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Measurement of the Turbulence Intensities in a Flat Plate Boundary Layer

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Abstract — Detailed information on the flow in the vicinity of the wall is of particular interest for various types of flow and heat transfer predictions and of basic importance for turbulence modelling. The time-averaged value can be determined accurately by a number of methods, however time resolved part is rather more difficult to measure. In this work, the results of measurements of the wall shear stress fluctuations in a turbulent boundary layer are presented. Described experiments are performed for the case of zero-pressure gradient flow on a flat plate at Reynolds number, Re_θ, ranging from about 1000 to 6000. A main feature of this work is that the miniature wall mounted hot wires fabricated with very high accuracy were implemented in the measurements.

1. Introduction

Wall shear stress can usually be measured quite easily in laminar fbws, however, it is the measurement in turbulent fbws that creates the most difficulty. In a turbulent fbw the wall shear stress has two components. The time averaged value can be determined accurately by a number of methods such as the Preston tube or fbating element balance. The second component is the time resolved part and provides a measure of the fine scale structures in the fbw that contribute to the skin friction.

Time resolved component of the wall shear stress is more difficult to measure and has been determined by various techniques including LDA, pulsed hot wire, fbsh photolysis and hot-films. There are, however, limitations that reduce the accuracy of the above methods that tend to make them unsuitable for measurements under some circumstances.

In the hope of overcoming some of the limitations of the previously mentioned methods, a MEMS (Micro Electro Mechanical Systems) wall mounted hot wire sensor has been developed at Thermo and Fluid Dynamics (TFD), at Chalmers University of Technology [1] for the purpose of measuring the instantaneous velocity gradient close to a wall. This sensor should be able to accurately measure the wall shear stress in airfbws, and a series of tests on the sensor has just been completed for laminar fbw [2]. Developed microsensor is not different from the traditional wall mounted hot wire and holds all benefits of this technique, and moreover the production method is advantageous.

The improvement of such a sensor, as compared to traditional wall mounted hot wire, is that due to the MEMS technology, it can be manufactured to a very small tolerance. Additionally, the production methodology allows the wire to be parallel to the wall and its position in relation to the wall can be accurately known, which are both important factors for this measurement technique. As traditional wall mounted hot wires, the microsensors are unaffected by near

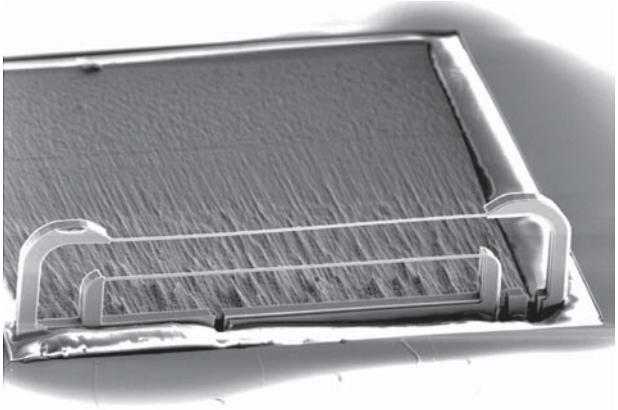

Figure 1: SEM of a two-wire MEMS rake.

wall effects and the miniaturization allows good spatial resolution. Due to these factors the microsensors are capable of determining the fluctuating velocity of the flow within the viscous sub-layer.

In this work, the results of measurements of the wall shear stress fluctuations in a turbulent boundary layer of a flat plate are presented. Hot wire sensors were calibrated *in situ* in the boundary layer against the mean shear stress, which was determined using a Preston tube, Clauser plot and the momentum integral relation. Great care was taken to avoid the temperature effects and uncertainty of the calibration fit.

2. Experimental Setup

The experiments were conducted in the wind tunnel laboratory of TFD. The closed circuit tunnel has a working test section of 1.8 m width, 1.2 m height and 3 m length and has a low turbulence intensity that is less than 0.1% of the free-stream velocity. A model used is a flat plate of 2500 mm long and 1000 mm wide. Thickness of the plate is 25 mm and it has rounded leading edge. The flow was artificially tripped at the front of the model by a 1.75 mm diameter wire spanning the width of the plate and located 100 mm aft of the leading edge.

Static pressure distribution was measured over the plate length for velocities in range from about 6 to 35 m/s using surface pressure taps. Zero pressure gradient was established on the plate, so that the modulus of the acceleration parameter, $K \times 10^{-6}$ was in the range from 0.01 to 0.045.

As mentioned, measurements of the fluctuations of the wall shear stress are performed using wall mounted hot wire microsensors of a classical design, which are fabricated, however, by MEMS technology, see [1]. The miniature wires of 400 μm lengths have allowed required spatial resolution of the unsteady part of the shear stress on the wall. A used sensor consisted of two wires at a height of 50 (lower wire) and 100 (upper wire) μm from the surface and only one wire was operated at a time in the constant temperature mode. A SEM picture of a two-wire MEMS rake used is shown in Fig. 1. The figure demonstrates the main characteristic feature of the used hot wire sensors, which is very good accuracy of their fabrication. Particularly, achieved precision of the wire height positioning and the wire bent is 1 μm what, as believed, is crucial for precise measurements. Microsensors were positioned on a surface-mounted chuck located 1.3 m from the leading edge of the plate.

Additional measurements in boundary layer were performed using gold plated probe of

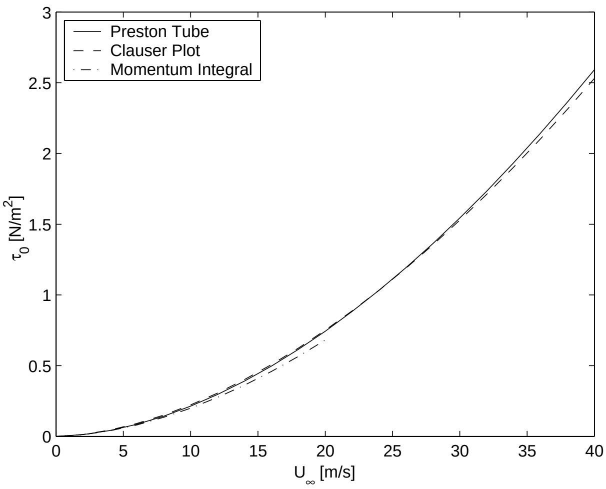

Figure 2: Mean shear stress comparison obtained by Preston tube, Clauser plot and momentum integral relation.

1.25 mm active length and 5 μm diameter, having distance between the prongs of 3.25 mm. The probe was positioned by an accurate automated traversing mechanism. The traverse system is equipped with servo-motors and can sustain an absolute coordinate system with accuracy of $10\,\mu$m in x and z, and $5\,\mu$m in y directions.

Sampling of data voltages is performed by the IOTech Wavebook 516 acquisition system, enabling 16-bit, $1\,$MHz sample and hold, in a maximum range of $\pm 12\,$V. Post processing of signal is performed using a PC.

3. Calibration of Wall Mounted Wires

Due to the design of the used micro hot wire being wall mounted, it is not suffer from the near wall influence, since the wall effects are taken into account by calibration. These sensors are calibrated *in situ* in a turbulent boundary layer against the mean wall shear stress relying on the presumption that velocity distribution in the sub-layer is linear.

For the range of velocities, the mean wall shear stress is measured using the Preston tube, Clauser plot and momentum integral relation, and a comparison of the results from each method is made as shown in Fig. 2. From this figure, it can be seen that the Preston tube results provide a reasonably smooth trend that is typical of this variation. The Clauser plot is found to provide values that are generally slightly higher than those for the Preston tube whilst the opposite is true for the values obtained by the momentum integral method. A comparison of obtained skin-friction coefficient vs Re_θ with a collection of data depicted in [5] led to the conclusion that the measurements using momentum integral underestimate the wall shear stress. Of these three methods, the Preston tube was determined to be the easiest to use and produced the most accurate results. The data obtained from the Preston tube were chosen for the microsensor calibration.

During the calibration, the instantaneous values of the anemometer voltage were read and stored. Afterwards, an additional iterative correction procedure of the calibration curve was applied for taking into account the nonlinearity of the wire response, see e.g. [3, 4]. Moreover, an extra care was taken to keep the flow temperature constant within 0.1 °C during the measurements, since temperature has a significant influence on the measurements [2]. Finally obtained

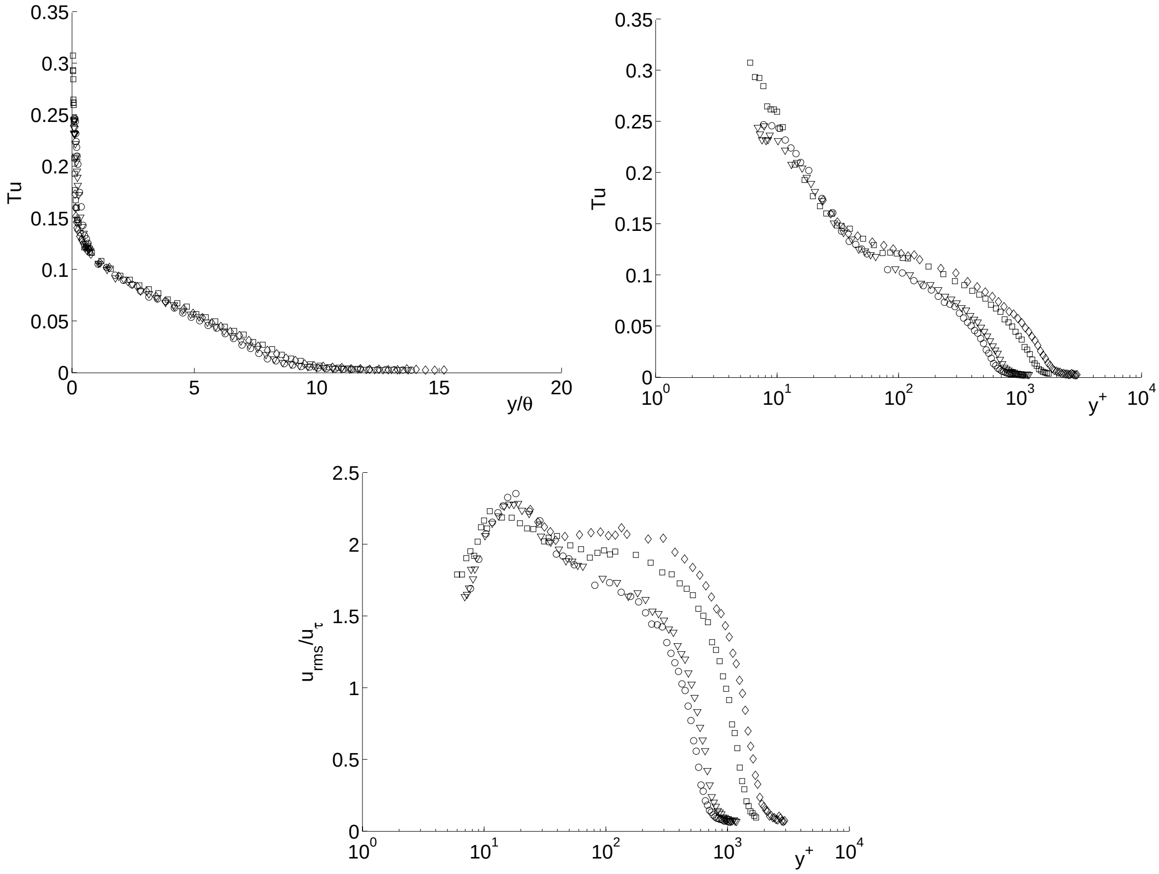

Figure 3: Wall-normal profiles of outer flow properties are shown. At the top, turbulence intensities in outer and inner scaling. At the bottom, profiles of u'_{rms}/u_τ in inner-law scaling. Symbols denote Re_θ: 1810 (○), 2010 (▽), 4130 (□), 5910 (◇). Corresponding values of dimensionless wire length, l^+ are about 22–75.

calibration points were fitted by modified King's law [2] and a polynomial.

The fluctuating wall shear stress in the turbulent boundary layer can range between 0.3 to 3 times the mean shear stress. For some of the data points presented here, extrapolation of the calibration curve was used and results that are obtained using outside part of the calibration range will be specified further on.

To check the accuracy of the calibration fit, the mean wall shear stress was determined using microsensors and compared to the presumed distribution. The largest deviation due to uncertainty of the calibration fit was found as about 4–6% and this was only for one data point, corresponding to lowest $\bar{\tau}$ of 100 μm from the wall wire. In other data points, except this, the uncertainty of the calibration fit was 0–2%.

4. Outer Flow Measurements

The quantity of primary interest in the present investigation is the fluctuating part of the streamwise wall shear stress, however, flow characteristics across the boundary layer are also identified. Measurements are performed using gold plated probe as described in sec. 2.

It was found from the measurements, that mean velocity profiles obey the logarithmic wall of the wall [6] for $980 \lesssim Re_\theta \lesssim 8000$ and obtained flow was treated as fully turbulent.

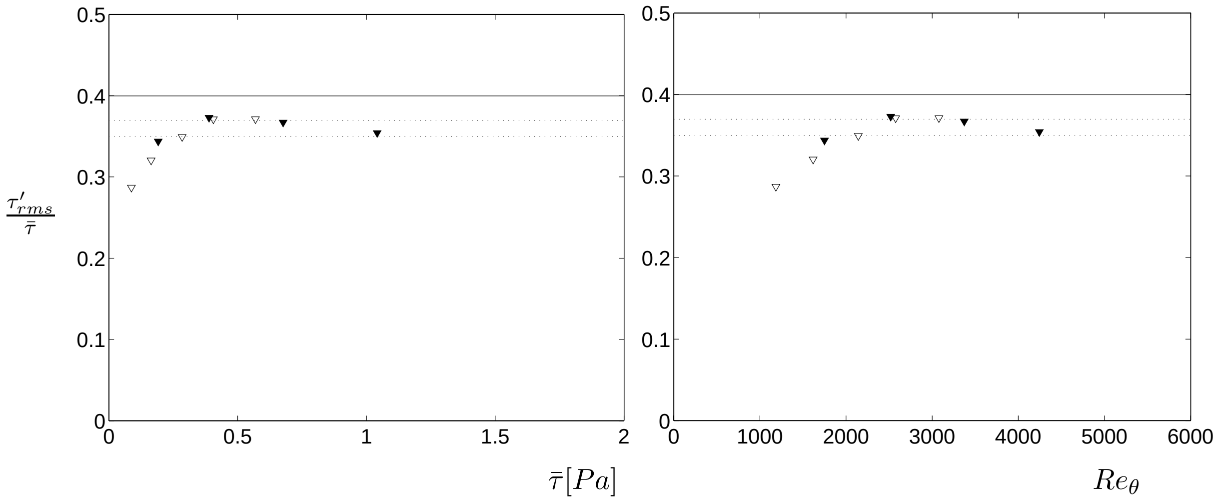

Figure 4: Variation of near-wall turbulence intensity $\tau'_{rms}/\bar{\tau}$ with mean wall shear stress $\bar{\tau}$ and Re_θ.

The wall-normal distributions of fluctuating quantities at four selected values of Reynolds number are shown in Fig. 3. In this figure profiles of turbulence intensity as well as u'_{rms}/u_τ profiles are depicted for values of $y^+ \gtrsim 10$. Turbulence levels for four Reynolds numbers collapse very well in outer scaling and, as usually, very well in the range of $y^+ \leq 100$ in the inner scaling. The best coincidence in the inner scaling is, however, for $y^+ \leq 40$. For u'_{rms}/u_τ similarity can be watched in the range $10 \leq y^+ \leq 40$, particularly, the maximum value and its position collapse very well. The position of maxima in this figure is $y^+ \approx$15, in agreement with other studies [5]. The magnitudes of observed maxima are around 2.3.

5. Inner Flow Measurements

The measurements in the viscous sub-layer are performed using miniature wall mounted hot wires, such as shown in Fig. 1 and the wires are calibrated as described in sec. 3. A velocity range was determined from the consideration of dimensionless wire height above the wall, h^+ being less than 5, so that assumption of linear velocity distribution can be applied. Hence, the velocity range was different for wires located 50 and 100 μm from the wall.

During measurements, an apparent influence of dimensionless wire length, l^+ on ability of the wire to measure fluctuating quantities was established, and this fact is in agreement with previous works, which consider spatial resolution of hot wires. According to work [3], to provide sufficient spatial resolution, the maximum recommended probe length should be l^+=20–25 to avoid averaging errors due to the integration over wire length. Similar observation was done in the current work and in all presented measurements, data points for which l^+ is greater than 25 are excluded.

Measurements are performed using two different wires and filled symbols in the graphs are used for lower wire, which is located 50 μm from the wall, while open symbols are used to depict data measured by upper (100 μm from the wall) wire.

The value of near-wall turbulence intensity was of particular interest of the current study. To determine the ratio of the r.m.s. of the fluctuating to the mean wall shear stress, the fluctuating wall shear stress was determined for a number of velocities. Figure 4 show how the ratio

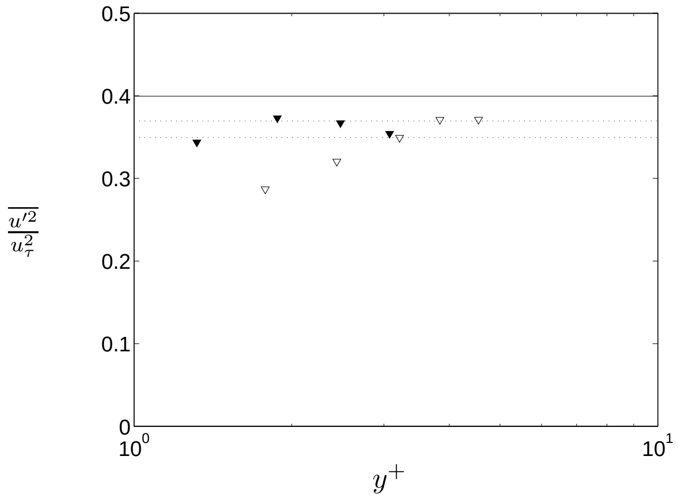

Figure 5: Variation of near-wall turbulence intensity $\tau'_{rms}/\bar{\tau}$ with dimensionless distance y^+.

$\tau'_{rms}/\bar{\tau}$ varies with mean wall shear stress and flow Reynolds number. It can be seen that all of the values obtained are below the 0.40 measured by Alfredsson *et al.* [3], however are very close. The maximum value is approximately 0.37 and the lowest is around 0.28. Horizontal dotted lines in the figures correspond to values of ratio of 0.35 and 0.37. Additionally, a general trend can be seen of decreasing the shear stress ratio as mean wall shear stress and Reynolds number decreases. This happens for $\bar{\tau} \lesssim 1.7$ and $Re_\theta \lesssim 1700$. The observed behavior can be explained, since as Reynolds number approaches zero, the laminar flow state should be obtained with zero turbulence intensity. However, fairly high value of Re_θ for which this trend starts is somewhat surprising, since outer flow demonstrates yet a fully turbulent behavior. Additionally, a consideration of the measuring device properties does not suggest that cause for this drop is a response characteristic of the sensors, since the wall shear stress values are not so low as those at which the behavior of hot wire sensors is altered [2] and a thermal inertia may appear. Moreover, the thermal inertia decreases as wire moved further from the wall, thus wires located at different wall distances would show different results and this is not observed. When a value of about 1700 is reached, the constant value of ratio is obtained with some scatter and most of the values in this figure are approximately 0.36±0.01.

As it was mentioned, in present work great care was taken to decrease uncertainty of the calibration fit and the effects of temperature, which may considerably affect the measurements. Particularly, the uncontrolled decay of temperature during calibration may increase the fluctuating wall shear stress. It should be noted here, that calibration range for upper wire was extrapolated after Re_θ of about 2200 and for lower wire the extrapolation is used above 3400. No extrapolation was used below these two values. However, the values outside of the calibration range for upper wire correlate very well with these for lower wire with no extrapolation and this fact is a supporting argument of validity of the extrapolation procedure used. Data for lower wire continue the trend of the shear stress ratio having a value of 0.36±0.01.

In Fig. 5 obtained data are rearranged to show the variation of near-wall turbulence intensity with dimensionless wall distance. As well, a nearly constant distribution is evident, and points which are outside of 0.36±0.01 values belong to discussed range of $Re_\theta < 1700$.

Further on, in Fig. 6 data are presented as variation of u'_{rms}/u_τ and the dimensionless Reynolds normal-stress component, both in inner law scaling. Solid line in this figure is used to demon-

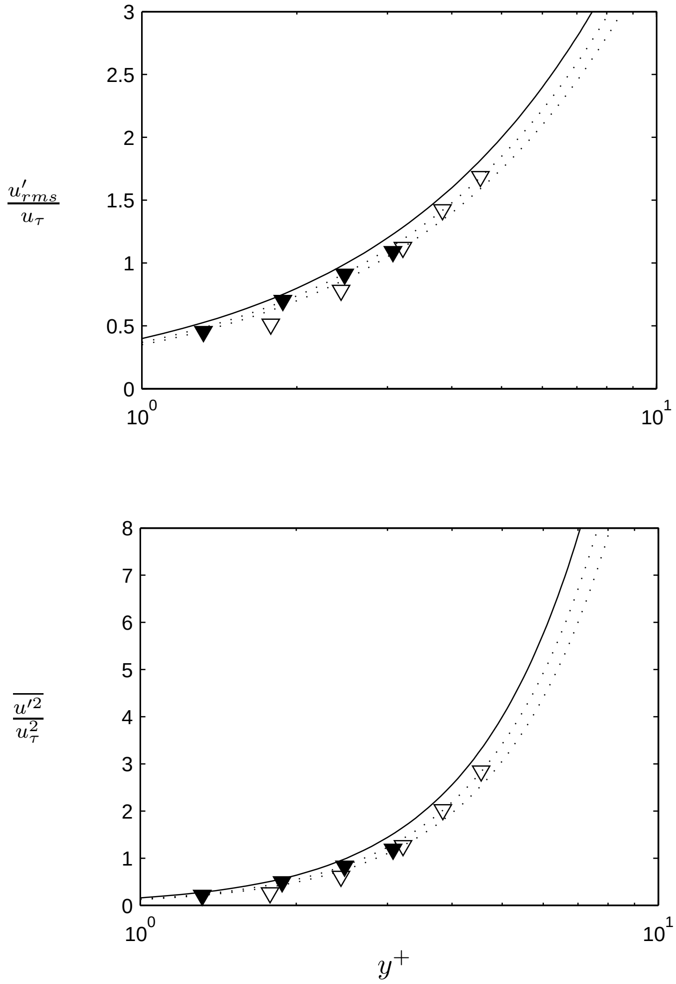

Figure 6: Variation of u'_{rms}/u_τ and the dimensionless Reynolds normal-stress component in inner law scaling.

strate trend which will take place if $\tau'_{rms}/\bar{\tau}$ is constant and equal 0.4 and dotted lines are for a similar assumption, however depict $\tau'_{rms}/\bar{\tau}$ equal to 0.35 and 0.37.

6. Conclusions

In the present experiments, two different miniature hot wires were calibrated in a turbulent boundary layer against the mean shear stress, which was determined using a Preston tube, Clauser plot and the momentum integral relation. The miniature probes used are unaffected by near wall effects and a lack of the spatial resolution and therefore capable of determining the fluctuating velocity of the flow within the viscous sub-layer. Additionally, the temperature effects were avoided. Using the MEMS hot wires, the ratio $\tau'_{rms}/\bar{\tau}$ was determined to be 0.36$\pm$0.01 except at Reynolds numbers lower then about 1700 where there was an apparent decrease in the measured value. A lower value of obtained turbulence intensity if compared to some other studies, where value of 0.4 was reported may be associated with a lower magnitude of observed maxima of u'_{rms}/u_τ which is 2.3 and also lower than a ”classical” value of 2.7, see [5].

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