Turbulent boundary layer separation and control

by

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Abstract

Boundary layer separation is an unwanted phenomenon in most technical applications, as for instance on airplane wings, ground vehicles and in internal flow systems. If separation occurs, it causes loss of lift, higher drag and energy losses. It is thus essential to develop methods to eliminate or delay separation.

In the present experimental work streamwise vortices are introduced in turbulent boundary layers to transport higher momentum fluid towards the wall. This enables the boundary layer to stay attached at larger pressure gradients. First the adverse pressure gradient (APG) separation bubbles that are to be eliminated are studied. It is shown that, independent of pressure gradient, the mean velocity defect profiles are self-similar when the scaling proposed by Zagarola and Smits is applied to the data. Then vortex pairs and arrays of vortices of different initial strength are studied in zero pressure gradient (ZPG). Vane-type vortex generators (VGs) are used to generate counter-rotating vortex pairs, and it is shown that the vortex core trajectories scale with the VG height \( h \) and the spanwise spacing of the blades. Also the streamwise evolution of the turbulent quantities scale with \( h \). As the vortices are convected downstream they seem to move towards an equidistant state, where the distance from the vortex centres to the wall is half the spanwise distance between two vortices. Yawing the VGs up to 20° do not change the generated circulation of a VG pair. After the ZPG measurements, the VGs where applied in the APG mentioned above. It is shown that the circulation needed to eliminate separation is nearly independent of the pressure gradient and that the streamwise position of the VG array relative to the separated region is not critical to the control effect. In a similar APG jet vortex generators (VGJs) are shown to as effective as the passive VGs. The ratio \( VR \) of jet velocity and test section inlet velocity is varied and a control effectiveness optimum is found for \( VR = 5 \). At 40° yaw the VGJs have only lost approximately 20% of the control effect. For pulsed VGJs the pulsing frequency, the duty cycle and \( VR \) were varied. It was shown that to achieve maximum control effect the injected mass flow rate should be as large as possible, within an optimal range of jet \( VR \)s. For a given injected mass flow rate, the important parameter was shown to be the injection time \( t_1 \). A non-dimensional injection time is defined as \( t^+_1 = t_1 U_{jet}/d \), where \( d \) is the jet orifice diameter. Here, the optimal \( t^+_1 \) was 100–200.

Descriptors: Flow control, adverse pressure gradient (APG), flow separation, vortex generators, jet vortex generators, pulsed jet vortex generators.
Preface

This doctoral thesis in fluid mechanics is a paper-based thesis of experimental character. The subject of the thesis is turbulent boundary layer separation control by means of longitudinal vortices. The thesis is divided into two parts in where the first part is an overview and summary of the present contribution to the field of fluid mechanics. The second part consists of five papers, which are adjusted to comply with the present thesis format for consistency. In chapter 7 of the first part in the thesis the respondent’s contribution to all papers are stated.

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Part I

Overview and summary
CHAPTER 1

Introduction

With the increase in oil prices and the increased environmental concerns, regarding both toxic exhausts, particulates and greenhouse gases, the reduction of fuel consumption is an important issue both for vehicle manufacturers and those who utilise the vehicles. Large improvements have been made over the last decades in terms of engine efficiency, aerodynamic drag etc. but there is still possibilities for future improvements. This thesis deals with a fundamental aerodynamic problem, namely how to control flow separation, a phenomenon that in most cases lead to increased aerodynamic drag. The results may be useful in many engineering situations, but the work is motivated by the possibility to reduce the aerodynamic drag on long haulage trucks.

Figure 1.1. The author performing a smoke visualisation on a Scania truck in the German-Dutch LLF wind tunnel in 2001. The largest test section, with a cross sectional area of 9.5 m × 9.5 m is used for this test.
1. INTRODUCTION

1.1. Truck aerodynamics

The aerodynamic drag is an important part of the total average tractive resistance of a long-haulage truck. A heavy truck (for example the Scania R-series truck shown in figure 1.1), with warm low resistance tires, at a speed $U_x = 80 \text{ km/h}$ on a flat dry road has a rolling resistance which is approximately 50% of the total tractive resistance. The remaining 50% is aerodynamic drag.

The rolling resistance coefficient $f_r$ is known to be almost independent of the speed and therefore the drag caused by the tires increases linearly with the speed ($F_{x, \text{tire}} = f_r U_x$). Also the aerodynamic drag coefficient ($C_D$) is fairly independent of the speed for a truck, which means that the aerodynamic drag $F_{x, \text{aero}} = \frac{1}{2} \rho C_D U_x^2$, where $\rho$ is the density of the fluid, increases quadratically with the speed. At speeds above approximately 80 km/h the contribution of the aerodynamic drag to the total drag overshadows that of the tires, as can be seen in figure 1.2.

The analysis above is however oversimplified, since very few long haulage routes in the real world are completely flat. Furthermore, vehicles occasionally have to slow down or even stop. Therefore it is necessary to take into account both "hill climbing" and acceleration. According to simulations performed by the author the aerodynamic drag constitutes around 30% of the total drag on moderately hilly long haulage routes, like Stockholm-Helsingborg. This is for a
1.1. TRUCK AERODYNAMICS


track trailer combination with a relatively smooth-sided trailer, low resistance tires and a modern 420 hp engine.

Since truck manufacturers do not develop tires and cannot change the topography (although there are systems to store brake energy), or do much about the traffic situation, aerodynamic drag is the component of the tractive resistance that is possible to reduce. Apart from the obvious environmental benefits of bringing down the fuel consumption, the economical gains are substantial. Figure 1.3 demonstrates the relation between aerodynamic drag, fuel consumption and the annual cost of fuel for a long haulage operator. The truck in figure 1.4 was developed at Scania in 1999 as a technology demonstrator and one of the main features was its low $C_{D,wa}$\textsuperscript{1}. In figure 1.3 this concept vehicle is chosen to represent the realistic limit for aerodynamic drag reduction. The Scania R-series in figure 1.1 is typical for an aerodynamically well-designed truck of today and the span of $C_{D,wa}$ given is a conservative estimation of the variation due to trailer choice.

\textsuperscript{1}Since $C_D$ increases with yaw for a normal truck, a wind averaged drag coefficient $C_{D,wa}$ is calculated by averaging weighted $C_D$ measurements at different yaw angles.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure13.png}
\caption{Fuel consumption and fuel cost for a truck used in long haulage operation. The fuel cost is based on an annual mileage of 200000 km and the price of diesel oil in December 2008 (11.40 kr/l). This is a slight overestimation since all large transport companies get discounts on fuel.}
\end{figure}
1. INTRODUCTION

Figure 1.4. A Scania low drag concept truck from 1998. The shown configuration is without the accompanying trailer.

A truck is a bluff body and a major part of the drag stems from pressure, which means that friction is less important. In the beginning of time, trucks were shaped like bricks, producing massive separation all around the front. During the 70s and 80s the front of the trucks went from sharp cornered to rounded and air deflectors were fitted to the roof and the sides to smooth the transition from the cab to the body. This is illustrated as the change from (a) to (b) in figure 1.5. When the front radii are greater than 300 mm and the air deflector kit is properly designed, there are no major improvements to be made on the front. However, there are still many areas to improve on the sides, around the wheels and on the underbody, but in order to drastically reduce aerodynamic drag the separation at the end also needs to be addressed.

\[\text{(a) Early truck} \quad \text{(b) Today's truck} \quad \text{(c) Low drag truck}\]

Figure 1.5. The aerodynamic development of trucks since the 1970s.
1.1. TRUCK AERODYNAMICS

Figure 1.6. A 1 m long boat tail attached to the back end of the 1998 Scania concept truck. The tapering angle is 15\degree and the flow is kept attached until the cut off of the boat tail.

The conventional - and very effective - way to reduce the wake is by tapering the rear end. Aerodynamically the best thing would be a full boat tail, like on an airplane, but this would result in a vehicle of illegal length or a vehicle with very limited cargo space. Fortunately the marginal benefit decrease with length and a cut off boat tail (so called Kamm back) like in figure 1.5(c) or figure 1.6 gives much of the benefit of a full boat tail without sacrificing the possibility to actually use the truck on the road. In figure 1.6 a boat tail tested by Scania can be seen. This particular 1 m device reduced $C_D$ about 0.10.

Unfortunately, even an elongation of only 1 m is very difficult to apply on a European long-haulage truck. This is because of the rigorous legislation on vehicle length in the European Union. Since most of the cargo is box shaped and geometrically adapted to the internal width of a trailer\(^2\) the tapered part must be an add-on device, or at least not a part of the effective cargo volume. Thus, a 1 m boat tail will lead to a loss of about 3–7\% of the cargo space in a standard 13.6 m trailer.

To make a boat tail more attractive the angle must be made much larger. Hence, the air must be made to withstand a steeper pressure gradient without

\(^2\)A Euro pallet is 1200×800 mm and the internal width of a trailer is approximately 2450 mm
1. INTRODUCTION

separation. In 2001 the author performed a wind tunnel test on a boat tail, where the boundary layer was energised using slot blowing. The device was mounted on the 1:2 scale model shown in figure 1.4. With the blowing turned on the maximum non-separating tapering angle increased from $15^\circ$ to $25^\circ$. Even though the concept was implemented in a very crude way the principle was shown to work. However, the energy consumption of the fans needed to supply air for the blowing slot was so high that it neutralised the gains from the drag reduction. Furthermore, the fans, valves and tubing needed not only reduces the cargo volume but impede access. Therefore, it would be desirable to find another technical solution for the separation control; one that would have a similar effect but would be easier to implement. Such a possible solution would be to use longitudinal vortices to transport high momentum fluid towards the wall.

1.2. Research outline

This thesis is paper-based, but there is a common storyline.

The theme is separation control and paper 1 describes the separated region that is to be controlled. The scaling of the velocity profiles of the separated region is also discussed.

In paper 2 the use of longitudinal vortices as a flow control method is introduced. The vortices are here produced by vane-type vortex generators (VGs) and the vortex characteristics are thoroughly investigated in a zero pressure gradient (ZPG) flow.

The next step is to apply the vane-type VGs of paper 2 to control the separation bubble of paper 1. These experiments are reported in paper 3 and focus mainly on the robustness of the control method.

In paper 4 and 5 the vane-type VGs are exchanged for jet vortex generators VGJs. The same separation bubble is first controlled by steady jets in paper 4 and then with pulsed jets in paper 5.
CHAPTER 2

Separation

Separation of boundary layers occurs either due to a strong adverse pressure gradient (APG) or due to a sudden change in the geometry of the surface. Typical examples of the latter is obtained where there is a sharp edge or strong curvature such as for a backward facing step, bluff bodies (typical truck geometries etc). For strong adverse pressure gradient flows along flat or mildly curved surfaces the occurrence of separation does however not only depend on the local pressure gradient but also on the local boundary layer state.

2.1. The separated region

The separation point and the so called ”separated region” or ”separation bubble” are not well defined quantities in a turbulent boundary layer. The separation point $x_s$ is usually defined as the point where the wall shear stress $\tau_w = 0$. However in a turbulent boundary layer this means that part of the time the fluctuating wall shear stress is positive and part of the time negative.

Another definition of $x_s$ uses the backflow coefficient ($\chi$), i.e. the fraction of time the flow is in the backward direction. The separation point is then defined as the point on the wall where $\chi = 0.5$. This position does only correspond to the position where $\tau_w = 0$ in case the probability density distribution of the fluctuating wall shear stress is symmetric around zero. The reattachment point, i.e. the position where the boundary layer reattaches to the surface (if it does), can be defined in a similar way as for the separation point. The value of the shape factor $H_{12} = \delta_1/\delta_2$, where $\delta_1$ is the displacement thickness and $\delta_2$ is the momentum loss thickness, can be used as an indication of how close the boundary layer is to separation.

The separated region can be defined as the region where the flow is recirculating in a time averaged sense. The demarcation line is hence called the dividing or separation streamline. Other definitions of the demarcation line is the contour line where the streamwise velocity is equal to zero or the contour line on which $\chi = 0.5$. The two latter definitions usually give regions of similar size whereas the dividing streamline definition naturally gives a larger separated region.

Many papers and reviews have been written on APG separation and only a few are mentioned here for further reference. Simpson (1989) reviews the field
up to 1989 and also references his own extensive research. Later work was done by Fernholz and co-workers on an axisymmetric body and Kalter & Fernholz (2001) also contain an up-to-date review of the literature.

In the present work, all APG experiments were performed in the KTH BL wind-tunnel, with a free stream velocity of 26.5 m/s at the inlet of the test section. The test section, which can be seen in figure 2.1 is 4.0 m long and has a cross-sectional area of 0.75 m×0.50 m (height×width). A vertical flat plate made of Plexiglas, which spans the whole height and length of the test section, is mounted with its back surface 0.3 m from the back side wall of the test section. The back side wall diverge in order to decelerate the flow and suction is applied on the curved wall to prevent separation there. The induced APG on the flat plate can be varied by adjusting the suction rate through the curved wall. All measurements are made with particle image velocimetry (PIV) and for a detailed description of the experimental set-up the reader is referred to Angele & Muhammad-Klingmann (2005a,b).

The three pressure gradients shown in figure 2.2(a) are compared in the experiment. Case I is a weak separation bubble similar to the case of Dengel & Fernholz (1990), whereas case III is the strongest APG and the strength of case II is approximately in between case I and case III. The separation bubble is here defined as the region where the backflow coefficient is χ > 0.5. Figure 2.2(b) shows the evolution of the shape factor in the three flow cases and figure 2.3 shows the separation bubble for case II. Upstream of x=1.8 m (before separation in all cases) there are no notable differences between the cases, but the maximum value of $H_{12}$ in the separation bubble varies between 4.1 for case I to more than 7 in case III. Furthermore, the value of $H_{12}$ at the point of separation increases with the size of the separation bubble.
2.2. The Zagarola-Smits Velocity Scale

There is still no consensus on the proper mean velocity scaling of the outer region in a strong APG and separated turbulent boundary layers. According to Townsend (1961), the criterion for similarity to exist in the mean velocity profile is that the ratio between the pressure gradient in the streamwise direction and $\tau_w$ is constant. This ratio is constant when $H_{12}$ is constant. The validity of

\[ \frac{C_p}{\partial x} \]

is indicated on the $x$-axis. (b) The shape factor.

2.2. The Zagarola-Smits velocity scale

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Figure 2.4. Mean velocity profiles for case II. The top three sets of curves show velocity profiles upstream of separation (○), between the separation point and the position of the maximum in $H_{12}$ (□) and after the maximum in $H_{12}$ (△), respectively. The lower three curves show the average of the above three sets.

Townsend’s criterion has been experimentally verified by Clauser (1954) and Skåre & Krogstad (1994).

Turbulent boundary layers developing towards separation clearly do not fulfill this criterion, as $\tau_w$ decreases towards zero and then changes sign, while $H_{112}$ monotonically increases. Usually the friction velocity, $u_r = \sqrt{\tau_w/\rho}$ is used as the velocity scale. However to avoid the singularity at separation Mellor & Gibson (1966) suggested to instead use the scale $u_p$ based on the pressure gradient and $\delta_1$. A different velocity scale, $u_s$, which explicitly depends on the maximum Reynolds shear-stress was suggested by Perry & Schofield (1973) and Schofield (1981). Here $u_s$ is determined from a fit to the velocity profile. However Angele & Muhammad-Klingmann (2005a) showed that, for their data, $u_p$ and $u_s$ scale the same data-set upstream and downstream of separation equally well.

Recently, Maciel et al. (2006b) proved the usefulness of the Zagarola-Smits velocity scale (Zagarola & Smits (1998)), which is defined as
2.2. THE ZAGAROLA-SMITS VELOCITY SCALE

Figure 2.5. Mean velocity profiles in the region between the separation point and the position of the maximum in \( H_{12} \) for cases I, II and III. The insert shows how the velocity profiles deviate from an average of all profiles. Note that the scale of the ordinate is increased in the insert.

\[
U_{ZS} = U_e \frac{\delta_1}{\delta},
\]

(2.1)

where \( U_e \) is the free-stream velocity and \( \delta \) is the boundary layer thickness. Their data before and after separation show similarity for the outer layer mean velocity distribution. Panton (2005) points out that \( u_\tau \) is proportional to the Zagarola-Smits velocity scale for high Reynolds numbers. Maciel et al. (2006a) reviewed APG data from Perry (1966), Maciel et al. (2006b), Skåre & Krogstad (1994), Dengel & Fernholz (1990) and others and showed that the Zagarola-Smits scaling works well.

In figure 2.4, the scaled mean velocity profiles of APG cases I-III are presented in three sets: upstream of \( x_s \), in the separated region upstream of the position of maximum in \( H_{12} \), denoted \( x_h \), and after the position of the maximum in \( H_{12} \). In the region upstream of \( x_s \), the four plotted profiles do not show self-similarity. However, the three profiles between \( x_s \) and \( x_h \) are self-similar when scaled with \( U_{ZS} \). The four velocity profiles for \( x > x_h \) are also self-similar, but only within that set of profiles, i.e. they are not self-similar when
they are plotted together with the profiles from upstream of \( x_h \), as is shown at the bottom of figure 2.4. Thus, there seem to be two different self-similar regions in the separated region: before and after \( x_h \).

To investigate whether the similarity holds between different sized separation bubbles, velocity profiles from the region \( x_s < x < x_h \) for flow cases I, II and III are scaled by \( U_{ZS} \) and plotted together in figure 2.5. In the outer region all profiles collapse, which is noteworthy since the differences in size of the separation bubbles are quite large.

In the recent study of Maciel et al. (2006a), it is shown that the mean-velocity defect profiles display self-similarity at some streamwise positions, but data from the different experiments do not collapse. They suggest that the reason is the difference in the pressure gradients. The present results on the other hand, show velocity profiles that are self-similar in all three pressure gradient cases. Both the streamwise positions and the ranges of \( H_{12} \) differ between the cases. Thus, it is rather the streamwise position relative to the point of separation and the bubble maximum that determines the similarity.
CHAPTER 3

Vane-type vortex generators

Control of separation of boundary layer flows can be achieved through different approaches. One common method, that has proved to be effective, is to introduce longitudinal vortices in the boundary layer. The vortices enhance mixing and transport high momentum fluid towards the wall.

The vortices are normally produced by vane-type VGs, i.e. short wings attached to the surface with the wingspan in the wall-normal direction and set at an angle $\alpha$ towards the mean flow direction. Such devices are commonly seen on the wings of commercial aircraft and their blade height ($h$) are often slightly larger than $\delta$. The first experiments on conventional vane-type passive VGs were reported by Taylor (1947).

A VG array can be designed to produce different vortex configurations. The three basic types are shown in figure 3.1. The main geometrical parameters of a VG array are shown in figure 3.2.

3.1. Vane-type VGs in ZPG

Pearcy (1961) published a comprehensive VG design guide. Here the vortex trajectories are also analysed, using the inviscid model from Jones (1957).

The evolution of a single vortices and vortex pairs embedded in a turbulent boundary layer was thoroughly investigated by Shabaka, Mehta & Bradshaw (1985) and later Mehta & Bradshaw (1988). They show that single vortices produce opposite sign vorticity around the vortex and that vortex pairs with common upflow are lifted out of the boundary layer. Another study of a single vortex in a boundary layer was performed by Westphal, Pauley & Eaton (1987). The overall circulation, when the vortex evolved downstream, either decreased slowly or remained almost constant depending on the case.

Pauley & Eaton (1988) examined the streamwise development of pairs and arrays of longitudinal vortices embedded in a zero pressure gradient (ZPG) turbulent boundary layer. In this study the blade spacing of VGs and the blade angle were varied, and the difference between counter-rotating vortices, with common upflow and downflow, and co-rotating vortices were examined. The proximity of other vortices does not affect circulation decay, but increases the diffusion of vorticity.
Wendt (2001) studied the initial circulation of an array of VGs. The vortex strength was observed to be proportional to \( U_e, \alpha \) and the ratio \( h/\delta \). Thus the circulation can be accurately modeled by a modified version of Prandtl’s relation between circulation and airfoil geometry.

In most of the earlier studies VGs with \( h/\delta > 1 \) have been used. However to reduce the drag penalty caused by the VGs, work has been done to reduce their size, without sacrificing efficiency. The comprehensive review on low-profile VGs by Lin (2002) shows that small (\( h/\delta \sim 0.2 \)) VGs can be as effective in preventing separation.

An experimental investigation of the streamwise evolution of longitudinal vortices in ZPG was carried out in the MTL low-turbulence wind tunnel at KTH Mechanics. A horizontal 5.8 m long flat plate, which spans the whole 1.2 m width of the test-section, was mounted with its upper surface 0.51 m from
the test-section ceiling at the leading edge. The ceiling was adjusted to give a zero streamwise pressure gradient at the nominal free stream velocity. At all velocity measurements $U_e$ was set to 26.5 m/s and the temperature was kept constant at 18.1 °C. The velocity measurements were performed using hot-wire X-probes with the anemometer operating in constant-temperature mode.

In order to set up the streamwise vortices inside the turbulent boundary layer traditional vane-type VGs were used (see figure 3.2). Three different sizes of the VGs were used and arranged both as single spanwise pairs ($p$) as well as spanwise arrays ($a$) to create counter-rotating vortices inside the boundary layer. The design follows the criteria suggested by Pearcy (1961) and uses $\alpha = 15^\circ$. The different VG sizes are geometrically "self-similar".

The vortices modify the base flow and in figure 3.3 the three mean velocity components of the VG$_{10}$ array configuration are contour plotted. The $U$- and $W$-components are symmetric, however the asymmetry in the $V$-component is due to the large velocity gradients which affect the cooling velocities of the two wires of the X-probe differently. The maximum magnitude of the cross-flow components are approximately 15-25 % of $U_e$ in the measurement plane closest to the VG array.

In figure 3.4(a) the vortex centre paths from VG pairs are projected on the $y$-$z$ plane. The paths of the vortices behind the VG$_{10}$ and the VG$_{18}$ seem to collapse on each other. The downward motion in the beginning is caused by the induced velocity by the neighbouring vortex. However, as the two vortices
move away from each other the influence from neighbouring vortex becomes weaker and the growth of the vortex causes the vortex centre to move away from the wall. An interesting behaviour of the VG$_6$ vortex path is that it turns back towards the centre line.

The corresponding vortex paths of the VG arrays are shown in figure 3.4(b). In the case of the array, when the vortices move away from each other they are moving closer to the vortex from the neighbouring vortex pair and eventually form a new counter-rotating pair – this time with common upflow. The induced velocities in the new pair will tend to lift the vortices and according to inviscid theory (Jones 1957) they will continue to rise from the wall. However, the measurements show that the vortex centre paths of the original pair, while still rising, start to move towards each other again. This is probably due to vortex growth; when the area of the vortex grows the vortices are forced to a spanwise equidistant state. The maximum vortex radius in an equidistant system of circular vortices is $D/4$, where $D$ is the spanwise distance between the VG pairs. If the distance from the vortex centre to the wall is $D/4$ ($2.08h$), the induced velocities from the real vortices and the three closest mirrored vortices...
3.1. VANE-TYPE VGS IN ZPG

Figure 3.5. Vortex centre paths plotted in plan view (the x-z plane). \((\cdot \cdot \cdot \cdot \cdot, \cdot \cdot \cdot \cdot \cdot \cdot \cdot)\) denote \(h = (6, 10, 18)\) mm. \((a)\) The paths downstream of a pair of VGs. \((b)\) The same planes for a VG array. Note that for the array the paths of the neighboring vortices are actually within the figure area, but for the sake of clarity they are not shown.

all cancel. Hence, if the assumption holds, the vortex centres should approach \((y/h, z/D) = (2.08, \pm 0.25)\). In figure 3.4\((b)\), these coordinates are marked with small circles, and there seem to be a tendency for the vortex centres to move towards the predicted position.

Now, it is possible to explain the peculiar vortex centre path produced by the VG\(_6\) in figure 3.4\((a)\). In analogy to the paths of the vortices generated by the array, the curving back motion indicates the existence of secondary vortices, outside of the primary pair. At \((x - x_{VG})/h = 445\) the circulation of the secondary vortices is about 55\% of the primary vortices. The secondary vortices probably originate from the very thin layer of stress-induced opposing \(\omega_x\) under the primary vortex.

In figure 3.5\((a)\) the vortex paths from the single VG pair are shown in plan view. A divergence of the paths, from all VG sizes, caused by the mirrored images can be observed. The angle of divergence increases with vortex strength. Vortex centre paths downstream of VG arrays are plotted in figure 3.5\((b)\). In plan view it is easy to see how the paths first move apart, roughly at the same rate as in the case of the single pairs, up to about \((x - x_{VG})/h = 50\) and then
how they converge towards the asymptotic spanwise location of $z/D = \pm 0.25$ as discussed earlier.

Also the turbulence quantities were measured and in figure 3.6 it is striking how well their maxima scale with $h$. Note, that here all three VG sizes have been plotted.

In many practical applications, especially on ground vehicles, the VGs operate in yaw most of the time. Therefore it is of interest to study vortex generation and decay under such non-ideal conditions.

When a VG pair is yawed the angle of attack of one blade is increasing while the angle of attack of the other blade is decreasing and therefore it is difficult to predict the total circulation generated by the VG pair. Figure 3.7(a) shows that the total circulation, up to a VG pair yaw angle of $\beta = 20^\circ$, is almost constant and that the circulation decay (seen vertically in the figure) also seems to be independent of yaw. In figure 3.7(b) the effect of yaw on the individual vortices in a VG pair is shown. When the yaw angle increases (one blade angle is increasing, while the other is is decreasing) the circulation of both vortices changes linearly and according to the figure the blade that is parallel to the flow at $\beta = 15^\circ$ is still producing a vortex. The reason for this could be that
3.2. Vane-type VGs in APG

Much research on VGs have been done in ZPG, but their real use is in APG. Schubauer & Spangenberg (1960) tried a variety of wall mounted devices to increase the mixing in the boundary layer. They did this in different APGs and they concluded that the effect of mixing is equivalent to a decrease in pressure gradient.

Godard & Stanislas (2006) made an optimisation study on co- and counter-rotating VGs submerged in a APG boundary layer. They found that the counter-rotating set-up was twice as effective as the co-rotating in increasing the wall shear stress. In another recent experiment Angele & Muhammad-Klingmann (2005a) made extensive PIV measurements to show the flow and vortex development inside a turbulent boundary layer with a weak separation bubble.

In the present study the VG arrays of section 3.1 were positioned upstream of the separation bubbles described in section 2.1. Due to the rapidly growing boundary layer in that region, which causes the velocity at $y = h$ to vary, four different VG arrays could be used to produce any vortex strength up to $\gamma_e = 4.0$ m/s by placing them at different streamwise positions ($x_{VG}$). The effect of the VGs on the separated region was studied with PIV.

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$^1\gamma_e$ is the circulation per unit width, calculated from $h$ and the velocity at $y = h$. 

**Figure 3.7.** (a) The total circulation, i.e. the contribution from both the vortices, in the VG$_{10}^p$ case versus the yaw angle at $(x - x_{VG})/h = 6$, 41, 116 shown by ($\circ$, $\Box$, $\Diamond$), respectively. (b) The individual contribution from the two vortices for the VG$_{10}^p$ case at $(x - x_{VG})/h = 6$.
In figure 3.8 the streamwise mean velocity profiles at the positions of inflow and outflow are shown for different VG configurations at $x_h$ in APG case II. The uncontrolled case is shown for comparison. At the position of inflow, more streamwise momentum is transported down, and a larger effect of the VGs can be seen. The two VGs which produce the smallest amount of circulation have negligible influence on $U_e$, but when the circulation is increased to $\gamma_e = 1.4$ separation is prevented. This is the most efficient VG configuration for eliminating separation in this particular flow case, in the sense that the drag generated by the VGs is expected to be less than that generated by the larger VGs. Even though this gives a pronounced efficiency maximum it could also cause a system designed for maximum efficiency to be sensitive to changes in the flow conditions.

Figure 3.9 summarizes the separation control effectiveness, in terms of $H_{12}$, of all examined VG configurations. Here $H_{12}$ at $x_h$ for cases I, II and III are compared for different magnitudes of $\gamma_e$. In the uncontrolled case, $H_{12}$ is about 4, 5 and 7 in the respective cases. The value of $\gamma_e$ at which the flow stays attached seems to be fairly insensitive to the pressure gradient, even though the difference in size of the separated region is quite large in the uncontrolled cases. When $\gamma_e$ is further increased, the average $H_{12}$ seems to asymptotically approach 1.4, which is the value of a ZPG turbulent boundary layer.

In order to investigate the influence of $x_{VG}$, the same level of circulation was produced at four different $x$ positions. This was accomplished by applying differently sized VGs at different streamwise positions so that $U_h$ at $y = h$ is constant. Two arrays are placed before the pressure gradient peak, one is placed at the peak-position and one is positioned right after the maximum. In figure 3.10(a) the resulting mean streamwise velocity profiles at $x_h$...
3.2. VANE-TYPE VGS IN APG

Figure 3.9. The shape factor $H_{12}$ at the position of inflow and the position of outflow plotted against $\gamma_e$ in case I, II and III. The measurements were made at $x_h$.

Figure 3.10. (a) Mean velocity profiles at the spanwise positions of inflow and outflow for four different VG configurations. The four rightmost profiles are measured at the position of inflow and the others at the position of outflow. (b) $H_{12}$ measured at $x_h$ for a generated $\gamma_e$ of 3.1 m/s. The upper curve is $H_{12}$ at the position of outflow and the lower curve is $H_{12}$ at the position of inflow. The grey line shows the average $H_{12}$. 
are presented. For the case of 6 mm high VGs the boundary layer seems two-
dimensional, but the 10 mm VG array shows a fuller profile at the position of inflow. For the next two cases of larger VGs, the shift of the profiles increases. However, if an average of the profiles at the inflow and outflow positions is taken for each VG size, the curves of the three largest VGs are similar. Hence, the shape factor of the average mean velocity profiles will be similar. This is shown in figure 3.10(b), where $H_{12}$ at the inflow and outflow positions are plotted versus the upstream distance to the VG arrays. From this figure one can conclude that $H_{12}$ at $x_h$, i.e. the control effect, is quite insensitive to the streamwise position of the VGs.
CHAPTER 4

Jet vortex generators

An alternative way of producing the vortices is by jets originating from the wall. Flow control by vortex generator jets (VGJs) was first described by Wallis (1952). He claimed that an array of VGJs could be as effective as passive VGs in suppressing separation on an airfoil. In the following the jet direction is given by the skew and pitch angle, see figure 4.1 for a definition of the geometry.

4.1. Steady jet VGs

A study by Johnston & Nishi (1990) demonstrated how streamwise vortices are produced by a VGJ array. A pitch angle of less than 90° was needed in order to generate vortices effectively. Some success in reducing the size of a separated region in an APG, was also demonstrated when the velocity ratio \( VR \), which is the ratio of jet speed to free stream velocity, was 0.86 or higher. Compton & Johnston (1992) studied VGJs pitched at 45°. A skew between 45 and 90° was found to give the strongest vortices. The circulation of the vortices was also found to increase as the \( VR \) was increased.

In a study on a backward facing 25° ramp, where the flow separates, Selby, Lin & Howard (1992) measured the pressure for different VGJ array configurations. The pressure recovery increased up to the highest tested \( VR \) ratio of 6.8. It was shown that a small pitch angle (15° or 25°) is beneficial and that the optimum skew angle appears to be between 60° and 90°.

According to the review by Johnston (1999) the \( VR \) is the dominant parameter in generating circulation. The exact streamwise location of the VGJ row seems less important since the boundary layer reacts likewise independent of where it is energised. Khan & Johnston (2000) performed detailed measurements downstream of one VGJ and showed that the flow field is similar to that of solid VGs.

Zhang (2000) showed that a rectangular jet can produce higher levels of vorticity and circulation compared to a circular jet of equal hydraulic diameter and \( VR \). Another experiment on the jet orifice shape by Johnston, Moiser & Khan (2002) showed that the inlet geometry affects the near-field but not the far-field. Zhang (2003) studied co-rotating vortices produced by a spanwise array of VGJs, where both skew and pitch are set to 45°, and described the complex
Figure 4.1. Schematic of a VGJ device producing counter-rotating vortices. \( U \) is the free stream mean direction and \( U_{jet} \) is the jet velocity. The direction of the jet is defined by the pitch angle \( \alpha \) and the yaw angle \( \beta \). The jet exit diameter is named \( d \), the distance between the jets of a VGJ pair \( L \) and the distance between the pairs in an array \( \lambda \). For a co-rotating array there is no \( L \) and thus \( \lambda \) is the distance between the jets.

near field. The ratio of the vortex strength of the primary and secondary vortices (cf. Rixon & Johari (2003)) are shown to depend on \( VR \).

In all previous reports the vortex strength has been reported to increase monotonically with \( VR \), but Milanovic & Zaman (2004) find a maximum in the region of \( VR = 2.0–2.8 \).

The most extensive investigation in recent years is the one by Godard & Stanislas (2006). They measure the skin friction increase for different VGJ configurations producing co-rotating and counter-rotating vortices. Their data shows that optimised VGJs produce results comparable to passive vane-type VGs in terms of skin friction increase. For a counter-rotating pair their optimal set of parameters are: \( \beta = 45 – 90^\circ \), \( \alpha = 45^\circ \) and \( L/d = 15 \). They show a strong increase in skin friction with jet velocities up to \( VR = 3.1 \). Above that
there is almost no increase. They also reported that the counter-rotating VGJ pair is still effective at free stream yaw angles up to $20^\circ$.

Here a counter-rotating configuration was chosen for the VGJ array and the geometry was chosen in agreement with the results of the above mentioned studies. The skew and pitch angles are chosen as $90^\circ$ and $45^\circ$, respectively, and the jet spacing is $L = 16d$. In figure 4.2 the set-up of the VGJ system is shown. The 9 unit (18 jets) array spans the full width (0.75 m) of the wind tunnel and deliver $VR = 8–9$ at a test section inlet velocity $U_{inl}$ of 26.5 m/s. One of the VGJ devices is placed outside the wind tunnel and a hot wire probe is used to continuously monitor the jet velocity during the experiments.

PIV is used to measure a $150 \text{ mm} \times 150 \text{ mm}$ plane at $y = 5 \text{ mm}$, parallel to the wall. Since the small gradient makes it possible to average the data in the streamwise direction the accuracy of the spanwise velocity profile is increased. The streamwise-averaged velocity, normalised by $U_{inl}$, is called $U_5$ in the following. From $U_5$ a scalar effect measure can be calculated by averaging the velocity over one period $\lambda$ in the spanwise direction. This scalar is termed $U_{5s}$.

Between the two counter-rotating vortices, at $z/D = 0$, the vortices produce a downflow that transport streamwise momentum towards the wall. The effect of this can be seen for $VR = 3$ in figure 4.3(a), where the velocity contours have a U-shape around $z/D = 0$. At $z/D = 0.5$ the vortices instead produce upflow and transport of low streamwise momentum from the wall. If $VR$ is increased to 6 the $U$ distribution in the cross-plane changes as can be seen when comparing figures 4.3(a, b). The velocity increases near the wall, but a high speed streak, unconnected to the free stream, is also formed at $z/D = 0$.  

\textbf{Figure 4.2.} Schematic of VGJ set-up.
With a fixed geometry the only variable parameter of the VGJs is \( VR \). In figure 4.4(a) the velocity profiles at different jet velocities are shown and in figure 4.4(b) the corresponding \( U_5 \) is shown. There is almost no change when the jets are activated at \( VR = 0.5 \). This is possibly because the jets are still too weak to produce any vortices. A further velocity increase to \( VR = 1.0 \) eliminates the mean backflow. Thus, there are now longitudinal vortices present in the boundary layer. From \( VR = 0.5 \) to \( VR = 2.0 \) the increase in \( U_5 \) with \( VR \) is nearly linear. After that and up to \( VR = 5.0 \) the control effectiveness is still increasing, but at a lower rate. Above \( VR = 5.0 \) there is a decrease in \( U_5 \).

The VGJ array is also tested at yaw. The VGJ devices of the array are yawed individually, at \( \theta = 0^\circ - 90^\circ \), and the resulting \( U_5 \) is shown in figure 4.5. \( U_5 \) decreases slowly with \( \theta \), down to a minimum at \( \theta = 60^\circ \). For increasing \( \theta > 60^\circ \),
4.2. Pulsed jet VGs

The flow control effect of pulsed VGJs can be due to several different physical mechanisms. They can influence the flow by amplifying natural frequencies in the boundary layer, like the shedding of a stalled airfoil. Furthermore, they can function like steady VGJs and produce longitudinal vortices that transport high momentum fluid towards the wall. In the experiment presented in this article pulsed VGJs of the last category are applied. If the VGJ geometry is set, there are three main parameters that decide the performance of a pulsed VGJ. It is the velocity ratio, the pulsing frequency $f$ and the duty cycle $\Omega$.

For steady VGJs the generated circulation depend strongly on $VR$ and the same is valid for for pulsed VGJs. This has been shown for arrays of VGJs by McManus et al. (1995) and Kostas et al. (2007). Also similar to steady jets is the occurrence of an circulation optimum in $VR$ above which the vortex is translated out of the boundary layer.

In McManus et al. (1995) and Scholz et al. (2008) the frequency had little effect on lift and drag, but in McManus et al. (1996) the magnitude of the upper side suction peak was strongly dependent on the pulsing frequency. The optimum frequency Strouhal number was found to be of the same order as that characterizing the natural eddy shedding behind blunt objects.

The duty cycle was shown by Scholz et al. (2008) to be important in increasing post-stall lift on an airfoil. They found $\Omega \leq 0.25$ to be most beneficial.

Figure 4.5. Effectiveness at different yaw angles. The open circles show $VR = 3$ and the filled circles show $VR = 5$. $60^\circ \overline{U}_5$ increases to a second maximum at $\theta = 90^\circ$. This is more pronounced for $VR = 5$. 

$60^\circ \overline{U}_5$ increases to a second maximum at $\theta = 90^\circ$. This is more pronounced for $VR = 5$.
In the study by Kostas et al. (2007) the wall shear stress increases nearly linearly with increasing $\Omega$. Johari & Rixon (2003) suggested that the maximum jet penetration determines the maximum circulation produced by a pulsed VGJ and suggested that the optimum injection time is $4–8 \frac{d}{U_{jet}}$.

In the same VGJ array as in figure 4.2 the jets were pulsed at $f = 12.5 – 400$ Hz. A typical jet pulse train is shown in figure 4.6. The nominal injection velocity is the average of the pulse plateau. $T$ is the period time and $t_1$ is the injection time. Thus $\Omega = \frac{t_1}{T}$. There is a leakage flow when the valve is closed, but the volume and impulse of the leakage flow is low.

In figure 4.7(a) the control effect variation with $VR$ is compared for steady and pulsed jets. The two lines show that the rate of increase of $U_5$ decreases
at $VR \approx 2.5 - 3$ for both configurations. The symbols show the data points at different frequencies and $VR$s plotted against $VR^* = \Omega VR$. When the pulsed data is compensated for the lower mass flow by using $VR^*$ as measure, the control effect is similar to that of the steady jets. In order to study whether there is a maximum volume efficiency, the control effect is recalculated as $\overline{U}_5 / VR^*$. If $\overline{U}_5 / VR^*$ is plotted against the jet based Strouhal number $St_{jet} = fd / U_{jet}$, there seems to be an optimum, as can be seen in figure 4.7(b).

The frequency and $\Omega$ were varied at a constant $VR = 3$. In figure 4.8(a) the resulting $\overline{U}_5$ is shown. Compared to $\Omega$, the influence of $f$ is small. A non-dimensional injection time is defined as $t_1^+ = t_1 U_{jet} / d$, and the variation of the control efficiency $\Delta U_5 / VR^*$ with $t_1^+$ is shown in figure 4.8(b). There seems to be a maximum at $t_1^+ = 100 - 200$

At a constant $f = 50$ Hz, the $VR$ and $\Omega$ is varied. As expected, figure 4.9(a) shows that a higher velocity ratios and longer duty cycles produce more control effect. If instead, the variation of $\Delta U_5 / VR^*$ with $t_1^+$ is studied, as shown in figure 4.9(b), it is possible to identify a maximum at $t_1^+ = 100 - 150$ for $VR = 2, 3$ and 4.
Figure 4.9. (a) $\bar{U}_5$ vs $\Omega$ for $VR = 1$ ($\ast$), $VR = 2$ ($\square$), $VR = 3$ (◦) and $VR = 4$ ($\triangle$). (b) $\Delta U_5/VR^+$ vs $t_1^+$ for the same data as in (a).
CHAPTER 5

Conclusions

In this chapter the main conclusions from the different investigations are summarised.

5.1. The separated region

- In the separated region the Zagarola-Smits velocity scaling was found to better scale the mean-velocity defect profiles than the methods suggested by Mellor & Gibson (1966), Perry & Schofield (1973) and Schofield (1981).
- There were two regions of similarity: before and after the maximum of $H_{12}$ and $\chi_w$ in the separation bubble. In these two regions velocity defect profiles are independent of the pressure gradient.
- $H_{12}$ increases linearly with increasing $\chi_w$ in the separated region. Downstream of their maxima, $H_{12}$ decreases linearly with decreasing $\chi_w$, but at a higher level of $H_{12}$.

5.2. Vane-type VGs

- The vortex core paths in plan view as well as in the plane normal to the flow, scale with the VG size in the downstream and spanwise directions.
- In this paper an asymptotic limit hypothesis of the vortex array path is stated and is shown to hold reasonable well. The limiting values for vortices far downstream are $(y/h, z/D) = (2.08, \pm 0.25)$, which the experimental data seems to approach.
- It is here shown, in the VG pair case, that the vortices are able to induce opposite sign vorticity, which is rolled up into a secondary vortex and strongly affect the primary vortex path.
- For VG arrays of different sizes, but with self-similar geometry, the generated circulation increases linearly with the vane tip velocity.
- In both the pair and the array configurations, the circulation decays exponentially at approximately the same rate.
- The maxima of the turbulence quantities scale with $h$ in the streamwise direction.
- The spanwise-averaged shape factor and circulation are unaffected by yaw.
5. CONCLUSIONS

- In order to capture the evolution of vortex core paths in the far region behind an array of counter-rotating vortices it has been shown through a pseudo-viscous vortex model that circulation decay and streamwise asymptotic limits have to be taken into account.
- For three separation bubbles of different size, separation was prevented at approximately the same $\lambda_e$. For higher $\lambda_e$, $H_{12}$ for all APGs approach a asymptotic value of 1.4.
- The streamwise position of the vortex generating devices is, within a certain range, of minor importance, which makes separation control by VGs robust and less sensitive to changing boundary conditions.

5.3. Jet VGs

- VGJs have been shown to be as effective as vane-type VGs. Furthermore, there seems to be a maximum possible value of $\overline{U}_5 \approx 0.4$, that is common for both systems.
- The maximum $\overline{U}_5$ is reached at $VR = 5$. The maximum volume flow efficiency and the maximum kinetic energy efficiency is obtained at $VR = 2.0$ and $VR = 1.0$, respectively.
- At yaw the control effect is decreasing slowly up to $\theta = 40^\circ$, where it is still 70–80% of the non-yawed level. Thus, the system robustness for yaw is good.
- When $VR$ is in the maximum efficiency range and more control is needed, the VGJ array should, if possible, be made denser instead of increasing $VR$. Similarly, to reduce control the VGJ array is made more sparse.
- The basic mechanism of pulsed VGJs is pulse-width modulation. The control effectiveness is primarily a function of $VR^* = \Omega VR$. Thus, for maximum effectiveness at constant $VR$ the duty cycle should be $\Omega = 1$.
- If they can be run at the optimum $VR$, pulsed jets can be more efficient than steady jets for a required level of $\overline{U}_5$.
- For a given $\Omega$ there is a optimum $St_{jet}$. The optimum $St_{jet}$ can be seen as a limit for a robust system, due to the rapid decrease in control effect at frequencies higher than the optimum.
- The injection time, and not $\Omega$, is the relevant parameter. Here the optimal injection time span is $100 < t_1^+ < 200$. The optimum $St_{jet}$ mentioned above can be expressed in $t_1^+$. Thus, there are only two non-geometry parameters that determine the efficiency: $VR$ and $t_1^+$.
- Johari & Rixon (2003) suggested that the optimal injection time for pulsed VGJs is in the range of 4–8 $d/U_{jet}$. In the present experiment the optimal $t_1$ has been shown to be approximately 25 times longer.
CHAPTER 6

Outlook

6.1. Practical applications

Flow control systems utilising vane-type VGs, steady VGJs or pulsed VGJs have been shown to be effective and robust. This make them suitable for use on ground vehicles. As mentioned earlier an array can be utilised to energise the boundary layer upstream of a steep tapering of the vehicle rear end and thus prevent separation. The effectiveness of VGs and VGJs are equal and therefore the choice can be based on which system is the most practical. Passive VGs are of course simpler, but sharp blades cannot be mounted on a ground vehicle due to safety reasons. Furthermore they can not be turned off while braking or when driving in a convoy\(^1\).

There are other areas on a ground vehicle that can benefit from flow control, as for example the underbody. The internal flow systems can also be improved. The air inlet to the engine should have a low pressure drop even though the pipes are bent. Also the important cooling air flow can be increased if the pressure drop is reduced.

An obvious application of VGJs is on airplanes. Vane-type VGs are already used on wings and in engine air intakes, however also on an airplane it is useful to be able to turn off the flow control system.

6.2. Further research

There are two main areas of interest that needs to be pursued: the application of the VGJ system on a bluff body and the exchange of pulsed jets for synthetic jets.

It would be valuable to study the effect of VGJs on a truck-like bluff body and analyse how the energy consumption will change. If the energy consumption of the jets is larger than the decrease in energy consumption caused by the drag reduction the system is less useful.

Synthetic jets are very attractive since they require no air supply and thus make the installation simple. Since a synthetic jet has little influence on the boundary layer during its suction phase their flow control mechanisms are the

\(^1\)The total drag of a convoy of trucks can probably be reduced if all vehicles except the last turn off their flow control systems to increase the wake size.
same as for non-synthetic jets. One example of a study using synthetic jets is the investigation by Amitay et al. (2001). Synthetic jets are probably the way ahead, but injection times in the order of 100–200 $d/U_{jet}$ requires actuators with large reservoirs.
CHAPTER 7

Papers and authors contributions

Paper 1

*On the scaling of turbulent boundary layers.*

Ola Lögdberg (OL), K. P. Angele (KA) & P. H. Alfredsson (HAL).


The experiments on APG case I was performed by KA and has already been reported in Angele & Muhammad-Klingmann (2006). APG cases II and III were measured by OL. The data analysis was done by OL and the writing was done by OL and KA jointly, in cooperation with HAL.

Paper 2

*Streamwise evolution of longitudinal vortices in a turbulent boundary layer.*


*J. Fluid Mech.* (In press).

The experiment was set up by OL, under the supervision of JF. The experiments and the data analysis were performed by OL. The writing was done by OL and JF jointly, in cooperation with HAL. Parts of this work was presented at the 6th European Fluid Mechanics Conference 2006, Stockholm. Some of the results have also been reported in Stillfried, Lögdberg, Wallin & Johansson (2009).

Paper 3

*On the robustness of separation control by streamwise vortices.*

Ola Lögdberg, K. P. Angele & P. H. Alfredsson

The experiments on APG case I was performed by KA and has already been reported in Angele & Muhammad-Klingmann (2005a). APG cases II and III were measured by OL. The data analysis was done by OL and the writing was done by OL, in cooperation with KA and HAL. Parts of this work was presented at the 4th International Symposium of Turbulence and Shear Flow Phenomena 2005, Williamsburg.
Paper 4
Ola Lögdberg

Paper 5
Ola Lögdberg
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