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## LETTERS

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## Stabilization of Tollmien–Schlichting waves by finite amplitude optimal streaks in the Blasius boundary layer

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In this Letter we show by numerical simulation that streamwise streaks of sufficiently large amplitude are able to stabilize Tollmien–Schlichting waves in zero pressure gradient boundary layers at least up to  $Re=1000$ . This stabilization is due to the spanwise averaged part of the nonlinear basic flow distortion induced by the streaks and occurs for streak amplitudes lower than the critical threshold beyond which secondary inflectional instability is observed. A new control strategy is implemented using optimal perturbations in order to generate the streaks. © 2002 American Institute of Physics. [DOI: 10.1063/1.1493791]

In boundary layer flows with low levels of background disturbances, transition is initiated by the exponential amplification of the unstable Tollmien–Schlichting (TS) waves followed by secondary instabilities and breakdown to turbulence as soon as the  $u_{rms}$  amplitude of the primary instability is of the order of 1% of the free stream velocity.<sup>1</sup> In the presence of free stream turbulence (FST), narrow elongated regions of alternated low and high streamwise velocity called “streamwise streaks” slowly oscillate in the boundary layer.<sup>2</sup> For sufficiently large values of FST “bypass transition” is observed. For intermediate levels of FST it was however surprisingly found<sup>3</sup> that the spatial amplification rate of small amplitude TS waves was lower than in the quiet case. This effect was mainly attributed<sup>3</sup> to the 2D mean distortion of the velocity profile observed in the presence of the FST,<sup>4</sup> which is produced by the nonlinear saturation of the streaks.<sup>5</sup> In this Letter we investigate by direct numerical simulation whether artificially induced streaks are able to completely stabilize TS waves. This could be an effective alternative way to control primary instabilities in boundary layers with low levels of ambient noise.

**Numerical method.** The incompressible 3D Navier–Stokes equations are integrated using a pseudospectral code described in Lundbladh *et al.*<sup>6</sup> The code uses Fourier expansions in the streamwise and spanwise directions and Chebyshev polynomials in the wall-normal direction. The time stepping scheme is a low storage third-order Runge–Kutta method for the nonlinear terms and a second-order Crank–Nicolson method for the linear terms. Dealiasing is used in the streamwise and spanwise directions. Two types of simulations are performed in the present study: in the case of “spatial simulations,” i.e., simulations of non-parallel basic

flows, a fringe region is employed to enforce inflow and outflow boundary conditions in a periodic domain; in the case of “temporal” simulations a volume force is used to keep the basic flow parallel.

**Basic flow.** The basic flows we consider are zero pressure gradient boundary layers with steady, nonlinearly saturated, spanwise periodic streaks of different amplitudes. We use optimal perturbations<sup>7</sup> in order to generate the streaks with minimum input energy. These optimal perturbations consist of vortices aligned in the streamwise direction which, owing to the “lift-up” effect,<sup>8</sup> have the highest potentiality for spatial transient growth.<sup>9,10</sup> As in Ref. 5, the optimal perturbation computed by Andersson *et al.*<sup>9</sup> is used as inflow condition close to the leading edge and its downstream evolution is followed until nonlinear saturation for different initial amplitudes. For the computation of the basic flows we use a box with inlet at  $Re=468.5$  and dimensions of  $1128 \delta_{*0} \times 20 \delta_{*0} \times 12.83 \delta_{*0}$ , in the streamwise, wall-normal and spanwise directions, respectively, where  $576 \times 65 \times 32$  collocation points are used. We denote by  $\delta_{*0}$  the boundary layer thickness at the inlet. The spanwise extension of the domain corresponds to one wavelength of the optimally growing streaks. Denoting by  $x$ ,  $y$ , and  $z$  the streamwise, wall-normal, and spanwise coordinates, respectively, we use the following definition of the streak amplitude:<sup>5</sup>  $A_s(x) = [\max_{y,z}(U - U_B) - \min_{y,z}(U - U_B)]/2U_\infty$ , where  $U_\infty$  is the free stream velocity,  $U_B(x, y)$  is the Blasius solution, and  $U(x, y, z)$  is the streamwise velocity of the streak. We list in Table I the five different cases considered. Case A is nothing but the Blasius boundary layer without streaks. In Fig. 1 we display the evolution of the amplitude of the streaks B, C, D, E versus the Reynolds number  $Re = U_\infty \delta_{*0} / \nu$  based on local boundary

TABLE I. Streak amplitude for the computed basic flows.

| Case | Inlet $A_s$ | Maximum $A_s$ | $A_s$ at $Re=1047$ |
|------|-------------|---------------|--------------------|
| A    | 0.0000      | 0.0000        | 0.0000             |
| B    | 0.0618      | 0.1400        | 0.1396             |
| C    | 0.0927      | 0.2018        | 0.2017             |
| D    | 0.1235      | 0.2558        | 0.2558             |
| E    | 0.1695      | 0.3199        | 0.3174             |

layer thickness  $\delta_*$ . It has recently been shown<sup>5</sup> that optimal streaks with amplitude  $A_s > 0.26$  are subject to secondary inflectional instabilities. Streak E is therefore secondarily unstable.

*Spatial stability.* In the same spirit as Boiko *et al.*,<sup>3</sup> we first test the spatial stability of the computed basic flows to two-dimensional harmonic perturbations of dimensionless frequency  $F = 2\pi f\nu/U_\infty^2$ . The same computational parameters adopted in the evaluation of the basic flows are used in this type of simulation. The perturbation is induced by a two-dimensional time periodic volume force localized at the inlet position, extending up to  $Re \sim 480$ , of amplitude small enough to ensure a linear evolution of the perturbations. The computations were carried on for sufficiently large times to achieve converged time periodic solutions in all the computational domain. In Fig. 2 we show the downstream development of the amplitude, based on the norm  $[\int_0^\infty (u'^2 + v'^2 + w'^2) dy]^{1/2} / 2U_\infty$ , of two-dimensional waves at the frequency  $F = 1.316 \cdot 10^{-4}$  of the forcing. In the Blasius boundary layer (case A) the perturbations decay until they reach branch I of the linear neutral stability curve situated at  $Re = 635$  in the parallel flow approximation. After, they begin to grow until branch II is reached at  $Re = 1000$ . When the basic flow contains a low amplitude streak (case B) an unstable domain still exists but the growth of the TS waves is attenuated in a way similar to that observed in the presence of free stream turbulence.<sup>3</sup> Case C presents a region of marginal stability around  $Re = 750$ , where the streak amplitude is about 0.17. In the case of largest amplitude streaks (case D), the forced TS waves are stable. Similar results apply to forcing frequencies  $F = 1.6 \cdot 10^{-4}$  and  $F = 2.0 \cdot 10^{-4}$ .

*Temporal stability.* In the spatial simulations we considered only some frequencies  $F$  and we forced only 2D perturbations. To verify the behavior of more general 3D perturbations of any frequency, we decided to investigate the temporal stability of the parallel basic flows  $(U(y, z), 0, 0)$

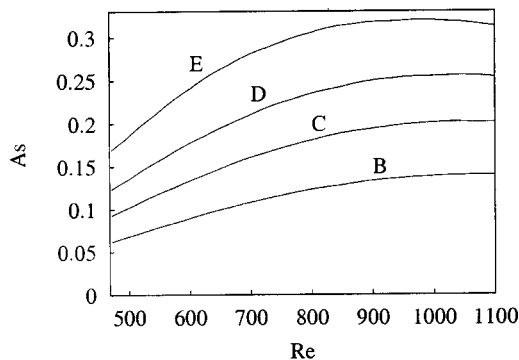


FIG. 1. Streamwise spatial evolution of the amplitude of streaks B, C, D and E.

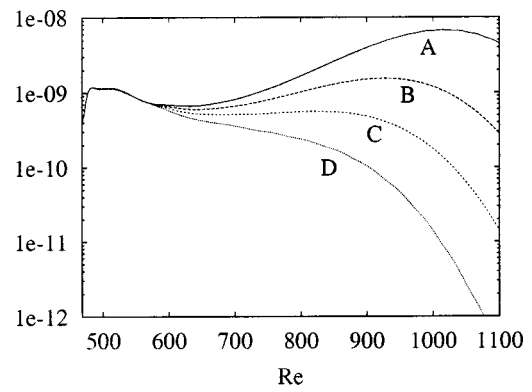
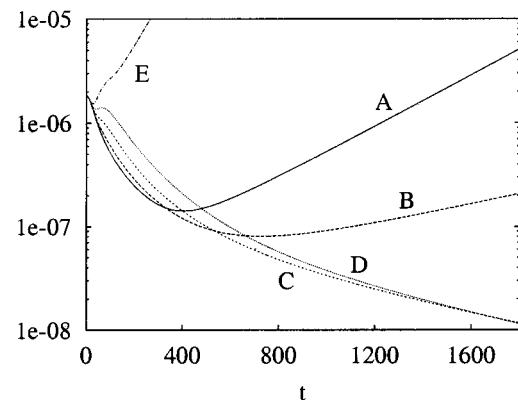


FIG. 2. Spatial evolution of the amplitude of 2D perturbations in the Blasius boundary layer without streaks (case A) and with streaks of increasing amplitude (cases B–D).

obtained by extracting the streak velocity profiles at the streamwise station corresponding to  $Re = 1047$ . As shown in Fig. 1, at that streamwise station the streak amplitude is very slowly varying in the streamwise direction. For this type of simulations, the computational domain measures  $1200 \delta_* \times 9 \delta_* \times 5.74 \delta_*$  in the streamwise, wall-normal and spanwise direction, respectively, where  $1024 \times 97 \times 32$  collocation points are used. In order to consider all the wavenumbers and frequencies at once, we study the flow response to an impulse-like initial condition. This initial condition, already used in other studies,<sup>11–13</sup> is given by  $(u_0, v_0, w_0) = (U, \partial \psi_0 / \partial z, -\partial \psi_0 / \partial y)$  with  $\psi_0 = P_0 \bar{x} \bar{y}^3 \bar{z} e^{-(x^2 + y^2 + z^2)}$ , where  $\bar{x} = (x - x_0) / p_x$ ,  $\bar{y} = y / p_y$ , and  $\bar{z} = (z - z_0) / p_z$ . We use an initial disturbance amplitude  $P_0$  sufficiently small to ensure a linear development of the perturbations and length scales  $p_x = 5 \delta_*$ ,  $p_y = 2 \delta_*$ , and  $p_z = 1.5 \delta_*$  small enough to reproduce a localized impulse within the limits of a good resolution in the truncated spectral space of our numerical simulations. In order to avoid any particular spanwise symmetry of the solution, the initial disturbance is centered off-axis, around  $z_0 = -2 \delta_*$ . The temporal evolution of the rms perturbation kinetic energy  $E$ , integrated over the whole computational domain, is shown in Fig. 3. Since all the modes are excited by the initial condition, any unstable mode would emerge after an initial transient. The Blasius boundary layer (case A) is linearly unstable at  $Re = 1047$  and TS waves

FIG. 3. Temporal evolution of the rms perturbation energy at  $Re = 1047$  for the Blasius boundary layer without streaks (case A), and with streaks of increasing amplitude (cases B, C, D, and E).

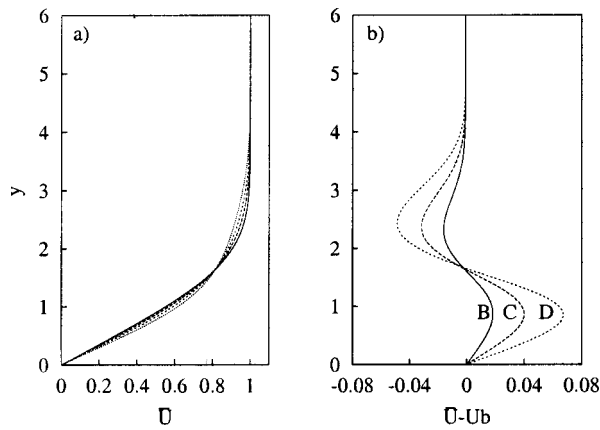


FIG. 4. (a) Spanwise averaged streamwise velocity profiles  $\overline{U}(y)$ , at  $Re = 1047$ , of the Blasius boundary layer (solid line) and of the streaky boundary layers B, C, and D. (b) Corresponding spanwise averaged basic flow distortions  $\Delta\overline{U}(y) = \overline{U}(y) - U_B(y)$ .

emerge clearly at times  $t > 600$ ; the perturbation growth is exponential, with values in agreement with the results of the linear Orr–Sommerfeld analysis. The low amplitude streak (case B) is also unstable but with a lower amplification rate. Streaks with larger amplitude (cases C and D) are stable and, after the initial transient, perturbations decay for large times. A too large amplitude of the streaks (case E), however, leads to inflectional instability.<sup>5</sup>

*Interpretation.* We now try to isolate the mechanism responsible for the observed stabilization of the Blasius boundary layer. The basic flow distortion  $\Delta U(y, z) = U(y, z) - U_B(y)$  can be separated into its spanwise averaged part  $\overline{\Delta U}(y)$  and its spanwise varying part  $\overline{\Delta U}(y, z) = \Delta U(y, z) - \overline{\Delta U}(y)$ . Note that nonlinear effects are essential to generate  $\overline{\Delta U}(y)$ . In Figs. 4(a) and 4(b) we reproduce the spanwise averaged velocity  $\overline{U}(y) = U_B(y) + \overline{\Delta U}(y)$  of the basic solutions at  $Re = 1047$  and the corresponding  $\overline{\Delta U}(y)$ . It can be seen how the increase of the streak amplitude leads to fuller  $\overline{U}$ -profiles and should thus have a stabilizing effect on the TS waves.<sup>3</sup> On the other hand, the term  $\overline{\Delta U}(y, z)$  leads to velocity profiles which, based on a 2D local stability analysis,<sup>14</sup> are more unstable, at some spanwise stations  $z$ , than the Blasius profile. The results of the complete 3D stability analysis, displayed in Fig. 3, may be interpreted as follows: without streaks (case A), the Blasius profile is unstable to TS waves due to a viscous instability. Low amplitude streaks (case B) are neither able to stabilize the viscous instability with  $\overline{\Delta U}(y)$ , nor to create, with  $\overline{\Delta U}(y, z)$ , shears strong enough to support fully 3D inflectional instabilities. For moderate streak amplitudes (cases C and D),  $\overline{\Delta U}(y)$  is able to completely stabilize the flow but, for too large amplitudes (case E) the term  $\overline{\Delta U}(y, z)$  supports inflectional instabilities and the basic flow becomes unstable again. To confirm this interpretation we performed 3D temporal simulations for the artificial basic flows  $\overline{D}$  and  $\overline{D}$  obtained by considering only the spanwise varying or the spanwise uniform part of the basic flow distortion, i.e.,  $U_{\overline{D}} = U_B + \overline{\Delta U}$  and  $U_{\overline{D}} = U_B + \overline{\Delta U}$ . The temporal evolutions of the rms perturbation energies pertaining to these basic flows and to the complete streak D are

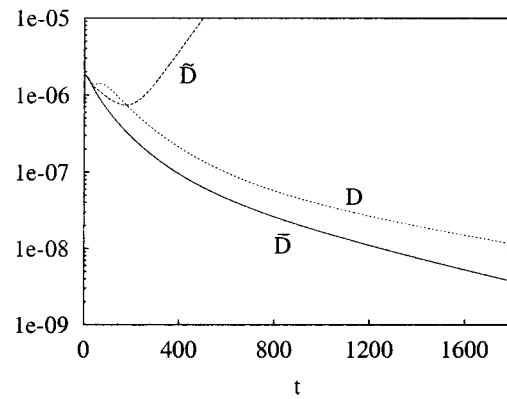


FIG. 5. Temporal evolution of the rms perturbation energy at  $Re = 1047$  for the complete streak D and for the artificial basic flows  $\overline{D}$  and  $\overline{D}$ .

displayed in Fig. 5; the figure reveals both the destabilizing role of  $\overline{\Delta U}(y, z)$  and, more importantly, the dominating stabilizing action of  $\overline{\Delta U}(y)$ , to which the global stabilization of TS waves can finally be attributed. The same result applies to case C.

*Boundary layer control.* We have shown that it is possible to modify an unstable Blasius boundary layer into a stable streaky flow introducing streamwise vortices near the leading edge. The “actuator” input energy is minimized by the choice of an optimal forcing and is of  $O(1/Re)$  when compared to the streak energy.<sup>9,10</sup> Moreover, it was recently observed<sup>5</sup> that the steady saturated streaks induced by the optimal vortices maintain an almost constant amplitude for a large distance downstream. The stabilization is obtained, in open loop, through a modification of the basic flow induced by actuators situated upstream of the unstable domain. The local skin friction coefficient of the streaky flow is increased, at worst, by less than 20%, compared to the Blasius boundary layer. We tested this control strategy for Reynolds numbers up to 1047 for a fixed spanwise periodicity of the streaks. For larger Reynolds number probably larger streak amplitudes would be necessary to achieve stabilization. The maximum allowed amplitude is however limited by the appearance of secondary instabilities on the streaks. We are therefore currently identifying stabilizing streak amplitude thresholds for a wider range of Reynolds numbers and of spanwise wavelength.

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