

The results obtained in the DNW-LLF experiment confirm that model and measuring techniques have sufficiently matured so that large-scale experiments can provide reliable experimental data for high-Reynolds number flows.

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