ACCURACY OF WALL-SHEAR STRESS MEASUREMENTS USING MICRO-PILLARS

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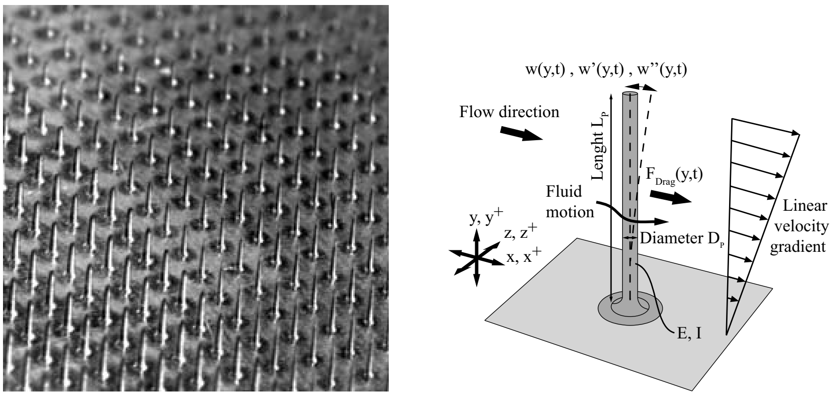
The micro-pillar shear-stress sensor MPS^3 is used to assess the quantitative wall-shear stress distribution in a flat plate turbulent boundary layer (TBL) at low to moderate Reynolds numbers. The sensor is based on a novel measurement concept comprising an array of highly flexible micro-pillars which are flush mounted on the surface measured. Figure 1(a) shows an array of micro-pillars similar to the array used for this work. The micro-structures protrude into the flow but are immersed in the viscous sublayer of the boundary layer thus experiencing a linear velocity gradient along its length. The micro-pillars bend due to the fluid forces on the structures and the recorded deflection is correlated with the locally prevailing wall-shear stress such that the wall-shear stress distribution can be determined.

The micro-structures possess a cylindrical profile such that the flow around the micro-pillars is symmetrical. Thus, the sensor is equally sensitive to both wall-parallel components of the wall-shear stress and does not suffer from cross-axis sensitivity. The deflection of the micro-pillars is detected by a highly magnifying optical system which is positioned perpendicular to the surface measured so that the stream-wise and span-wise deflections are detected simultaneously. This makes the recorded deflection a direct representative of the exerted forces, both in magnitude and angular orientation.

Figure 1(b) shows a sketch of the measurement principle. The measurement technique belongs to the indirect group of measurement techniques [3] since the wall-shear stress is derived from the relation between the detected velocity profile and the local surface friction.



(a) (b)

Figure 1. (a) Array of micro-pillars as used for the measurement of the wall-shear stress distribution in a TBL, (b) measurement concept of the MPS^3 [1]

Measuring both components of the wall-shear stress offers the possibility to analyze the flow near the wall. The turbulent wall-shear stress distribution is regarded as the foot-print of the turbulent structures near the wall and serves as an indicator of the momentum transfer in the boundary layer. Many experimental and numerical studies in the past concluded from their findings that only a spatially distributed view of the flow field in its instantaneous and in its statistical representation will allow for a better comprehension of the highly nonlinear processes involved in the self-sustaining processes of turbulence production and conservation in turbulent shear flows. Thus, an accurate measurement of the wall-shear stress distribution at high spatial and temporal resolution is a prerequisite for a deeper understanding of wall bounded turbulence.

The measurement principle of the micro-pillar shear-stress sensor has been demonstrated for example by Große and Schröder [1] or Nottebrock et al. [4]. Große and Schröder [2] applied micro-pillars to visualize the turbulent wall-shear stress distribution in a duct flow where the fluid is water. The turbulent scales in the flow were well within the measurement regime of the sensor. The micro-pillars were immersed 3.4 viscous units into the flow. However, the protruding length and the frequency response of the sensor are limiting constraints for measurements in higher Reynolds number flows. The sensor possesses a low-pass filter behaviour ranging from an over-damped system in highly viscous fluids, e.g. water, to a system with pronounced resonance behaviour as in air flows [4]. Hence, only the unamplified frequency bandwidth of the sensor can be used if no further corrections on the signal are implemented.

First results concerning an improvement of the measurement range were already obtained and indicated an aeroelastic behaviour of the sensor [4]. However, to capture the highest frequency content of the turbulent spectrum, the aeroelastic properties of the sensor have to be further investigated since the highest frequencies of the flow can be considerably higher than the eigenfrequency of the micro-pillars – especially at high Reynolds numbers . Furthermore, the protruding

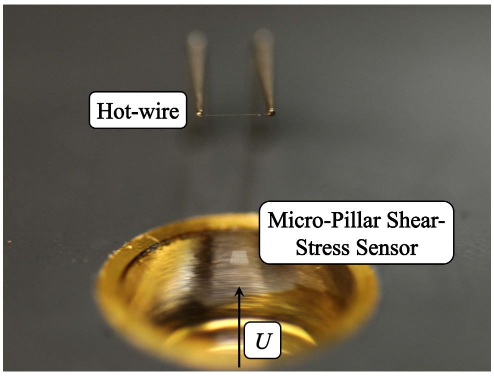


Figure 2. Experimental setup with hot-wire downstream of the MPS^3

length is limited to the viscous sublayer. For higher Reynolds numbers the thickness of shear layer decreases leading to sensors protruding out of the viscous sublayer. However, recent investigations show that the sensor is applicable even when protruding into the lower buffer layer.

To quantify the accuracy of the MPS^3 and the effect of the aforementioned measuring constraints, hot-wire anemometry of the velocity fluctuations in the stream-wise direction in the near-wall flow is conducted. The hot-wire is placed downstream of the MPS^3 in order to determine the wake of the MPS^3. The near-wall velocity measured by the hot-wire is compared to the wall-shear stress signal of the MPS^3 allowing for a further investigation of the dynamic behaviour of the sensor. Furthermore, the influence of the sensor length on the wake of the sensor can be addressed since the hot-wire is positioned downstream of the sensor array. The length of the micro-pillars is varied in the range of $l^+ = 5$ to $l^+ = 10$. The simultaneous measurement of the wake by the hot-wire system gives insight into the momentum exchange between the micro-pillars and the flow if the sensor protrudes out of the viscous sublayer.

Figure 2 shows the setup for the combined hot-wire and MPS^3 measurements. To measure, a specially designed single hot-wire probe is used. It is located directly downstream of the MPS^3. To prevent vibrations induced by the flow, the probe mounting is integrated into the plate so that it is not exposed to the flow. The bent prongs allow velocity measurements down to the wall. Moreover, disturbances caused by the vertical part of the prongs and by the holes in the flat plate are generated downstream of the hot-wire sensor. A traversing unit enables the probe to be moved in the vertical direction in steps of $\Delta y \approx 0.3$ µm up to a wall distance of $y = 5$ mm.

The wall-shear stress distribution of the TBL will be measured using the MPS^3 at $x = 1.5$ m downstream of a tripping wire ($d = 0.5$ mm), which is located at the leading edge of the flat plate. That is, the viscous sublayer is approximately 94 µm such that micro-pillars with a length of $L_P = 100$ µm and 150 µm, corresponding to 5.3 and 8 viscous units, can be used. The resonance frequency of the smallest micro-structures is as high as 4 kHz and the spatial resolution is 5 – 10 l^+. The sensor is flush mounted on the flat plate and the micro-pillar tips are illuminated by a laser-light sheet parallel to the wall. A Photron Fastcam SA5 high-speed camera with a K2/Infinity long-distance microscope will be used to detect the deflection of the micro-structures. The distance between the optical system and the flat plate is 0.55 m so that it does not influence the boundary layer. Furthermore, a windshield protects the optical system to avoid camera excitation due to the free stream flow. The camera is operated at 10 kHz, such that it provides the necessary resolution and magnification.

The results of the measurement considering the impact of the length of the sensors outside the viscous sublayer and the comparison of the hot-wire and MPS^3 data will be presented at the conference.

References

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