EXPERIMENTAL AND NUMERICAL INVESTIGATION OF RIBLETS IN A FULLY DEVELOPED TURBULENT CHANNEL FLOW

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It is a well established fact that riblets can reduce the skin friction drag in turbulent flows. Drag reduction results are typically presented as a function of s^+ which represents the riblet size normalized with the wall shear velocity and the viscosity of the fluid. Figure 1 summarizes the available experimental literature data for one specific riblet geometry. There is obviously quite some scatter between the different measurements but also within some of the data sets. Out of the available data the measurements obtained in the Berlin oil tunnel seem to be the most accurate ones and the corresponding measurement procedure as well as details of the facility are well documented [1].

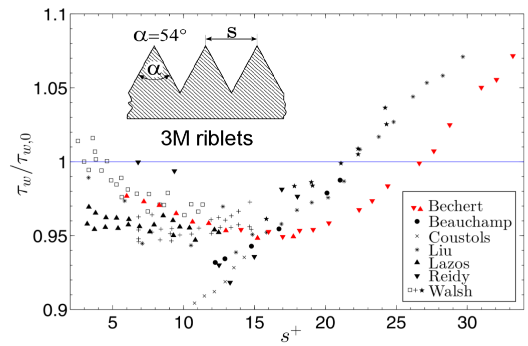

Figure 1: Experimental literature data for one specific riblet geometry.

We recently designed an experimental facility with air as working medium with the goal to investigate drag reduction techniques under well defined fully turbulent and quasi two-dimensional conditions (thus similar to the conditions in numerical investigations). In this facility a conventional blower wind tunnel set-up is used, which is connected to a channel test section with aspect ratio 12 : 1 and a length of more than 150 channel heights. Pressure taps on the channel side walls allow the measurement of the pressure drop along the test section that is used to determine the skin friction drag in the channel. The flow is tripped at the inlet and the skin friction drag is evaluated after reaching a fully developed state only. The top and bottom plates of the channel can be changed, which allows riblet walls to be inserted in part of the test section in such a way that they can directly be compared to smooth walls for a fixed flow rate. In order to avoid variations of the bulk velocity in the consecutive parts (riblets and smooth walls) of the test section the riblet plates are inserted into the channel facility in such a way that the channel cross sections with and without riblets are identical.

The flow rate in the channel is measured with an orifice meter or an inlet nozzle at the suction side of the wind tunnel. All ambient parameters are carefully monitored to correctly determine the fluid density and viscosity. Reference measurements with flat plates along the entire test section are shown in Figure 2. It can clearly be seen that the c_f-value based on the measurement results show very little scatter and matches the Dean correlation well.

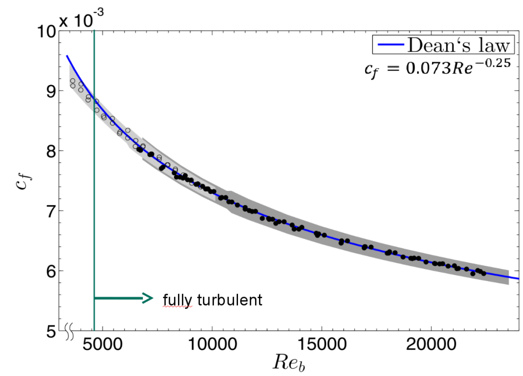

Figure 2: Distribution of the skin friction coefficient in the channel with flat plates. Closed symbols refer to flow rate measurements with the inlet nozzle, open symbols with the orifice meter. The grey shaded area indicates the measurement uncertainty.

The riblet walls for the present experiment were specifically manufactured, since riblet structured foils are presently not available on the market. The chosen riblet design - as shown in Figure 3 - is thus a compromise between manufacturing capabilities and the optimal drag reduction shapes.

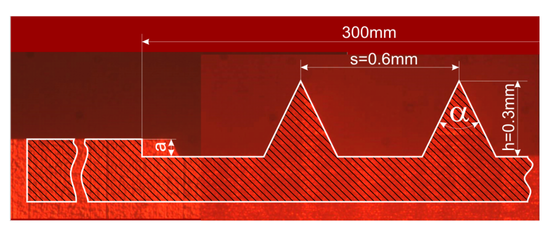

Figure 3: Riblet test plates manufactured at Fraunhofer IPT in Aachen.

The obtained drag reduction results in the air channel are shown in comparison to the Berlin oil tunnel data in Figure 4. This data shows that careful pressure drop measurements in air can indeed reproduce the experimental accuracy obtained with friction balance measurements in oil. An uncertainty estimation for the air channel flow data reveals that the increased scatter for small s^+-values mainly originates from uncertainties in the flow rate measurement; i.e. the correct determination of the Reynolds number. Overall, the obtained drag reduction data for the present riblet geometry with a tip angle of 53.5° show reasonable agreement with the Berlin data [1] as they are located in between the oil tunnel data for 45° and 60°. One noticeable difference between the data sets is the different slope of the drag reduction curve for small s^+-values. Bechert et al. [1] already indicated that this limiting behavior for very small riblets is sensitive to the applied measurement procedure. One potential reason for experimental deviations from the theoretically expected behavior for small riblet sizes [6] lies in the assumption of two-dimensionality that cannot fully be achieved experimentally.

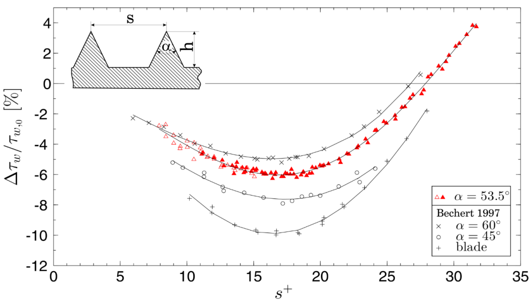

Figure 4: Drag reduction measured in the fully developed turbulent air channel flow in comparison to oil tunnel data [1].

The two dimensional channel flow is the typical test case scenario for direct numerical simulations (DNS), which are widely used for the evaluation of active flow control techniques. However, for riblets there is a very limited number of numerical studies available [2, 3, 4]. A shortage that is probably due to the fact that the characteristic sharp riblet tips cannot be well captured with the structured grids typically employed in DNS codes.

In order to complement the present experimental data with numerical results, we therefore decided to use OpenFOAM® for a DNS with exactly the riblet shape of the experiment. This code allows resolving the riblet shape with an unstructured mesh with a trade-off in respect to the numerical accuracy (second-order finite volume method instead of higher-order finite difference or spectral methods). Part of the employed polyhedral mesh is depicted in Figure 5.

In order to evaluate the simulation quality, reference DNS for a smooth channel with a polyhedral mesh in OpenFOAM® are carried out. The obtained results are in reasonable agreement with literature data so that this data is used as reference state for the riblet simulation.

In the riblet DNS one point in the drag reducing regime ($s^+ = 17$) is considered. In analogy to the experiment the riblets are inserted on the top and the bottom of the channel in such a way that the average channel height (channel cross section) is not altered. While the experiments are carried out in a Reynolds number range of $5000 < Re_b = HU_b/\nu < 25000$ with the maximum drag reduction in the range of $10000 < Re_b < 13000$ the DNS is limited to lower Reynolds numbers. For the present investigation the flow rate is fixed such that $Re_b = 5600$, which corresponds to $Re_\tau = 178$ for smooth channel walls. The numerically obtained results in terms of drag reduction differ from the experimental values. The DNS yields about 2%, while the experimentally measured drag reduction for this dimensionless size of the riblets is about 6%.

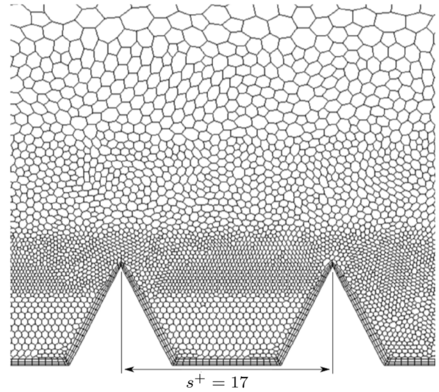

Figure 5: Small fraction of the mesh. The total number of cells is almost 14 million cells with a channel length of $4\Pi\delta$ and a streamwise resolution of $\Delta x^+ = 9.3$. Riblet results are averaged for about 30 eddy turnover times.

This discrepancy is an open issue to be discussed. Unfortunately, there is no other literature data available that provides a direct comparison between experimental and numerical results for the same riblet geometry.

In order to further evaluate the simulation quality, error bars for the obtained results will be estimated according to Oliver et al. [7]. It is likely that they are significantly higher than the ones in the experiment in which skin friction changes of 0.4% can be reliably detected. Other issues that might lead to differences in the results are the limited two-dimensionality in the experiment and the difference in Reynolds number. The former is more likely to lead to an underestimation of the drag reduction rate in the experiment due a spanwise variation of the wall shear stress. In respect to the Reynolds number dependency we note that riblet experiments are typically carried out for $Re_b > 10000$ [5]; a Reynolds number that is quite challenging to reach with a realistic representation of the riblet tips in DNS.

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