A98-31569

ICAS-98-3,10,3

# SKIN FRICTION MEASUREMENTS DOWNSTREAM OF A BACK-FACING STEP

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## Abstract

The flow behind a back-facing step in a channel with fully developed turbulent flow has been analysed, with reference to the unsteady behaviour of the separated region.

Time resolved skin friction measurements have been made using a double hot wire wall probe, ad hoc designed, for three Reynolds numbers, Re = 3200, 6500, 13000.

Details of the primary and secondary recirculation regions have been shown in terms of probability distribution of having forward flow and in terms of skin friction coefficients.

Large negative values of the wall shear stress, depending on the Reynolds number, have been measured in the reverse recirculation region; the larger negative value, $C_f$= -0.0042, has been found for the lowest Reynolds number.

A spectral analysis of the $\tau_w$ fluctuations has revealed that the most energetic frequencies are around 10 Hz in the secondary bubble and in the range from 30 to 80 Hz in the main bubble.

## Introduction

The behaviour of flows behind a back-facing step in ducts is important for many reasons, the main of which are the following:

- It has a direct application in industrial pipes or channels with sudden changes of section.
- It is a good representation of flows over geometries with steps and of flows of practical engineering interest where separation and reattachment occur.
- It provides an excellent opportunity for the study of separated flows, not only in the experimental, but also in the numerical field. Its simple geometry characterized by a complex flowfield provides an excellent test-case for computational methods.

There have been a large number of experimental [1, 2, 3, 4, 8, 9] and, recently, numerical [5, 10, 11, 12, 13] investigations on the flow structure over a two-dimensional backward-facing step, but still some aspects are not clear. In particular, the unsteady flow behaviour in the reattachment region and the interaction between this unsteadiness and the large-scale structures forming behind the step and developing in the free shear layer need further investigation to be completely understood. Moreover it is of practical importance to control the separated flow unsteadiness by passive methods in order to reduce structural stresses, aerodynamic drag and noise.

At the "Modesto Panetti" Aerodynamic Laboratory of the "Politecnico di Torino" experimental research is progressing on the unsteady behaviour of separated flows and their control. In order to perform this study, a probe for time resolved skin friction measurements has been developed. In this paper results obtained using this probe in the reattachment region downstream of a back-facing step are presented and discussed.

## Experimental Set-up

The measurement of skin friction in a separated region is a rather difficult task, as classical methods like Preston tube or Clauser chart, based on the existence of the universal near wall law, are bound to fail in a region where such a law does not hold. It is therefore necessary to make use of a skin friction measurement device independent from the law of the wall. In our laboratory wall shear stress probes have been studied for some years now [6, 7]. Full description of design,

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21st ICAS Congress
13-18 September 1998
Melbourne, Australia

building, testing and validation of the probe employed in the present research will be reported in a forthcoming article, presently in preparation. Only a brief description will be given here.

The probe is a special wall double hot wire device. Two wires are wall-mounted, parallel to each other (see Fig. 1) across a circular cavity 1 mm deep and

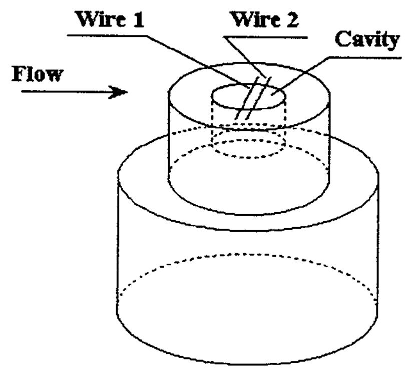


Figure 1: Sketch of the skin friction probe.

with a diameter of 1 mm. Inside the hole, a cavity flow is established. This flow is driven by the shear stress over the cavity, which is assumed to be continuous with the wall skin friction, $\tau_w$, around the cavity itself. The wire cooling depends on the velocity of the upper edge of the cavity flow. Moreover, one of the two wires is in the wake of the other one; this allows the detection of the sign of $\tau_w$. As was remarked earlier, $\tau_w$ is correlated to the cavity flow velocity and so to the mean signal from the two wires. It is assumed that this kind of probe allows skin friction measurements regardless of the existence of the universal near wall law.

The wall hot wires were controlled by two Dantec Series 55M constant temperature anemometric bridges; signals were digitalized and sampled by a National Instruments 16 bits analog to digital converter board and processed via LabView software.

At each measurement position, $2^{17}$ samples were recorded with an acquisition frequency of 4000 Hz. The Nyquist frequency of 2000 Hz is much higher than the frequencies expected to be involved in the phenomena of interest in this research. On the other hand, the acquisition period is enough to describe low frequency events.

The calibration of the probe was performed in the 2D calibration *Channel 1*, having an aspect ratio of 14:1 with fully developed turbulent flow. The wall skin friction in the channel is known by pressure gradient measurements and may be then correlated to the probe signal. A typical calibration curve is shown in Fig. 2.

The experimental work described in the present paper was carried on in the quasi-2D *Channel 2*, having

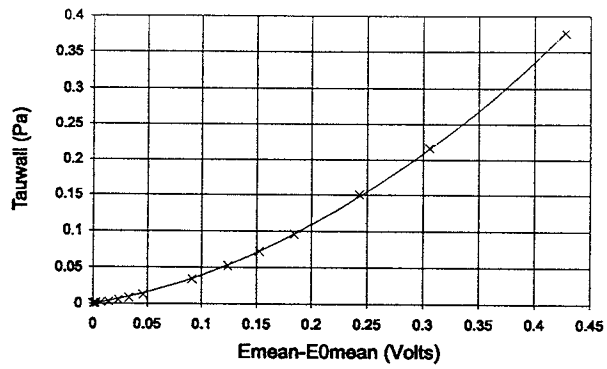


Figure 2: Skin friction vs. probe voltage calibration curve.

a cross section of 7 cm × 30 cm. This facility is an open circuit one; the working fluid is air. The flow is compressed by a propeller into a settling chamber where swirl and turbulence components are reduced by use of honeycombs and grids and expands through a convergent with contraction ratio 19:1. The step, on the lower wall of the channel, is located 53 hydraulic diameters downstream of the inlet. The height of the step is $H = 2$ cm. The ratio between the channel width and $H$ is thus 15:1, which allows to consider the step flow as two-dimensional.

The skin friction probe is placed on the lower wall centerline downstream of the step and can be continuously displaced by means of a longitudinally moving sled that allows positioning from $0.3H$ to $20H$ downstream of the step.

Experiments have been performed at Reynolds numbers 3200, 6500 and 13000. Reynolds number here is defined as:

$$Re = \frac{U_0 H}{\nu} \tag{1}$$

where $U_0$ is the velocity of the flow on the channel axis upstream of the step.

## Results and Discussion

The flow conditions upstream the step are representative of a fully developed turbulent channel flow. The mean velocity profile follows the law of the wall well and the longitudinal fluctuation velocity profile is in good agreement with data from the literature. Only results of the skin friction probe measurements are here presented. In Fig. 3 the probability of having forward flow as a function of the distance from the step (x/H) is reported for the three Reynolds numbers. Starting from the step, one can observe the presence of a region of high probability of forward flow right downstream of it. This probability is reduced to 0.2 for x/H ≈ 2 and becomes nearly 0 for x/H ≈ 2.5, where the flow is thus always reversed. This behaviour

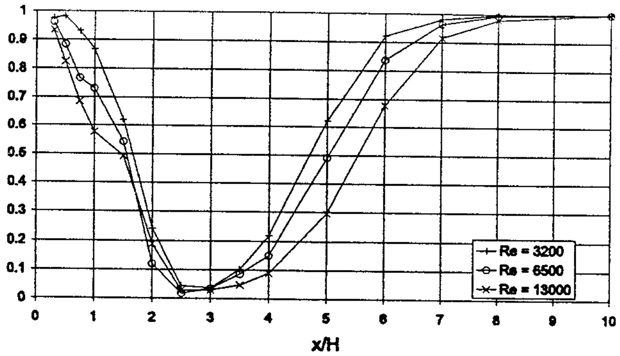


Figure 3: Probability distribution of forward flow downstream of the step.

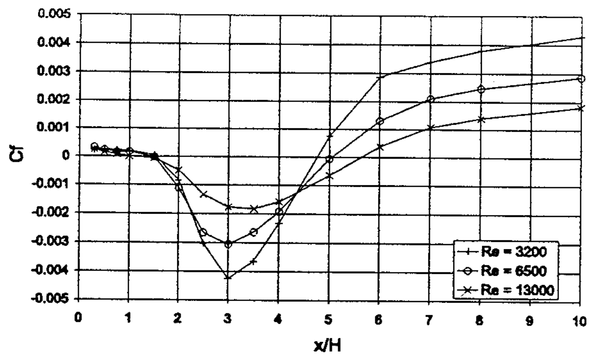


Figure 4: Mean skin friction coefficient distribution downstream of the step.

indicates the presence of the secondary recirculation bubble upstream of the primary one. Going downstream, in the region of the primary bubble and of the mean reattachement point, the forward flow probability increases, reaching again a value of about 0.9 for x/H $\approx 6 \div 7$, depending on the Reynolds number. For x/H $\geq$ 8 the flow is always directed downstream. The effect of the Reynolds number is evident from the diagram: for increasing Re, the probability of forward flow in the same position decreases.

The mean reattachment locations of the primary bubble and the extent of the secondary bubbles may be determined by the probability of having 50% forward flow. Using this criterion the mean length of the secondary recirculation region results to be x/H $\approx$ 1.7, and nearly independent of the Reynolds number. The reattachment location of the primary bubble depends on the Reynolds number and increases from x/H $\approx$ 4.5 to x/H $\approx$ 5.5, for increasing Re from 3200 to 13000.

Another deduction from this diagram is that the zone where the flow is quasi-steadily upstream directed is quite reduced ($2 \leq x/H \leq 4$), while the zone where the flow shows changes in direction is much larger. This implies that a large zone exists which is subject to unsteady stresses.

In Fig. 4 the distribution of the mean skin friction coefficient $C_f$ downstream of the step is reported; $C_f$ is defined as:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho U_0^2} \qquad (2)$$

Assuming that points where $C_f = 0$ are representative of the mean lengths of the two recirculation bubbles[12], we deduce from fig 4 nearly the same bubble extensions as from fig. 3.

The presence of the secondary bubble is again evident in the region of positive and very low $C_f$ near the step. Downstream, $C_f$ crosses the zero line and the mean skin friction takes negative values, as expected in the primary bubble. At higher distances, $C_f$ becomes positive again, and shows a trend towards a constant value, which indicates that the flow is approaching a new equilibrium condition; though, the asymptotic value is still not reached for x/H = 10. The shear stress distribution in the primary bubble is clearly influenced by the Reynolds number. A very high peak value of $C_f$, equal to -0.0042, is found for Re=3200. This value is reduced to -0.0018 for Re=13000.

Downstream of the mean reattachment point all curves show the same asymptotic trend, but the values towards which they tend decrease as the Reynolds number is increased.

The secondary bubble appears to be only slightly influenced by Reynolds number.

The results obtained at Re = 6500 were compared, Fig. 5, to the ones obtained by Le, Moin and Kim [12] via direct numerical simulation (DNS) for a similar Reynolds number (Re = 5100) and to the ones of the validation experiment of Jovic and Driver [8, 9]. It is possible to deduce from this comparison the following considerations.

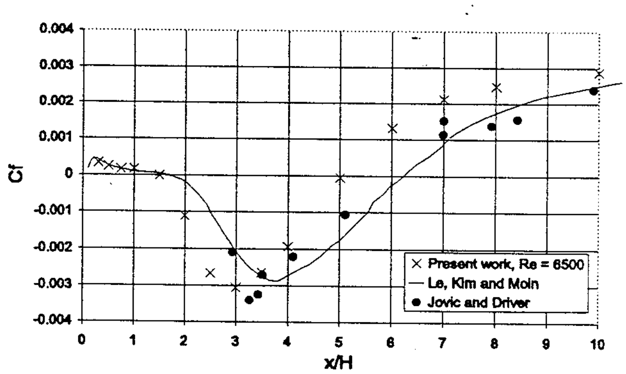


Figure 5: Comparison of mean skin friction distribution for the present work at Reynolds = 6500 against refs. [12, 8, 9]

The skin friction distributions show very similar trends and the negative $C_f$ peak value is nearly the same.

The $C_f$ distribution in the secondary bubble region is essentially coincident with the numerical simulation results. Downstream, the trend of $C_f$ exhibits a shifting towards lower values of x/H.

These differences have been attributed to the fact that the DNS data was obtained for a boundary layer flow upstream of the step, while the present results are relative to a step in a fully developed channel flow.

Figure 6 is a plot reporting the power spectra of the $\tau_w$ fluctuations multiplied by the frequency as a function of the frequency, for Reynolds number 6500. These spectra were computed in five of the experimental x/H positions; each of them is representative of one of the important regions in the flow field studied.

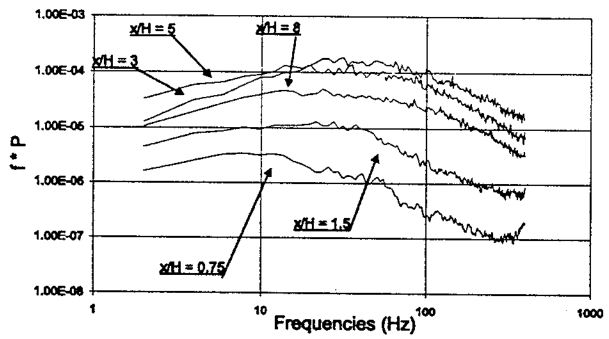


Figure 6: Spectral analysis of the wall shear stress fluctuations at various x/H position for Reynolds = 6500.

In the region of the secondary bubble (x/H = 0.75) the maximum contribution to the variance of $\tau_w$ is given in a range of frequencies around 10 Hz. Downstream, in the recirculating and reattachment regions, the greatest contribution to the energy is given by higher frequencies, in the range from 30 to 80 Hz.

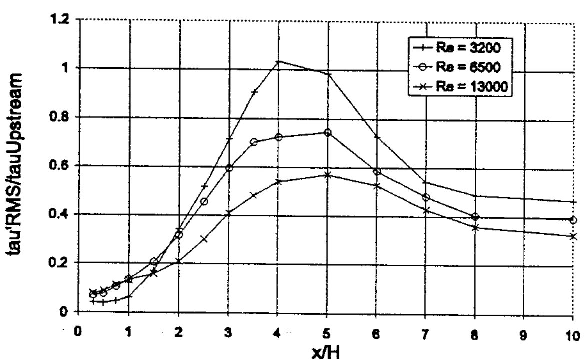


Figure 7: Distributions of the wall shear stress fluctuations downstream of the step for different Reynolds numbers.

The distribution of the root mean square of the skin friction fluctuations downstream of the step, nondimensionalized by the mean skin friction upstream of the step, are displayed in figure 7 for the three Reynolds numbers. It may be seen that in the secondary recirculation region $\tau'_{RMS}$ takes the lowest values. Greater unsteadiness is present in the reattachment region for all the three Reynolds numbers.

## Conclusions

A wall skin friction probe has been used to investigate of the unsteady aspects of the flow behind a back-facing step in a channel. Details about the mean extent of the primary and secondary bubbles are demontrated by the probability of having forward flow in the region of interest and by the distribution of the mean skin friction coefficient downstream of the step.

It has been found that the mean extension of the secondary recirculating region is about 1.7 times the step height, for all the Reynolds number tested. The primary mean reattachment location varies from x/H = 4.5 to x/H = 5.5, increasing Re from 3200 to 13000.

Large negative skin friction values have be seen in the reverse recirculation region, showing a very high negative value, $C_f$ =-0.0042, for the lowest Reynolds number tested. Downstream, $C_f$ tends to values also depending on the Reynolds number.

Spectral analysis of the skin friction fluctuations has shown that in the secondary recirculating region most energy is contained in frequencies around 10 Hz and higher in the main bubble, ranging from 30 to 80 Hz, for Re=6500.

## Acknowledgements

This research was funded in part by the MURST and in part by the CNR.

The authors also wish to thank Mr. Grivet and Mr. Mantovani, technical personnel of the DIASP and CNR-CSDF, for their excellent work in the manufacturing of the special wall probes.

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