Base flow modulations for skin-friction drag reduction

Jens H. M. Fransson¹, Alessandro Talamelli¹,²

¹ Linné Flow Centre, KTH Mechanics, SE–100 44 Stockholm, Sweden
² Università di Bologna, I–471 00 Forlì, Italy

E-mail: jensf@mech.kth.se

Abstract. Recent experimental investigations have shown that spanwise modulations of the base flow may delay transition to turbulence. In this paper we explore the possibility to generate streaks of much larger amplitude than previously reported by using a row of miniature vortex generators (MVGs). Here, we present the first boundary layer experiment where streak amplitudes exceeding 30% have been produced without having any secondary instability acting on them. Furthermore, the induced drag due to the streaky base flow is quantified and it is demonstrated that the streaks can be reinforced by placing a second array of MVGs downstream of the first one. In this way it is possible to make the control more persistent in the downstream direction. We conclude that the specially designed set of MVGs, as a boundary layer modulator, is a promising candidate for successfully setting up robust and persistent streamwise streaks, which is a prerequisite for a successful flow control.

1. Introduction

This experiment is part of a large research programme, AFRODITE¹ (Fransson et al., 2011), aimed at developing a passive control method for viscous as well as pressure drag reduction on aerodynamic bodies. The viscous drag reduction is obtained by extending as much as possible the laminar region, i.e. by delaying the onset of transition to turbulence in the boundary layer. In the past numerous strategies have been attempted to delay transition, where most of them have been active (in contrary to passive) in the sense that external energy has to be added to the flow system in order to perform the control. In this research programme we are interested in developing a passive flow control technique, which acts twofold in the sense that both transition and separation could be delayed or even prevented. Today it is known that each one of the above flow phenomena can be controlled individually by means of a passive flow control mechanism. One of the most recent findings is for instance the transition delay (cf. Fransson, Talamelli, Brandt & Cossu, 2006) realizable by introducing spanwise mean flow gradients in the boundary layer while, classically, wing-type vortex generators have been used to delay or prevent separation (see e.g. Pearcey, 1961), reducing the pressure drag. Remaining challenges in the strive after a successful twofold passive control method is to secure robustness and persistency of the modulated laminar boundary layer. This means that the generated streaks have to be stable in the sense that no trace of secondary instability on the streaks

¹ AFRODITE – Advanced Fluid Research On Drag reduction In Turbulence Experiments
should be present and that the streaks, which decay in the downstream direction, might be re-
generated reinforcing the stabilizing mechanism without causing destructive vortex interaction
and breakdown to turbulence. Here, we aim to illustrate the potential of using miniature
vortex generators (MVGs) for the aforementioned twofold passive control method by generating
considerably higher amplitude boundary layer streaks than previously reported.

The experimental activity on the passive transition delay method has been inspired both
by previous experimental works (cf. Kachanov & Tararykin, 1987; Westin, Boiko, Klingmann,
Kozlov & Alfredsson, 1994) and numerical linear stability analyses (cf. Cossu & Brandt, 2002,
2004), where it was concluded that the presence of spanwise modulations of the boundary layer,
so called streamwise streaks, can have a stabilizing effect on low amplitude Tollmien-Schlichting
(TS) waves, which for low levels of external perturbations, characterize the initial stage of the
transition scenario. On the other hand, in many practical applications, transient growth of
disturbances may be initiated by the presence of free-stream turbulence, resulting in unsteady
streamwise streaks, which give rise to a by-pass transition scenario. These unsteady streaks,
even though they act stabilizing on the boundary layer and are able to damp the evolution of
turbulent spots (cf. Fransson, 2010), they are likely to breakdown to turbulence at a subcritical
Reynolds number by some secondary instability acting on the streaks, and hence the stabilizing
control effect will cease to exist. For the aforementioned passive control method to be applicable,
one must be able to generate high amplitude laminar and steady streamwise streaks by means of
some device, which only weakly interact with free-stream disturbances. Therefore, we must rely
on the use of specific roughness elements or disturbance generators mounted in fixed positions
on the surface.

White (2002) investigated the transient growth of disturbances of small amplitude steady
streaks generated by using a spanwise periodic array of roughness elements of circular section
and small height. The maximum amplitude of the streaks was below 4% of $U_\infty$. This work
inspired Fransson et al. (2004) who were searching for means to generate high amplitude streaks
for TS-wave control. By means of a similar roughness element configuration, they were able
to generate stable streaks up to 12% of $U_\infty$ where the streaks are generated by the lift-up
mechanism (cf. Landahl, 1980). From the measurements performed by Fransson et al. (2005a)
it could be also assessed that a critical roughness Reynolds number was approximately 420. In
fact, for this particular geometry, the limitation in the roughness height to create steady and
stable streaks of large amplitudes, necessary to improve the transition delay control, was not
due to an inviscid instability of the streaks themselves but rather due to a near wake instability
associated to the generating device (e.g. vortex shedding).

A clear damping effect of the growth of TS-waves was reported by Fransson et al. (2005a),
and it was shown, for the first time experimentally, that an increase in the streak amplitude was
directly correlated with a less growth of the TS-waves. The stabilizing mechanism, compared
to the two-dimensional boundary layer, is ascribed to the additional turbulence production
term, namely $\langle uw \rangle$ acting on the spanwise gradient of the mean streamwise velocity component,
$\partial U/\partial z$, which turns out to be negative (Cossu & Brandt, 2004). Even though the amplitude
was found to be limited, in following works, it was demonstrated that the generated streaks were
really effective in reducing the growth of the TS-waves, as predicted by the theory, and that, by
using this passive control technique, it was possible to sensibly delay transition to turbulence
Fransson et al. (2006).

In the present investigation our goal is to obtain stable streaks, which may reach significantly
larger amplitude values than the ones reached above. This aim is pursued by looking at
disturbance elements which possibly do not undergo a near wake instability phenomenon. For
this purpose we decided to test an array of miniature vortex generator pairs mounted on the
plate. The idea is to generate directly steady counter rotating vortices inside the boundary
layer capable to set-up the desired streaks through the lift-up mechanism. Similar vortices were
recently generated in a zero-pressure-gradient turbulent boundary layer by Lögberg, Fransson & Alfredsson (2009), by using rectangular bladed vortex generators, to study their downstream evolution and dynamics. In their paper different configurations were tested. By tracing the vortex core motion, they showed that the vortex paths asymptotically reach a precise position in the cross-flow plane. These results allowed the development of a pseudo-viscous vortex model, which can be used in the design work of blade type vortex generators.

Pearcey (1961) explored in his work also the possibility to re-generate or re-inforce the vortices by means of multiple arrays positioned downstream. In his paper he stated that the position of the following arrays is crucial and should be carefully chosen in both spanwise and streamwise direction according to the actual position of the vortices. More recently, Holland & Cossu (2009) proved that it is possible to physically increase the streak amplitude in a plane Poiseuille flow by means of a multi-stage generation process. This concept has been firstly analyzed numerically and finally tested experimentally in a water channel. In their experiment they reached an amplitude close to 22% of $U_\infty$. However, this result cannot be directly transposed to a boundary layer flow since it was already proven by Elofsson et al. (1999) that in a channel flow very high amplitude streaks can be reached with values up to 35% without any instability acting on the streaks.

In this investigation we present experimental results, which strongly support the idea of using miniature vortex generators (MVG) to generate high amplitude streamwise streaks and with the potential to re-generate these streaks with subsequent arrays of MVGs (the latter not treated in this paper), which in turn reinforce the stabilizing mechanism without causing destructive vortex interaction and breakdown to turbulence.

2. Experimental setup

2.1. The apparatus

The experiments were carried out in the Minimum-Turbulence-Level (MTL) wind tunnel at KTH Mechanics on a 4.2 m long flat plate. The plate was mounted horizontally in the test section which is 7 m long, 1.2 m wide and 0.8 m high. The tunnel has an adjustable ceiling to regulate the pressure gradient in the streamwise direction. A heat exchanger, positioned in the return circuit just after the fan, is capable to maintain a variation of the temperature below ±0.05 °C. The total pressure variation is less than ±0.06%. For further details on the wind tunnel and its flow quality see Lindgren & Johansson (2002). Figure 1(a) shows a schematic of the experimental setup. The flat plate is equipped with a leading edge, which is designed in order to get a short pressure gradient region without any suction peak, and a with a trailing edge flap, which is mounted in order to compensate for the extra blockage below the plate due to the presence of the plate supports. A cartesian coordinate system is introduced with the origin
Table 1. Parameters of the boundary layers under investigation, case I–III, and their corresponding symbols throughout the paper. $U_\infty$ corresponds to the free-stream velocity at the leading edge for each case. $Re$ and $Re_h$ denote the displacement thickness and the MVG blade height Reynolds numbers, respectively, at $x = x_{VG}$. Parameters with the superscript 0 are based on the streamwise position $x = x_{VG}$. $\beta$ denotes the spanwise wavenumber of the MVG pairs.

| Case | $U_\infty$ (m s$^{-1}$) | $Re$ | $Re_h$ | $\delta^0$ (mm) | $\delta_1^0$ (mm) | $\delta_2^0$ (mm) | $H_{12}^0$ | $\beta^0$ | Symbol |
|------|-----------------|------|--------|----------------|-----------------|----------------|-------------|----------|--------|
| I    | 3.0             | 371  | 355    | 1.00          | 1.85            | 0.70           | 2.64        | 0.30     | (□)    |
| II   | 3.5             | 401  | 440    | 0.92          | 1.71            | 0.64           | 2.67        | 0.28     | (△)    |
| III  | 4.0             | 429  | 528    | 0.86          | 1.60            | 0.60           | 2.67        | 0.26     | (○)    |

located on the centreline at the leading edge with $x$, $y$, and $z$-axis directed along the streamwise, wall-normal, and spanwise directions, respectively. A single hot-wire probe was used to measure the streamwise velocity component using a DANTEC constant temperature anemometer. The probe is built at KTH Mechanics and is made of a 2.5 $\mu$m platinum wire with a distance between the prongs of approximately 0.5 mm. The probe is operated at 50% overheat and is calibrated in situ far outside the boundary layer against a Prandtl tube. The calibration function proposed by Johansson & Alfredsson (1982), which compensates for the natural convection effect at low velocities, was used.

2.2. The vortex generators

The streamwise vortices inside the boundary layer were generated by means of triangular miniature vortex generators (MVGs) (see figure 1b). A first row is positioned at $x_{VG} = 200$ mm from the leading edge. In this row the MVGs are arranged as an array of 16 spanwise pairs to generate a sequence of counter-rotating vortices equally spaced inside the boundary layer. The blade angle is kept at 15$°$ and the design follows the criterion suggested by Pearcey (1961) for persistent streamwise existence of the vortices. The length ($L$) of each blade is 7.5 mm, the distance between the blades of each pair ($d$) is 5.2 mm while the spanwise distance between each MVG pair ($D$) is 20.8 mm. The height ($h$) is 2.5 mm. A second row of vortex generators is available to test the possibility to reinforce the streak amplitude. In this case the row constitutes of 5 spanwise MVG pairs. The elements are geometrically similar to those of the first row and are mounted on a thin support which can be fixed in any position on the plate.

3. Streamwise evolution of the streaks

The experiments with miniature vortex generators were performed at three different free-stream velocities, viz. 3.0, 3.5 and 4.0 m s$^{-1}$, which will be denoted case I, II and III, respectively. The free-stream velocities were measured at the leading edge of the plate. In this section we present the evolution of the streaks downstream of a single array of MVGs. The local boundary layer length scale, $\delta$, is close to 1 mm at $x = x_{VG}$ and the local spanwise wavenumber $\beta^0 = 2\pi/D$, becomes 0.28 for case II. The stationary streamwise velocity perturbation in the cross-stream $yz$-plane at different streamwise stations is shown in figure 2 as contour plots. Here, the perturbation velocity is defined as the difference of the local velocity $U(y, z)$ to the Falkner-Skan mean profile $U_{FS}(y)$ without the presence of the MVGs (this reference base flow is not shown here but has a weak adverse pressure gradient with a deceleration parameter of $m = -0.021$). Solid black and white contour lines correspond to velocity excess
Figure 2. Cross-sectional planes behind the MVG-array. Dashed lines correspond to contours of constant velocity $U/U_\infty = (0.1:0.1:0.9)$ with inverted colors compared to the colormap. Solid black and white lines correspond to contours of velocity access $(0.05 0.1:0.1:0.3)$ and deficit $(-0.05:-0.05:-0.2)$, respectively, compared to the Falkner-Skan base flow without the MVG-array. $\beta^* = 0.302$ (mm)$^{-1}$.

3.1. Streak amplitude distribution and boundary layer parameters

In figure 3 the downstream evolution of the streak amplitude, defined as

$$A = \max_y \{\Delta U(y)/2\}/U_\infty,$$

where $\Delta U(y) = \max_z \{U(y,z)\} - \min_z \{U(y,z)\},$ (1)

is shown with open symbols. Note that this amplitude measure maximizes over both $z$ and $y$, meaning that the spanwise distance between the points used to calculate $\Delta U(y)$ will differ depending on the downstream location and the considered wall-normal position. This measure is introduced in order to make direct comparisons with previous studies where similar definitions have been used.

For the same experimental setup, stronger streaks are induced by increasing the free-stream velocity. The different cases I–III give maximum amplitudes around 25, 28 and 32% of $U_\infty$, respectively, and the corresponding streamwise location of these maxima appears around $(x-x_{VG})/h = 40$. Note that full $yz$-planes of case II were only measured at three streamwise locations and this is the reason for such a poor streamwise resolution. In the same figure the location above the wall where the amplitude has been defined is also shown for each streamwise
position with filled symbols (see the right ordinate axis) for case I and III. One may observe that the wall-normal position of the maximum velocity deviation moves away from the wall with the downstream distance. Note also that as far downstream as $600h$ of the MVGs the amplitude is above $15\%$ of $U_\infty$ for case III, and is still higher than what is possible to generate with circular roughness elements, i.e. $12\%$ before the onset of an unsteady wake flow.

The streaky base flows may be characterized by their boundary layer parameters and in figure 4(a), $\delta_1$, $\delta_2$ and $H_{12}$ are plotted for case III in particular (see the caption). It is clear that the spanwise modulation of the mean streamwise velocity is reflected in an increase of the shape factor in the low speed streak with a maximum of 3.5 and a corresponding decrease in the high speed streak with a minimum of 1.9. The difference between the two values decreases moving downstream due to the decay of the streak amplitude. Noteworthy is that the average shape factor is very similar to the one measured in the base flow without the presence of the MVGs (cf. dashed line), despite the fact that both $\delta_1$ and $\delta_2$ follow a slightly different behaviour with an increase in average compared to their corresponding dashed line. This deviation seems to persist until the streak amplitude has decayed to about 50\% of its maximum amplitude at $(x-x_{VG})/h = 400$.

### 3.2. Induced skin-friction drag analysis

An important issue in the strive after drag reduction is the amount of induced drag one obtains due to the generation of the streamwise streaks. This induced drag has to be taken into account as a cost in any performance improvement estimation. The skin-friction drag was calculated by introducing the spanwise-averaged local skin-friction coefficient ($c_f$) and by considering the momentum-integral equation for two-dimensional incompressible boundary layers:

$$c_f(x) = 2 \frac{\tau_w}{\rho U_\infty^2}, \quad \text{where} \quad \frac{\tau_w(x)}{\rho U_\infty^2} = \frac{d\delta_z^2}{dx} + \frac{1}{U_\infty} \frac{dU_\infty}{dx} (\delta_1^2 + 2\delta_2^2).$$  \hfill (2)

The boundary layer parameters ($\delta_z^k$) are obtained by integrating over one spanwise wavelength, corresponding to $D$:

$$\delta_z^k(x) = \frac{1}{D} \int_{-D/2}^{D/2} \delta_k(x, z) \, dz, \quad \text{with} \quad k = 1, 2.$$  \hfill (3)

Here $\tau_w$, $\rho$, $\delta_1$, $\delta_2$ are the wall-shear-stress, fluid density, displacement thickness and the momentum thickness, respectively. Note that the induced drag associated with the pressure
drag of the vortices themselves has been neglected in above measure since it is difficult to access. On the other hand Fransson & Corbett (2003) calculated optimal perturbations and showed that the vortices themselves significantly affect the region behind the location of the optimal perturbation only up to 1/10 of the distance of the maximum amplitude by considering the pressure and the cross-component fluctuations. A crude, but to our opinion fair, estimation would suggest that the vortices themselves will only affect above drag measure up to about 4h behind the MVG array, and hence the neglect is justified without any significant impact on the results shown in figure 4(b). In this figure the skin-friction coefficient is normalized with the value obtained in the Falkner-Skan base flow without the presence of the MVGs ($c_f^{FS}$), giving a direct measure of the skin-friction drag increase along the plate for two different $Re_h$. In order to improve the accuracy of the streamwise momentum thickness derivative, which appears in the RHS of eq. 2, the following relation

$$\delta_z^2 = Ax^p + B,$$

was fitted to the spanwise averaged momentum thickness data ($\delta_z^2$), cf. eq. 3, and then it was differentiated exactly with respect to $x$ to give $\tau_w(x)$ used in eq. 2. Relation 4 is consistent with the results shown in figure 4 where a scaling of the spanwise averaged $\delta_z^2$ (+-symbols) with $\delta$ ($\propto \sqrt{x}$) is shown and it is clear that $p \neq 0.5$, the fitted parameters to the data give a nice fit to the data for each case (not shown).

Figure 4(b) shows, as expected, a significant increase of the skin-friction drag coefficient behind the MVGs compared to the base flow. After this increase behind the MVGs both drag coefficient distributions decrease and become lower than the base flow case at around 300h and 500h for the cases I and III, respectively. An interesting remark is that an originally larger amplitude base flow gives rise to a lower skin-friction in the far field. For the highest amplitude case III, with a maximum amplitude of 32% of $U_\infty$, the induced skin-friction drag is about 47%, but decreases to about 12% for case I, with a maximum amplitude of 25% (compare figure 3 and 4b). An important figure to keep in mind is the amount of drag reduction one actually accomplishes if transition to turbulence is nullified. Here, one order of magnitude of reduction

![Figure 4](image-url)

**Figure 4.** (a) Spanwise averaged boundary layer parameters and their evolution in the streamwise direction for case III if otherwise is not stated. Displacement thickness (+), momentum thickness ($\ast$), and the shape factor ($\bullet$ case III, $\square$ case I). The ($\circ$)-symbols enclosing the gray area correspond to the local shape factor in the high (lower curve) and low (higher curve) speed streak. (b) Induced drag coefficient $c_f$, see eq. 2, normalized with the Falkner-Skan value representing the skin-friction drag of the base flow without the presence of streaks versus the downstream distance for case I and case II.
Figure 5. (a) Intermittency function (Γ) calculated in a high (○) and low (⋆) speed streak at \((x-x_{VG})/h=560\). The solid line is a curve fit to all the data using eq. 5. Dashed lines and the black square symbol indicate the critical \(Re_h\). (b) Streak amplitude (left ordinate axis ○-symbols) and its corresponding disturbance level (right ordinate axis ×-symbols) at \((x-x_{VG})/h=52\) versus the Reynolds number based on MVG height (lower horizontal axis) and on the displacement thickness measured at \((x-x_{VG})/h=0\) (upper horizontal axis). In the background, contour plot of the intermittency function (eq. 5) with the fitted parameters to the data in figure 5(a).

in the local \(c_f\) can be obtained, which is far much more than the induced skin-friction drag even for the highest amplitude case.

4. Transitional MVG height Reynolds number

The stability of the generated streaks has been studied by computing the intermittency factor (Γ) at a fixed downstream position \((x-x_{VG})/h=560\), both inside a high and a low speed streak close to the wall. The wind tunnel speed has been varied from 3.72 to 4.41 m s\(^{-1}\) resulting in \(496 \leq Re_h \leq 623\). The exact wall normal position is not crucial for the repeatability since the intermittency is fairly constant up to at least \(y/\delta=2\) (see e.g. Matsubara et al., 1998). For each point 40 000 samples were collected at a rate of 1000 Hz, which were used for the intermittency calculations. The intermittency factor, computed as described in the work by Fransson et al. (2005b), is determined for increasing \(Re_h\) in order to show a local measure of the transitional flow.

Figure 5(a) shows that the critical \(Re_h\), defined as the \(Re_h\) where the intermittency equals 0.5, is 547 for this particular MVG array and for this particular setup in the MTL wind tunnel. The (○) and (⋆) symbols correspond to the spanwise location in the streaky base flow, with the former and latter symbols corresponding to a high and a low speed streak, respectively. The solid line is a curve fit to all the data in a least square sense using the function

\[
\Gamma(Re_h) = 1 - e^{-\alpha(Re_h-\beta)^2},
\]

resulting in \(\alpha = 0.0022\) and \(\beta = 529.4\). In figure 5(b) the streak amplitude measured at the fixed downstream position \((x-x_{VG})/h=52\) is shown for all the considered \(Re_h\) with (○)-symbols. The (×)-symbols are the corresponding disturbance level indicated on the right ordinate axis of the
figure. In the background the intermittency function (eq. 5) with the fitted parameters to the data in figure 5(a) is plotted as a contour plot. Figure 3 shows that the amplitude measure at \((x - x_{VG})/h=52\) is a good approximation of the maximum streak amplitude, which presents only small changes in position for the different cases. The figure shows an almost linear increase of the maximum amplitude with \(Re_h\) at very low values of the intermittency. Just after the onset of instability (i.e. \(\Gamma > 0\)) the maximum streak amplitude reaches a plateau. This figure suggests that there is no need to approach the critical \(Re_h\) to obtain a high streak amplitude. Increasing further \(Re_h\) does not increase the streak amplitude significantly, but the streaks start to become rapidly unstable. Note that the disturbance level is below 1% for all \(Re_h\). The reason for \(u_{rms}/U_\infty\) being less than 1% even at the farthest downstream position where \(\Gamma > 0.8\) is that \(\Gamma\) is determined at \((x - x_{VG})/h = 560\) while the maximum amplitude was determined at \((x - x_{VG})/h = 52\). It must be pointed out that when the streaks are generated by means of circular roughness elements, the instability of the streaks may be observed at lower roughness Reynolds numbers due to the onset of a vortex shedding instability. In Fransson et al. (2005a) a critical roughness Reynolds number of 422 was reported for circular roughness elements in the same wind tunnel but for a slightly milder, and therefore more stable, adverse pressure gradient, i.e. \(m = -0.0046\) which should be compared with the present \(m = -0.021\).

5. Summary

In this investigation we present experimental results, which strongly support the idea of using miniature vortex generators (MVGs) to generate high amplitude streamwise streaks and with the potential to re-generate these streaks with subsequent arrays of MVGs (not shown in this paper), which in turn reinforce the stabilizing mechanism without causing destructive vortex interaction and breakdown to turbulence.

Acknowledgments

This work is part of a recently granted research programme AFRODITE funded by the European Research Council, which is gratefully acknowledged by JHMF. We wish to thank Mr. Göran Rådberg and Mr. Joakim Karlström in the workshop for their assistance in the manufacturing of the MVGs. AT acknowledges financial support from STINT during his stay at KTH.

References

Cossu, C. & Brandt, L. 2002 Stabilization of Tollmien-Schlichting waves by finite amplitude optimal streaks in the Blasius boundary layer. Phys. Fluids 14, L57–L60.

Cossu, C. & Brandt, L. 2004 On Tollmien-Schlichting-like waves in streaky boundary layers. Eur. J. Mech./B Fluids 23, 815–833.

Elofsson, P. A., Kawakami, M. & Alfredsson, P. H. 1999 Experiments on the stability of streamwise streaks in plane Poiseuille flow. Phys. Fluids 11, 915–930.

Fransson, J. H. M. 2010 Turbulent spot evolution in spatially invariant boundary layers. Phys. Rev. E 81, 035301(R).

Fransson, J. H. M., Brandt, L., Talamelli, A. & Cossu, C. 2004 Experimental and theoretical investigation of the nonmodal growth of steady streaks in a flat plate boundary layer. Phys. Fluids 16 (10), 3627–3638.

Fransson, J. H. M., Brandt, L., Talamelli, A. & Cossu, C. 2005a Experimental study of the stabilisation of Tollmien-Schlichting waves by finite amplitude streaks. Phys. Fluids 17, 054110.
Fransson, J. H. M. & Corbett, P. 2003 Optimal linear growth in the asymptotic suction boundary layer. Eur. J. Mech. B/Fluids 22, 259–270.

Fransson, J. H. M., Fallenius, B. E. G., Shahinfar, S., Sattarzadeh, S. S. & Talamelli, A. 2011 Advanced Fluid Research On Drag reduction In Turbulence Experiments. In Proc. of 13th European Turbulence Conference, 12-15 Sept., Warsaw.

Fransson, J. H. M., Matsubara, M. & Alfredsson, P. H. 2005b Transition induced by free stream turbulence. J. Fluid Mech. 527, 1–25.

Fransson, J. H. M., Talamelli, A., Brandt, L. & Cossu, C. 2006 Delaying transition to turbulence by a passive mechanism. Phys. Rev. Lett. 96, 064501.

Holland, M. & Cossu, C. 2009 Adding streamwise streaks in the plane poiseuille flow. C.R. Mecanique 337, 179–183.

Johansson, A. V. & Alfredsson, P. H. 1982 On the structure of turbulent channel flow. J. Fluid Mech. 122, 295–314.

Kachanov, Y. S. & Tararykin, O. I. 1987 Experimental investigation of a relaxing boundary layer. Izv. SO AN SSSR, Ser. Tech. Nauk 18.

Landahl, M. T. 1980 A note on an algebraic instability of inviscid parallel shear flows. J. Fluid Mech. 98, 243–251.

Lindgren, B. & Johansson, A. V. 2002 Evaluation of the flow quality in the mtl wind-tunnel. Tech. Rep. KTH/MEK/TR–02/13–SE, KTH Mechanics, Stockholm.

Lögberg, O., Fransson, J. H. M. & Alfredsson, P. H. 2009 Streamwise evolution of longitudinal vortices in a turbulent boundary layer. J. Fluid Mech. 623, 27–58.

Matsubara, M., Alfredsson, P. H. & Westin, K. J. A. 1998 Boundary layer transition at high levels of free stream turbulence. ASME paper 98-GT-248.

Pearcey, H. H. 1961 Shock-induced separation and its prevention. In Boundary Layer and Flow Control, its Principle and Applications (ed. G. V. Lachmann). Oxford England: Pergamon Press.

Westin, K. J. A., Boiko, A. V., Klingmann, B. G. B., Kozlov, V. V. & Alfredsson, P. H. 1994 Experiments in a boundary layer subject to free-stream turbulence. part i: Boundary layer structure and receptivity. J. Fluid Mech. 281, 193–218.

White, E. B. 2002 Transient growth of stationary disturbances in a flat plate boundary layer. Phys. Fluids 14, 4429–4439.