ON A MECHANISM OF DELAYING LAMINAR-TURBULENT TRANSITION

Hui Xu, & Spencer J. Sherwin
Department of Aeronautics, Imperial College London, London SW7 2AZ, UK

Abstract In this paper we investigate the boundary layer flows over a flat plate on which smooth localized imperfections are located. The localized imperfections have the width scale (d) comparable with the wavelength (λ_{TS}) of the Tollmien-Schlichting (T-S) waves and the height scale (h) less than the boundary layer thickness δ_{99}. The existence of the localized imperfection gives rise to the change of the instability property of the boundary layer. The investigations are focused on the interaction between the T-S waves and the base flows distorted by smooth forward-facing steps and aim to forge links between the localized imperfections and the mechanisms of stabilizing the T-S waves. Numerical investigations show that isolated smooth forward-facing steps can perform as a robust strategy of delaying laminar-turbulent transition. Finally, direct numerical simulations are implemented to validate the strategy.

BACKGROUND & MOTIVATION

In environments with low levels of disturbances such as free flight, boundary layer laminar-turbulent transition is initiated by the exponential amplification of the Tollmien-Schlichting (T-S) waves followed by secondary instabilities and subsequent breakdown as the amplitude of the primary instability is up to the order of 1% of the freestream velocity magnitude [9, 3]. The process of laminar-turbulent transition is subdivided into three stages: receptivity, linear eigenmode growth and nonlinear breakdown to turbulence. If the growth of the T-S waves could be reduced or completely suppressed and providing that no other instability mechanism comes into play, transition could be postponed or even eliminated [5].

Over the past two decades, a large mount of researches have been devoted to the study of the T-S waves' stabilization. In the presence of unsteady and randomly distributed steaks, the T-S waves are stabilized in mean flow when their amplitudes are small [2]. If the streaks reach a critical amplitude, bypass transition is triggered [12]. Numerical simulations and stability analysis were subsequently done to address the effect of streaks on the T-S waves. It is found that narrow spanwise modulations of the boundary layer thickness, the so-called streak, can stabilize the low amplitude T-S waves [3, 4]. Experimentally, it is showed that steady and stable streaks of moderate amplitude can be induced by generating nearly optimal vortices with cylindrical roughness elements placed near the leading edge and proved that these streaks have a stabilizing effect on the T-S waves [6, 7]. Correspondingly, more evidences were offered to show that well-designed roughness can reduce the viscous drag [8]. And the transition delay can be attributed to the reduction of the exponential growth of the T-S waves in the presence of streaks, and to the absence of strongly destabilizing nonlinear interaction between two types of perturbations. It should be pointed out that none of them, except Fransson *et al.* [8], has successfully shown transition delay. The passive flow control method should guarantee that bypass transition is not activated by the instability of the streak or the receptivity of an incoming T-S wave by the roughness array. Shahinfar *et al.*[14] showed that classical vortex generators, known for their efficiency in delaying or even inhibiting boundary layer separation, are really effective in delaying transition. However, in the presence of miniature vortex generators (MVGs), the T-S waves are being generated upstream, leaving a receptivity process of the incoming wave of the MVG array, which challenges the passive flow control method. Beyond the above strategies, there exist several other approaches to stabilizing the T-S waves have been studied in the past such as wall suction [10], Lorentz force actuators [1], plasma actuators [13]. In this paper, a simple stabilization strategy is studied based on smooth forward-facing steps. We consider that the height scale for smooth forward-facing steps is smaller than the boundary layer thickness and analyse effects of multiple smooth forward-facing steps on the T-S waves. By the present numerical work, we observed that surprisingly, stabilizing T-S waves by smooth forward-facing steps performs well as a robust strategy.

SOME RESULTS

Direct numerical simulations (DNS) with the full Navier-Stokes equations and the linearised Navier-Stokes equations are employed to study the linear and non-linear interaction between the distorted base flows and the T-S waves. Nektar++ is used to carry out the calculations. For three dimensional (3D) non-linear calculations, the spanwise direction is assumed to be periodic and is treated by Fourier modes to reduce computational cost. A stiffly stable splitting scheme developed by [11] is adopted which decouples the velocity and pressure fields and the second-order implicit-explicit (IMEX) scheme is used for time integration. In Figure 1, the linear results are given to show that two isolated steps can stabilize the Tollmien-Schlichting waves and the transmitted behaviours are presented to describe the stabilization performance quantitatively. In Figure 2, the instantaneous iso-surfaces by Q-Criterion are illustrated which are coloured by the streamwise velocity for K-type transition. It is clear that by two smooth steps, the laminar-turbulent transition is prohibited.

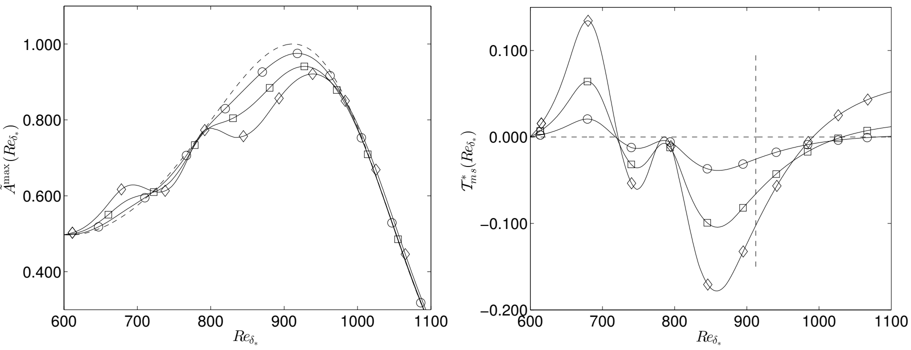

Figure 1. Results of linear analyses: (Left) Envelopes of Tollmien-Schlichting waves; (Right) Behaviours of transmitted Tollmien-Schlichting waves

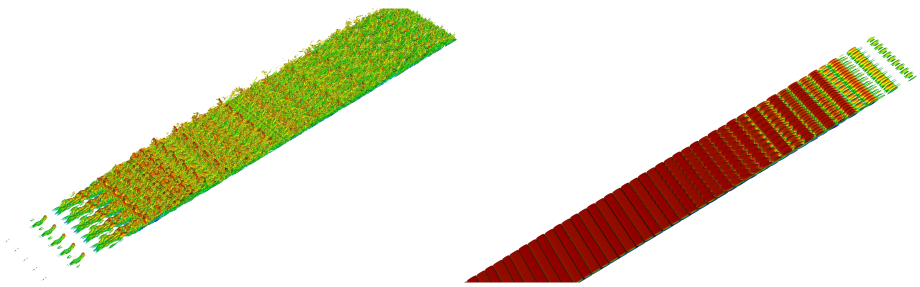

Figure 2. Instantaneous iso-surfaces by Q-Criterion; (Left) with control strategy; (Right) with control strategy.

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