TIME-RESOLVED WALL SHEAR STRESS MEASUREMENTS USING MEMS

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Summary A number of MEMS (Micro Electro Mechanical Systems) wall mounted hot wire sensors have been developed at the Thermo and Fluid Dynamics department (TFD) at Chalmers University of Technology. The sensors were used to investigate the fluctuations of the velocity within the viscous sublayer of a zero-pressure-gradient turbulent boundary layer flow. The measurements performed at Reynolds numbers, R_θ ranging between 1000 and 15000 are discussed and compared to other relevant data collected from literature.

INTRODUCTION

For flow control purposes, wall shear stress is an essential quantity to compute and measure. In a turbulent flow the time-averaged values of this quantity are indicative of the global state of the flow along a surface, while the time-resolved component is a measure of the unsteady structures of the flow field which are responsible for the individual momentum transfer events in the boundary layer. Different methods for the measurement of wall shear stresses have been developed, and most rely on the premise that the mean velocity gradient is proportional to the heat transfer rate at the wall. A general conclusion to be made is that our knowledge of the wall shear stress, and in particular its fluctuating or time-resolved component, is limited. A clear trend in all wall shear stress measurements is that the sensors used have increasingly smaller active sensor areas in order to improve the resolution. In this process, MEMS fabrication technology has in recent years played a central role [1].

The MEMS sensors developed at TFD, Chalmers (final design and production courtesy to the KTH group) are hot wire sensors that are mounted on the wall at a small distance from it. A major advantage of this design is that the performance and accuracy are increased as compared to hot film type sensors. Furthermore, the fixed height of the sensing element from the wall is known precisely at all times, which is not easily achieved with, for example, a standard hot wire attached to a traverse mechanism. Recently, the sensors have been proven to accurately measure the wall shear stress in laminar airflows as is reported in [2]. A first attempt was made at using the sensors to measure the time resolved part of the wall shear stress in turbulent flows in ref. [3]. Due to the design of the MEMS hot wire being wall mounted and to account for near wall effects, the MEMS hot wire is calibrated *in situ* in a turbulent boundary layer against the mean wall shear stress.

While continuing the research into the use of the MEMS sensor in turbulent flows the current tests were designed with the primary aim of increasing the accuracy of the measurements. The relative intensity of the streamwise wall shear stress fluctuations was taken as the primary quantity of interest. The experiments performed by Alfredsson et al. [4] are widely accepted to be the most accurate measurement of the ratio, for which it was claimed that a constant value of 0.4 should be observed. However, an extensive review of papers published since then reveals that this is not necessarily the case as values are found to range from 0.3 to 0.5. This leads to the problem that either the ratio is not a constant value of 0.4 or the other techniques used suffer inadequacies which make their results unreliable. Further investigation of these findings provides an additional motivation for the current research.

EXPERIMENTAL PROCEDURE

Three variations of MEMS sensor wires were utilized for the measurements, a wire measuring $400\times2\times2\ \mu\mathrm{m}^3$ at a height of 50 μm from the wall, (one of five shown in figure 1, *left*) and wires with dimensions $200\times1\times2\ \mu\mathrm{m}^3$ at heights of 50 μm and 100 μm above the wall (figure 1, *right*). The dimensions of these MEMS sensors give rise to very good spatial resolution within the viscous sublayer of the turbulent boundary layer and this therefore enables them to determine the fluctuating velocity of the flow in this region.

The experiments were conducted in the wind tunnel laboratory of TFD. The closed circuit tunnel has a working test section measuring $3\times1.8\times1.2$ m^3 and has a low turbulence intensity of less than 0.1% of the free-stream velocity. The tests were performed on a zero-pressure gradient flow on a flat plate of dimensions $2500\times1000\times25$ mm^3 with Reynolds number, R_θ, ranging from approximately 1000 to 15000. A wire of 5 mm diameter placed 190 mm from the leading edge was used to trip the flow. The MEMS sensors were positioned on a surface-mounted chuck located 1930 mm from the leading edge of the plate. The sensors were calibrated *in situ* in turbulent boundary layer. This means that near wall effects are accounted for by the calibration.

Twelve independent runs were made using the different wires and great care was taken while conducting the experiments to reduce the errors involved with the measurements. The tests were made at a wide Reynolds number range to observe the effect of this parameter on the fluctuating wall shear stress. A temperature compensation circuit (via a temperature sensitive resistor) was introduced into the constant temperature anemometer bridge to avoid the effect of temperature drift, which can influence the measurements significantly [2].

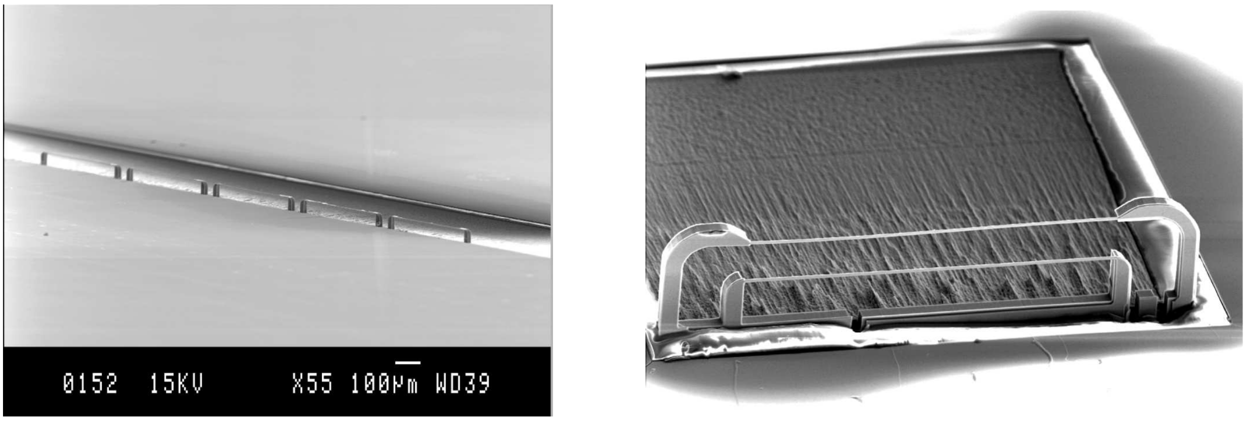

Figure 1. Micrographs of single wire MEMS line rake (*left*) and two-wire MEMS rake (*right*).

A number of methods were also introduced to ensure that the calibration fit was as accurate as possible.

RESULTS AND DISCUSSION

To begin with, extensive measurements were taken using a standard hot wire on the inner and outer regions of the boundary layer to ensure that the flow was of a classical formation at the point on the plate where the MEMS sensors were deployed. The mean shear stress was determined using a Preston tube. The mean velocity close to the wall was proven to be of the form $u^+ = y^+ + c_4 y^{+4} + c_5 y^{+5}$ with $c_4 = -0.0003$ and $c_5 = 1.35 \times 10^{-5}$ up to a value of y^+=11. A comparison between the measurements achieved by employing this distribution for the sensor calibrations and those derived from the calibrations against the Preston tube, was then performed.

The spatial resolution achieved by the sensors employed was taken into account at each Reynolds number range and any measurements made outside the range of $l^+ > 25$ were discarded from the analysis. The calibrations were performed in the range up to R_θ ≈15000 and the time-dependant results were obtained only up to R_θ ≈7500 for spatial resolution reasons. The energy spectrum was analysed and this was found to give a satisfactory distribution with the signal-to-noise ratio being reasonably high. Probability density functions were also calculated and these gave a distribution very close to the lognormal distribution.

An analysis of experimental as well as DNS data available at present was carried out to see if the limiting value of turbulent intensity on the wall of 0.4 was being consistently achieved. A well-known problem encountered during this study was that many of the techniques used to evaluate this parameter have serious flaws when being used in the viscous sublayer of the boundary layer as is discussed e.g. in [4]. From the reliable data available and from the current experiments, it can be deduced that while the value of 0.4 for the limiting ratio is not obtained very often, this figure is indeed a valid approximation as it was to be found at the centre of the spread of data.

References

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