WALL-SHEAR STRESS MEASUREMENTS OF TURBULENT FLOW OVER RIBBED SURFACES USING THE MICRO-PILLAR SHEAR STRESS SENSOR MPS^3

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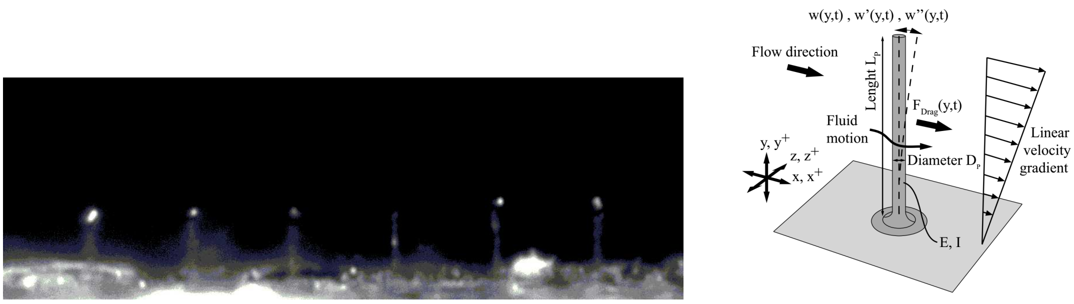
Abstract The drag reduction effect of a semi-circular riblet-structured surface in a turbulent boundary layer is experimentally investigated using the micro-pillar shear stress sensor MPS^3. The MPS^3 sensor is a novel tool for the quantitative measurement of the wall-shear stress distribution and possesses a high spatial and temporal resolution. The effectiveness and mechanisms of a ribbed surface in skin friction reduction are to be examined in comparison with the flow case of a flat surface.

Skin friction drag reduction is of increasing significance for the coming generation of transportation systems with respect to both commercial and environmental concerns. As one passive flow control technique inspired by nature, riblet structures modify the near-wall flow patterns[2]. Choi [1] applied hot-wire/film anemometry in windtunnel and concluded the role of riblet in modifying the near-wall activity sequence by passive spanwise forcing. Bechert [3] used a shear stress balance in an oil channel and reached maximum drag reduction as 10% through a systematic experimental optimization for riblet surfaces with different geometries. Li [4] conducted micro-particle tracking velocimetry (μ-PTV) and obtained the friction velocity based on the velocity profile in the near wall region. Though these measurement techniques manage to quantitatively obtain the friction velocity, they either do not have spatial or temporal resolution, or they may yield an increasing measurement error at near wall positions due to wall-effects or reflections. Thus, aiming at investigating the wall-shear stress distribution at high spatial and temporal resolution and further exploring the underlying mechanisms of turbulent drag reduction by riblets, the micro-pillar shear-stress sensor (MPS^3) is introduced to this flow case.

The MPS^3 sensor consists of an array of flexible cylinders flush-mounted to the surface (Figure 1(a)). Those structures protrude into the viscous sublayer and bend as a result of the fluid forces. The cylindrical shape guarantees the sensor's equal sensitivity to both streamwise and spanwise components and the deflection of pillar tips directly represents the corresponding local wall-shear stress due to the linear velocity gradient along the length. Metallic coated spheres on the pillar tips and a highly magnifiying optical system installed perpendicular to the surface are used to detect the deflections of the pillars. A sketch of the measurement principle is shown in Figure 1(b).



(a) (b)

Figure 1. (a) Array of micro-pillars flush-mounted on a plate (side view), (b) MPS^3 sensor measurement principle [7]

The capability and accuracy of the MPS^3 sensor for wall-shear stress measurements have been validated for various flow cases [5] [6] [7] and characteristics. The primary drag-reduction mechanism by riblets was stated to be a restriction of spanwise movement of longitudinal vortices which weakens the near-wall burst events [2]. By the employment of Taylor's hypothesis, the wall-shear stress distribution is obtained from the temporal two-component wall-shear stress values measured by a sensor array [5], in which the near-wall burst events are identified as the high-shear regions lying in between long meandering low-shear zones. Thus, the difference of flow structures over ribbed and flat surfaces can be distinguished by the analysis of the local distribution of high-shear and low-shear regions. The influence of riblets on bursting frequencies can also be reflected by the measured energy spectrum as the MPS^3 sensor resolves a bandwidth covering the frequency of large-scale structures [6]. Furthermore, the statistics such as the turbulence intensity value can provide a direct quantitative comparison for both flow cases. Former μ-PTV results [4] showed no spanwise variation of wall-shear stress downstream the riblet structure, hence the MPS^3 results can be used to validate this finding due to its high spatial resolution.

The experimental setup for the wall-shear stress measurements are shown in Figure 2. A flat plate is mounted in the test section of a low speed closed-loop wind tunnel. A tripping wire downstream of the leading edge ensures transition and a fully turbulent flow condition at the measurement position. An aluminium surface of 330 $\times$ 370 mm^2 area structured by

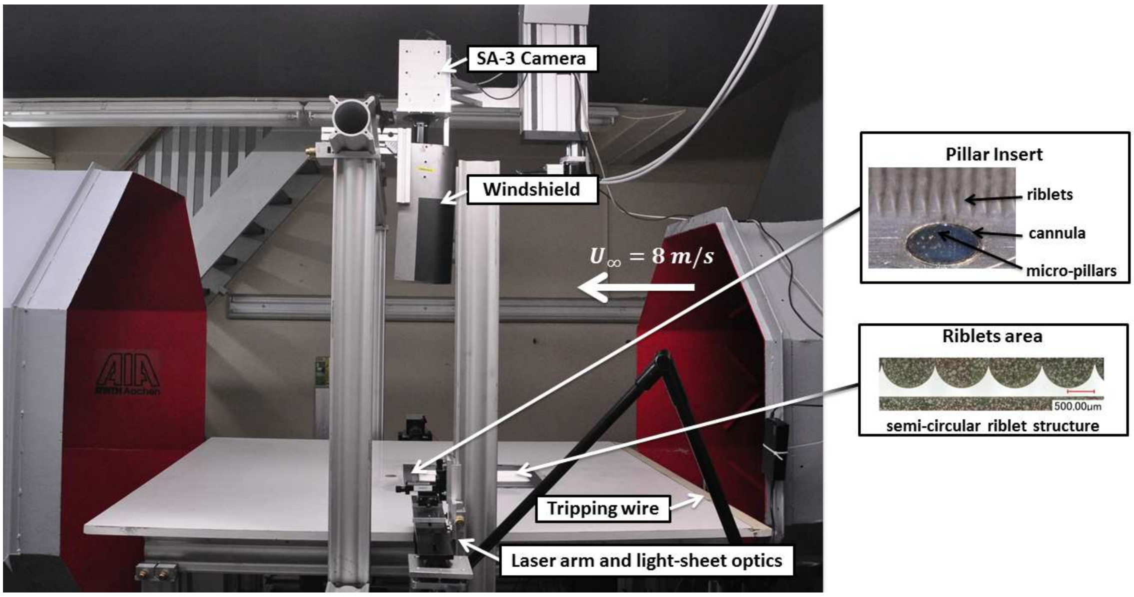


Figure 2. Experimental setup

semi-circular riblets is located in center of the flat plate. The distance between aluminium surface front and the tripping wire is 532 mm. The riblet structure possesses a lateral spacing of $s = 1.0\ mm$ and a height of h = 0.3 mm; the area of riblets is 174 $\times$ 360 mm^2.

The MPS[3] sensor is flush-mounted to the aluminium surface downstream of the riblets as shown by the enlarged view in Figure 2. The micro-pillars possess a height of 240 μm and a diameter of 18 μm. The spacing between each pillar is 350 μm. The wind tunnel is operated at a free-stream velocity U_∞ = 8.0 m/s, and the corresponding Reynolds number based on momentum thickness Re_θ = 1200. Thus, at the measurement position $x \approx 892\ mm$, the viscous sublayer is approximately 204 μm thick and the pillar height corresponds to 6 viscous units. The pillar tips are illuminated by a laser-light sheet (Stabilite 2017 Laser, Spectra Physics) parallel to the wall, and a Photron Fastcam SA3 high-speed camera with a K2/Infinity long-distance microscope lens is used to detect the tip deflections at operating frequencies of 5000 Hz and 10000 Hz. A windshield protects the optical system from vibrations due to the free stream flow. Measurements of the flow over the flat plate at the same position will be conducted as reference. Measurement results concerning comparisons of the wall-shear stress distribution as well as statistics for both flow cases will be presented in the final paper.

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