Separation control in a plane asymmetric diffuser by means of streamwise vortices – experiment, modelling and simulation

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Introduction

Separating interior flows are of the utmost importance for the performance of a wide variety of technical applications. Many industrial designs today have to be compromises between the aerodynamical function and other competing functions e.g. size or mechanical function. In such compromised designs undesired separation is more likely to occur, this can drastically decrease the performance of the design. Sometimes it might even be impossible to achieve a design where separation is avoided. In such cases, active or passive devices which increase the near wall momentum can be used to remove or reduce the separation.

This investigation is a continuation of our previous work on the plane asymmetric diffuser (see e.g. Gullman-Strand *et al.* (2004) and Törnblom *et al.* (2003)) which aimed at studying the uncontrolled flow in the plane asymmetric diffuser (see figure 1), in order to produce a reliable experimental database and test turbulence models. The previous work, on the uncontrolled case, showed that a fluctuating separated region was formed on the inclined wall with a mean separation point at $x/H = 9$ and a mean reattachment point at $x/H = 31$.

The aim now is to investigate ways to reduce the size and/or the motion of the separated region. It is well known that vortex generators are efficient when it comes to delay separation and preliminary tests of vortex generators (VGs) in our experiment have been very successful. By placing a spanwise row of VGs slightly above (at $x/H = 7$) the mean separation point we managed to increase the efficiency (as compared to an ideal, frictionless case) from 0.76 to 0.84.

Vortex generators introduce streamwise vortices which bring fluid with a high level of streamwise momentum down close to the wall. When the streamwise vortices are introduced the spanwise coherence of the flow is broken which is a key element in our control strategy. The DNS results presented in the present paper (see also Herbst & Henningson (2003)) show that control with a spanwise periodic input is more effective in the control of flow separation than a spanwise homogeneous control input. In the DNS the separation is induced on a flat plate by a pressure distribution.

In the present paper we describe the first steps of the experiments with vortex generators and a first attempt to compute the controlled flow by means of a simplified modelling approach. We also illustrate the control strategy by means of some new DNS results of control of a separation bubble on a flat plate.

The plane asymmetric diffuser

The first investigation of the flow characteristics in a plane asymmetric diffuser was done by Obi *et al.* (1993). In that investigation the opening angle of the diffuser was 10° which is somewhat larger than that (8.5°) in our experiment. The 8.5° angle combined with a very large aspect ratio (50:1) of the inlet channel and boundary layer removal on the side-walls, together contribute to enhance the two-dimensionality of the flow.

Description of the uncontrolled flow

Figure 2 shows streamlines in the uncontrolled flow-case, a region with average backflow is formed in the diffuser on the inclined wall. Between the region of high velocity and the region of backflow there is a free shear layer with large velocity gradients and an inflection point. The largest production rates of Reynolds stresses are found in this free shear layer. The recirculation region is given by the zero streamline.

Experiment with vortex generators

Figure 3 shows the pressure coefficient along the centerline of the diffuser with and without vortex generators applied. For the case without VGs we observe a plateau region in the C_p-curve, which can be seen as a result of the displacement of streamlines caused by the recirculation zone. No such region can be seen when the vortex generators are applied. No velocity measurements have yet been done with vortex generators applied, so the evidence of inhibited separation is still somewhat of an indicative nature. The shape of the C_p-curve clearly indicates that the size of the recirculation zone has been diminished substantially. The increased efficiency of the diffuser with VGs applied can be seen in figure 3 as a difference in the final levels of the two curves.

Modelling of vortex generators

The introduction of streamwise vortices by means of vortex generators in the asymmetric diffuser configuration gives a three-dimensional character to the flow. However, the periodicity of the VG positions allows us to take averages, in the spanwise direction, over an integer number of periods and consider that as a two-dimensional representation of the flow. This can be utilised in order to model the effects of vortex generators in a two-dimensional RANS-computation.

A first approach is to assume that the vortices introduced can be approximated as Lamb-Oseen vortices which have a tangential velocity distribution given by

$$U_\theta = \frac{\Gamma_0}{2\pi r}\left(1 - \exp(-r^2/r_0^2)\right). \tag{1}$$

This approximation has been shown to be reasonable by Wendt (2001) who carried out an extensive parameter study on VGs. The vortex characteristics are determined by the far field circulation Γ_0 and the parameter r_0 which sets the radial position of maximum U_θ. Results from the investigation by Angele (2003) and from planned experiments with vortex generators in the asymmetric diffuser will be used to find appropriate values for these parameters. Figure 4a shows the flow pattern in a spanwise-wall-normal plane from a row of periodically space vortex generator pairs and 4b is the resulting wall-normal distributions of v_{rms} and w_{rms} taken over one period.

The distributions in figure 4b are used in a forcing term

$$F_{ij}(x,y) = \lambda(x,y)\left[\mathcal{F}_{ij}(x,y) - \overline{u_i u_j}(x,y)\right], \tag{2}$$

introduced in the right hand side of the transport equations for the Reynolds stresses in a two-dimensional DRSM (Differential Reynolds stress model). The desired values of the Reynolds stresses

$$\mathcal{F}_{ij} = \overline{u_i u_j}^{\mathrm{uc}}(x,y) + \mathcal{F}_{ij}^{\mathrm{vg}}(y) \tag{3}$$

are derived from a computation of the uncontrolled case ($\overline{u_i u_j}^{\mathrm{uc}}$) and from the vortex distributions ($\mathcal{F}_{ij}^{\mathrm{vg}}$) shown in figure 4. The function $\lambda(x,y)$ is a fringe function which allows the forcing to be smoothly applied in the limited area of the computational domain where the VGs are located.

DNS of control of a separation bubble on a flat plate

The simulations of a turbulent boundary layer exposed to an adverse to favourable pressure gradient have been performed using a code developed at the Department of Mechanics by Lundbladh *et al.* (1999). The inflow Reynolds number is $Re_{\delta_0^*} = U_\infty \delta_0^*/\nu = 400$ based on the displacement thickness δ_0^* of the boundary layer and the freestream velocity U_∞ at the inflow $x = 0$. All quantities are non-dimensionalized by U_∞ and δ_0^* at $x = 0$. At this position, a laminar Blasius boundary layer profile is assumed. Downstream at $x = 10$ laminar-turbulent transition is triggered by a random volume force near the wall. The computational box is $450 \times 50 \times 24$. A resolution with 480 modes in streamwise, 193 modes in wall-normal and 64 modes in spanwise direction is used, which gives a total of 6 million points.

To generate periodic excitation, we use an oscillating wall-normal body force that exponentially decays from the boundary layer wall and is centred around x_0. We assume the force to be given by

$$F_y = f_0 e^{-y/c} e^{-[(x-x_0)/x_{scale}]^2} \cos(\omega t)\cos(\beta z), \tag{4}$$

where f_0 is the forcing amplitude, ω the oscillation frequency, x_{scale} a parameter controlling the decay of the forcing in x-direction and c a parameter controlling the wall normal decay. The force is causing a wall normal flow. If the parameter $\beta \neq 0$, the force is also varying in spanwise direction.

From figure 5 it is seen that steady spanwise forcing is very effective in eliminating the separated region. The effect on the skin friction coefficient is for that case significantly stronger as compared to the case with time varying forcing with the same amplitude ($f_0 = 0.1$).

Planned investigations

In the future we are planning to do more experiments on separation control by decreasing spanwise coherence, using other actuators and possibly try out a feedback control system. Possible actuators to test are discrete inclined jets, VGs with variable angle of attack and spanwise varying suction/blowing. It is aimed to extend the simulation study also to the plane diffuser geometry.

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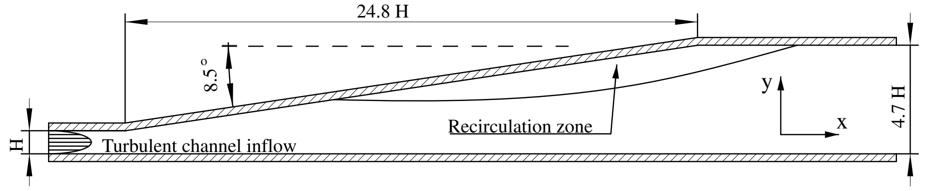

Figure 1: The geometry of the plane asymmetric diffuser.

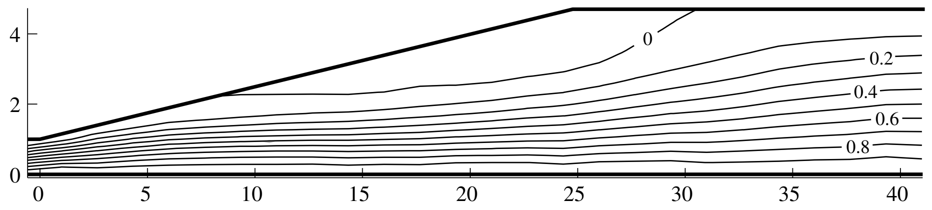

Figure 2: Streamlines of the uncontrolled flow.

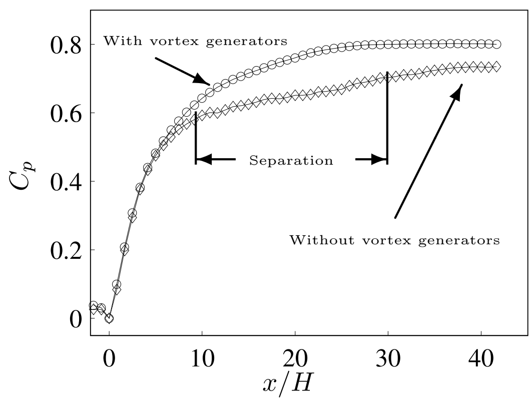

Figure 3: Variation of the pressure coefficient through the diffuser, with and without vortex generators.

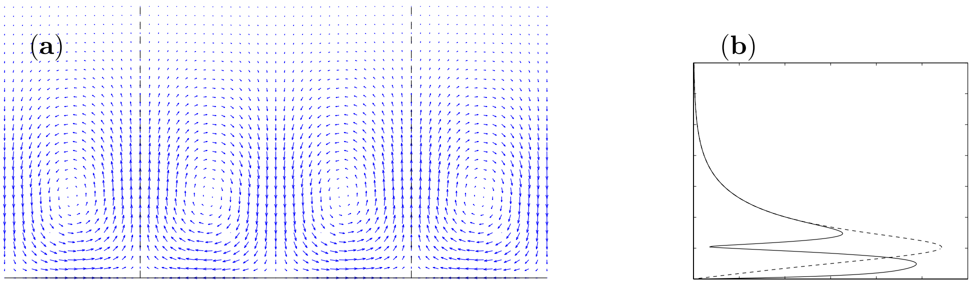

Figure 4: (**a**) Vortex distribution used as approximation in vortex generator model. One period is indicated by the dashed lines. (**b**) The dashed line shows the distribution of v_{rms} in the wall normal direction and the solid line the distribution of w_{rms}.

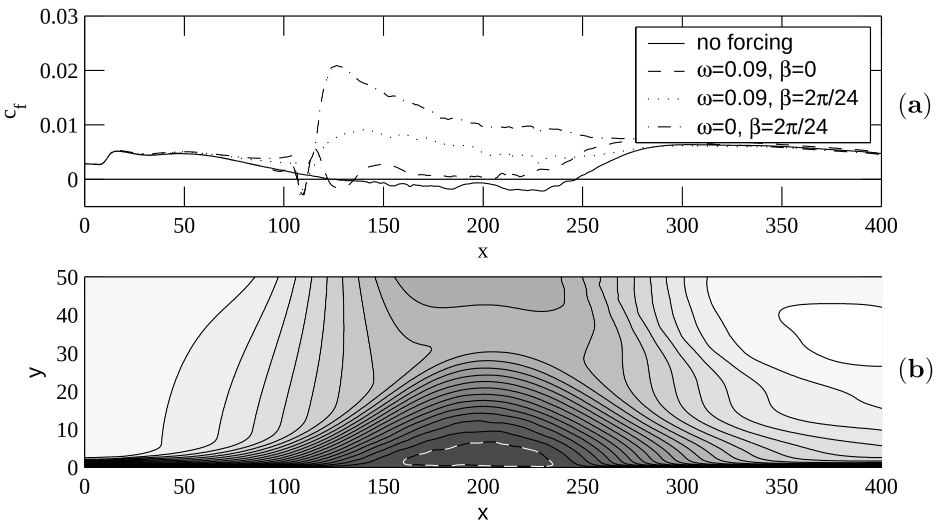

Figure 5: (**a**) Mean skin friction coefficient, (**b**) Contours of streamwise mean velocity for simulation without forcing (neg: *dark grey* to pos: *white*, *white dashed line*: -0.025)