Advanced Fluid Research On Drag reduction In Turbulence Experiments –AFRODITE–

J. H. M. Fransson, B. E. G. Fallenius, S. Shahinfar, S. S. Sattarzadeh and A. Talamelli
Linné Flow Centre, KTH Mechanics, SE–100 44 Stockholm, Sweden
E-mail: jensf@mech.kth.se

Abstract. A hot topic in today’s debate on global warming is drag reduction in aeronautics. The most beneficial concept for drag reduction is to maintain the major portion of the airfoil laminar. Estimations show that the potential drag reduction can be as much as 15%, which would give a significant reduction of NOx and CO emissions in the atmosphere considering that the number of aircraft take offs, only in the EU, is over 19 million per year. An important element for successful flow control, which can lead to a reduced aerodynamic drag, is enhanced physical understanding of the transition to turbulence process.

1. AFRODITE in brief

AFRODITE is a recently funded research programme by the European Research Council, and stands for Advanced Fluid Research On Drag reduction In Turbulence Experiments.

In previous tuned wind tunnel measurements it has been shown that roughness elements can be used to sensibly delay transition to turbulence (cf. Fransson et al., 2006). The result is revolutionary, since the common belief has been that surface roughness causes earlier transition and in turn increases the drag, and is a proof of concept of the passive control method per se. The beauty with a passive control technique is that no external energy has to be added to the flow system in order to perform the control, instead one uses the existing energy in the flow.

Within the research programme –AFRODITE– we will take this passive control method to the next level by making it twofold, more persistent and more robust. Transition prevention is the goal rather than transition delay and the method will be extended to simultaneously control separation, which is another unwanted flow phenomenon especially during airplane take offs. AFRODITE will be a catalyst for innovative research, which will lead to a cleaner sky.

2. Background

Today, it is well known that the boundary layer can transition to turbulence via different routes depending on surrounding parameters, such as surface imperfections, free-stream turbulence (FST) and background acoustic noise (Kachanov, 1994). For a clean base flow, i.e. a flow with low background disturbance levels typically encountered in free flight, and a hydraulically smooth surface the classical transition scenario takes place with exponentially growing disturbance modes (Tollmien, 1929; Schlichting, 1933; Schubauer & Skramstad, 1947). The least stable mode, denoted Tollmien-Schlichting (TS) wave, starts to grow at some critical Reynolds number.
Another modal scenario takes place on swept leading edges with favorable pressure gradient, where the primary exponential disturbance is denoted the cross-flow mode, which can both be stationary and/or traveling depending on the surrounding parameters (Saric et al., 2003). However, for an increasing level of FST disturbances will be induced from the boundary layer edge into the boundary layer, which give rise to streamwise oriented structures of low and high speed fluid (Kendall, 1985; Westin, 1997; Jacobs & Durbin, 2001; Matsubara & Alfredsson, 2001; Brandt & Henningson, 2002; Fransson & Alfredsson, 2003) typically encountered in turbomachinery flows where the flow approaching the turbine blades is often highly disturbed. These structures grow in amplitude and their spanwise size depends both on the FST intensity $Tu$, defined as the streamwise root mean square velocity $u_{rms}$ over the free stream velocity $U_\infty$, and the characteristic length scales in the FST. Today, this correlation is not clear despite both experimental and numerical attempts (Jonáš et al., 2000; Brandt et al., 2004; Ovchinnikov et al., 2004; Shahinfar, 2011) to clarify this receptivity process.

The primary instability of streaks was originally called the breathing mode (Klebanoff, 1971), since the wall-normal disturbance profile resembles that which would result from a locally continuous thickening and thinning of the boundary layer edge (Taylor, 1939). However, this mode is nowadays recognized as the Klebanoff mode (Kendall, 1985), and can be viewed as one scenario of by-pass transition (Morkovin, 1969). It is a relatively rapid process bypassing the classical modal growth scenario often resulting in breakdown to turbulence at subcritical Reynolds number, when compared with the predicted value by classical theory. The mechanism governing this type of transition scenario is the transient growth, i.e. an algebraic growth of the disturbance energy until viscosity becomes significant, which eventually causes an exponential decay of the energy. Algebraic growth is a consequence of the non-normality of the governing differential operator (Trefethen et al., 1993): as the normal modes are not orthogonal, constructive and destructive interference may give rise to transients before the classical modal growth sets in. When the primary instability, i.e. the TS-wave or the streamwise streaks, reaches a certain amplitude it breaks down to turbulence, probably through a secondary instability mechanism (see e.g. Herbert, 1988; Andersson et al., 2001), which locally give birth to turbulent patches.

The simplest configuration used to test transition prediction and control tools is the boundary layer on a flat plate. In this case, the laminar boundary layer flow is given by the family of Falkner-Skan self-similar solutions and are the type of base flows which have been used in the following brief review of drag reduction by means of a passive control method.

3. Realizing drag reduction by means of a passive control

Early this decade Cossu and Brandt Cossu & Brandt (2002, 2004) found, by using temporal linear stability analysis, that steady optimal streaks of moderate amplitude, i.e. sufficiently large but not exceeding the critical amplitude for the inflectional instability, are able to reduce the growth of TS-waves up to their complete stabilization. Experimentally, Boiko et al. (1994) found that, in the case of a boundary layer subject to free-stream turbulence and unsteady streaks, TS-waves are stabilized in the mean when they are of small amplitude. However, when forced at larger amplitudes, they promote transition due to the non-linear interaction between the TS-waves and the streaks. Given above results it was suggested that the optimal forcing of steady streaks could be used as a possible appealing method to delay transition in boundary layers within a low noise environment.

3.1. Setting up the streamwise streaks in an experiment

White (2002) investigated the transient growth of disturbances of small amplitude (stable) steady streaks generated by using a spanwise periodic array of roughness elements of circular section
Figure 1. A and B without streaks, without and with excitation (V), respectively. C and D with streaks without and with excitation (> 2V), respectively. E shows a half-straky boundary layer without and with excitation (≈ 0.8V), respectively. Smoke visualization images published in Fransson et al. (2006). The flow is from left to right.

and small height. The maximum amplitude of the streaks was below 4% of $U_{∞}$. This work was inspiring for Fransson et al. (2004) who were searching for means to generate high amplitude streaks for TS-wave control. They were able to generate stable streaks up to 12% of $U_{∞}$ by using another roughness element configuration in which the streaks are generated by a completely different physical mechanism as explained below.

Comparison of the results by Fransson et al. (2004) with similar experimental studies in the literature showed that the flow may be modulated differently depending on the roughness element configuration. They are all characterized by the formation of streamwise elongated velocity perturbations and differ in the relative position of the high and low speed streaks with respect to the roughness elements. For instance, in the experiments by Gaster et al. (1994) and related simulations by Joslin & Grosch (1995); White (2002); Asai et al. (2002) a region of defect velocity is formed straight behind the element. This is due to the presence of the wake, which persists downstream forming the low speed streak. Conversely, in the experiments reported in Fransson et al. (2004), similarly to what was observed by Bakchinov et al. (1995); Kendall (1990), after a complex region of growing and decaying modes a high speed region is induced behind the roughness element. An explanation for this behavior can be found by considering the perturbation induced by a roughness element in a wall-bounded shear flow (Hunt et al., 1978; Acarlar & Smith, 1987; D`elery, 2001). The spanwise vorticity of the incoming shear flow is wrapped around the front part of the obstacle forming a steady horseshoe-shaped vortex structure with the two streamwise legs pointing downstream. The vorticity associated with these two counter-rotating streamwise vortices is such that high speed fluid is pushed towards the wall in the region behind the obstacle and low speed fluid is lifted on the outer sides (Hunt et al., 1978; D`elery, 2001). The amount of vorticity concentrated in the streamwise legs of the standing vortex depends on the relative height of the element with respect the boundary layer thickness $k/δ$. It must be pointed out that the experiments by Acarlar & Smith (1987) show a more complicated flow pattern. Indeed, depending on the top edge geometry of the elements and for sufficiently high values of the roughness Reynolds number $Re_k$, a shedding of periodic hairpin vortices may be present. The legs of each vortex consist of two counter-rotating streamwise vortices, which in this case increase the defect velocity induced in the wake and generate relatively high levels of root means square (rms) velocity fluctuations (larger than 5%
of $U_\infty$). Nevertheless, the low level of the streamwise rms velocity fluctuations (less than 0.6% of $U_\infty$) and the absence of any power spectra peak show that this phenomenon is not present in the experiment by Fransson et al. (2004).

It can be concluded that there is a competition between the perturbation induced by the vortex generated by the incoming vorticity upstream of the element and the wake downstream of it. In the experiments by Fransson et al. the former mechanism is most likely to dominate and a high speed region is located in correspondence with the roughness element.

3.2. Physical mechanism behind the disturbance damping effect
A clear damping effect of the growth of TS-waves was reported by Fransson et al. (2005), and it was shown, experimentally, for the first time that an increase in streak amplitude was directly correlated with 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 $\partial U / \partial z$, which turns out to be a negative contribution (Cossu & Brandt, 2004).

3.3. Transition to turbulence delay: drag reduction
Despite above findings there were still skeptics in the field regarding the possibility to delay transition by this passive control technique due to the non-linear interaction between the TS-waves and the streaks, which was argued to promote the transition instead of delaying it. The proof of concept, regarding the possibility to delay transition to turbulence was shown one year later by the same authors (Fransson et al., 2006), and these results are shown in figure 1.

The TS-waves were introduced by unsteady blowing and suction at the wall through a slot in the plate. The sinusoidal signal is computer generated through a D/A board to an audio amplifier driving two loudspeakers, which were connected to the slot through vinyl hoses. A frequency of 32 Hz was selected so that transition could be triggered within the observation and measurement regions after the exponential growth of the TS-waves. The amplitude of the signal to the loudspeakers was quantified by measuring the AC output voltage from the amplifier with a voltage-meter. The three-dimensional modulated base flow was generated by placing roughness elements, small standing coin-like cylinders, in an array in the spanwise direction. This array generates a sinusoidal spanwise distribution of alternating high and low speed streaks some distance downstream the array. Smoke visualizations and hot-wire anemometry measurements were used to quantify the transition delay by means of this passive control method (Fransson et al., 2006). Figure 1 shows visualization images ($210 \times 168$ mm$^2$), with and without streaks and two-dimensional forced disturbances, located 1434 mm downstream of the leading edge.

4. Summary
The aim with the AFRODITE programme is to take advantage of the current state-of-the-art to develop a passive flow control method that act twofold in the sense that both turbulence and separation are delayed or even prevented. Furthermore, the control has to be made robust and persistent for real flow applications. The former, robustness, will be realized by using miniature vortex generators (MVGs) instead of cylindrical surface roughness in order to set up the streamwise vortices, which modulate the base flow. By using MVGs really stable streaks with an amplitude of 20% of the free-stream velocity can be generated (maximum amplitude is 32%) and still not taking any risk for causing by-pass transition right at the location of the MVGs (Fransson & Talamelli, 2011). The latter, persistency, will be realized by adding additional spanwise arrays of an appropriate MVG configuration in the streamwise direction in order to regenerate the streamwise streaks and in turn reinforce the control. This idea, to reinforce a passive control, was proposed already in 1961 by Pearcy and hence is not new, but to our knowledge it has not been used extensively.
In summary, the three distinctive features of the novel passive control method that will be developed in the AFRODITE programme are: twofoldness, robustness and persistency.

Acknowledgments

JHMF would like to acknowledge the European Research Council for their financial support of the Starting Independent Researcher Grant AFRODITE.

References

ACARLAR, M. S. & SMITH, C. R. 1987 A study of hairpin vortices in a laminar boundary layer. Part 1. Hairpin vortices generated by a hemisphere protuberance. J. Fluid Mech. 175, 1–41.

ANDERSSON, P., BRANDT, L., BOTTARO, A. & HENNINGSON, D. S. 2001 On the breakdown of boundary layers streaks. J. Fluid Mech. 428, 29–60.

ASAI, M., MINAGAWA, M. & NISHIOKA, M. 2002 The instability and breakdown of a near-wall low-speed streak. J. Fluid Mech. 455, 289–314.

BACCHINOV, A. A., GREK, G. R., KLINGMANN, B. G. B. & KOZLOV, V. V. 1995 Transition experiments in a boundary layer with embedded streamwise vortices. Phys. Fluids. 7, 820–832.

BOIKO, A. V., WESTIN, K. J. A., KLINGMANN, B. G. B., KOZLOV, V. V. & ALFREDSSON, P. H. 1994 Experiments in a boundary layer subjected to free stream turbulence. Part 2. The role of TS-waves in the transition process. J. Fluid Mech. 281, 219–245.

BRANDT, L. & HENNINGSON, D. S. 2002 Transition of streamwise streaks in zero-pressure-gradient boundary layers. J. Fluid Mech. 472, 229–262.

BRANDT, L., SCHLATTER, P. & HENNINGSON, D. S. 2004 Transition in boundary layers subject to free-stream turbulence. J. Fluid Mech. 517, 167–198.

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

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

DÉLERY, J. M. 2001 Robert Legendre and Henry Werlé: Toward the elucidation of three-dimensional separation. Annu. Rev. Fluid Mech. 33, 129–54.

FRANSSON, J. H. M. & ALFREDSSON, P. H. 2003 On the disturbance growth in an asymptotic suction boundary layer. J. Fluid Mech. 482, 51–90.

FRANSSON, J. H. M., BRANDT, L., TALAMELLI, A. & COSNU, 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. & COSNU, C. 2005 Experimental study of the stabilisation of Tollmien-Schlichting waves by finite amplitude streaks. Phys. Fluids 17, 054110.

FRANSSON, J. H. M. & TALAMELLI, A. 2011 Base flow modulations for skin-friction drag reduction. In Proc. of 13th European Turbulence Conference, 12-15 Sept., Warsaw.

FRANSSON, J. H. M., TALAMELLI, A., BRANDT, L. & COSNU, C. 2006 Delaying transition to turbulence by a passive mechanism. Phys. Rev. Lett. 96, 064501.

GASTER, M., GROSCH, C. E. & JACKSON, T. L. 1994 The velocity field created by a shallow bump in a boundary layer. Phys. Fluids 6 (9), 3079–3085.
HERBERT, Th. 1988 Secondary instability of boundary-layers. *Annu. Rev. Fluid Mech.* **20**, 487–526.

HUNT, J. C. R., ABELL, C. J., PETERKA, J. A. & WOO, H. 1978 Kinematical studies of the flows around free or surface-mounted obstacles; applying topology to flow visualization. *J. Fluid Mech.* **86**, 179–200.

JACOBS, R. G. & DURBIN, P. A. 2001 Simulations of bypass transition. *J. Fluid Mech.* **428**, 185–212.

JONÁŠ, P., MAZUR, O. & URUBA, V. 2000 On the receptivity of the by-pass transition to the length scale of the outer stream turbulence. *Eur. J. Mech. B/Fluids* **19**, 707–722.

JOSLIN, R. D. & GROSCH, C. E. 1995 Growth characteristics downstream of a shallow bump: Computation and experiment. *Phys. Fluids* **7** (12), 3042–3047.

KACHANOV, Y. S. 1994 Physical mechanism of laminar boundary-layer transition. *Annu. Rev. Fluid Mech.* **26**, 411–482.

KENDALL, J. M. 1985 Experimental study of disturbances produced in a pre-transitional laminar boundary layer by weak free-stream turbulence. *AIAA Paper* **85**, 1695.

KENDALL, J. M. 1990 The effect of small-scale roughness on the mean flow profile of a laminar boundary layer. *Instability and transition, eds. Hussaini and Voigt*, pp. 296–302.

KLEBANOFF, P. S. 1971 Effect of free-stream turbulence on the laminar boundary layer. *Bull. Am. Phys. Soc.* **10**, 1323.

MATSUBARA, M. & ALFREDSSON, P. H. 2001 Disturbance growth in boundary layers subjected to free stream turbulence. *J. Fluid. Mech.* **430**, 149–168.

MORKOVIN, M. V. 1969 The many faces of transition. In *Viscous Drag Reduction* (ed. C. S. Wells). Plemion Press.

OVCHINNIKOV, V. O., PIOMELLI, U. & CHOUDHARI, M. M. 2004 Inflow conditions for numerical simulations of bypass transition. *AIAA Paper 2004-0591*.

PEARCY, H. H. 1961 *Boundary layer and flow control, its principle and applications*, Vol 2, chap. Shock-induced separation and its prevention, pp. 1170–1344. Pergamon Press, Oxford, England.

SARIC, W. S., REED, H. L. & WHITE, E. B. 2003 Stability and transition of three-dimensional boundary layers. *Annu. Rev. Fluid Mech.* **35**, 413–440.

SCHLICHTING, H. 1933 Berechnung der anfachung kleiner störungen bei der plattenströmung. *ZAMM* **13**, 171–174.

SCHUBAUER, G. B. & SKRAMSTAD, H. K. 1947 Laminar boundary layer oscillations and the stability of laminar flow. *J. Aero. Sci.* **14**, 69–78.

SHAHINFAR, S. 2011 Transitional boundary layers caused by free-stream turbulence. Licentiate thesis, Dept. Mechanics, KTH, Stockholm.

TAYLOR, G. I. 1939 Some recent developments in the study of turbulence. *Proc. 5th Intl. Congr. Appl. Mech.*, ed. J. P. Den Hartog and H. Peters, Wiley, pp. 294–310.

TOLLMAN, W. 1929 Über die entstehung der turbulenz. *Nachr. Ges. Wiss. Göttingen 21-24*, English translation NACA TM 609, 1931.

TREFETHEN, L. N., TREFETHEN, A. E., REDDY, S. C. & DRISCOLL, T. A. 1993 Hydrodynamic stability without eigenvalues. *Science* **261**, 578–584.

WESTIN, J. 1997 Laminar-turbulent boundary layer transition influenced by free stream turbulence. PhD thesis, KTH, Stockholm, TRITA-MEK Tech. Rep. 1997:10.

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