FULLY LOCALISED EDGE STATES IN BOUNDARY LAYERS

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Abstract Investigation of the laminar–turbulent boundary is performed in a boundary-layer flow. Constant homogeneous suction is applied at the wall in order to prevent the spatial growth of the layer, leading to the parallel Asymptotic Suction Boundary Layer (ASBL). Edge tracking is performed in a large computational domain allowing for full spatial localisation of the structures on the laminar–turbulent separatrix. The obtained dynamics of the state goes through calm and bursting phases. During the latter the structure grows in size, shedding vortices downstream of its core which viscously decay during the calm phases. Comparison with the computation in spatially growing boundary layer is made. The influence of the Reynolds number and the path leading from the edge state to turbulent flow are considered.

INTRODUCTION

Transition to turbulence leads to dramatic losses in energetic efficiency and has a profound influence on design strategies in aerodynamics, ship hydrodynamics, transport in pipelines, etc. Thus understanding turbulence and the processes leading from the laminar to turbulent regime are of tremendous importance. Lately, a stimulating breakthrough occurred when researchers started to borrow tools from deterministic chaos theory and dynamical systems, aided by the on-going progress of computer simulations.

Of special interest for both theory and control applications is the intrinsically nonlinear concept of "edge states": nonlinear flow structures living at the dynamical border between laminar and turbulent flow [6]. These vortical structures are exact equilibria of the Navier–Stokes equations. They are relative attractors within the laminar–turbulent boundary and can be simple objects, like fixed points or periodic orbits, or more complicated chaotic structures. In all cases they serve as an example of simple dynamics in the high-dimensional system. As such they can be used for understanding the mechanisms of the sustained non-trivial flow behaviour. In addition, being saddles of the system, they guide the evolution of the flow going towards turbulence. The ones that are localised in space are thought as the precursors of turbulent spots observed in transitional flows.

Recently, the edge states concept was applied to the Blasius boundary-layer flow over a flat plate [1]. There the additional complication is the spatial growth of the boundary layer, which makes the proper asymptotic dynamics inaccessible. This problem can be circumvented by applying suction at the plate which counteracts the spatial growth. If the suction is constant and homogeneous the boundary-layer thickness saturates and the associated flow is known as the Asymptotic Suction Boundary Layer (ASBL) [5].

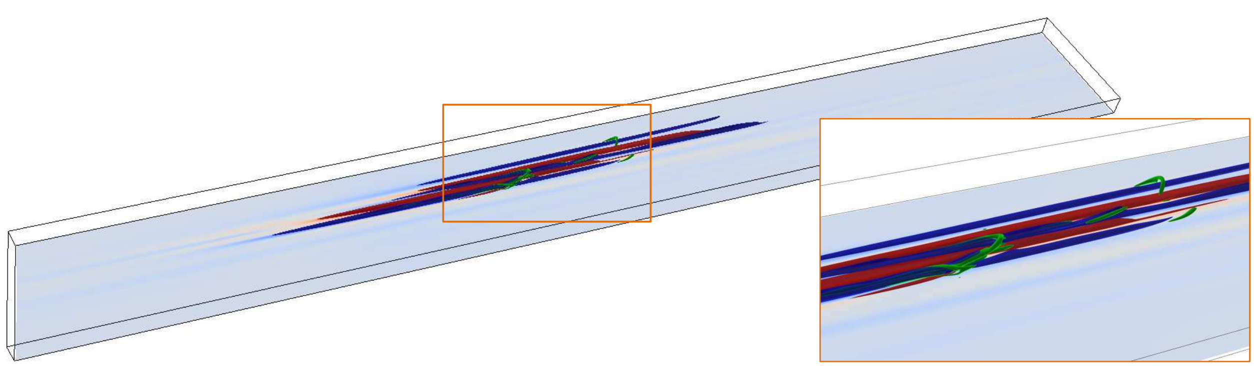

Figure 1. Three-dimensional visualisation of the fully localised edge state in ASBL at $Re = 500$. The low- and high-speed streaks are represented with blue and red isosurfaces, respectively, and the vortices are visualised using the λ_2 criterion [2] with green. Flow from lower left to upper right. The full computational domain is shown.

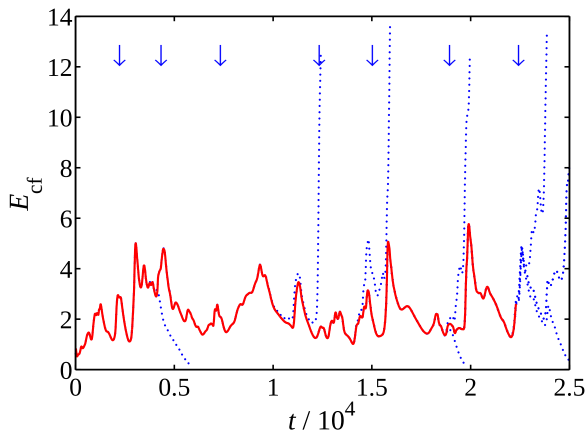

Figure 2. Time evolution of the cross-flow energy E_{cf} on the edge for $Re = 500$ is shown with the red line. The blue dotted lines represent individual trajectories diverging from the edge and going either turbulent or turbulent. The blue arrows indicate the positions where refinements of the edge trajectory were made. The time is given in units of δ^*/U_∞, where U_∞ is the free-stream velocity.

FULLY LOCALISED EDGE STATES IN THE ASYMPTOTIC SUCTION BOUNDARY LAYER

Studies on edge states in geometrically constrained computational domains [4] usually focus on temporal degrees of freedom, but are not able to explain experimentally observed large scale spatial phenomena such as early development of turbulent spots and spatio–temporal intermittency. Calculation in a spanwise extended box [3] has shown localisation properties in the spanwise direction. Thus the emphasis is now on the full spatial localisation of the structures on the edge of chaos, which requires large computational domains.

We perform edge tracking in domain of size $[L_x, L_y, L_z] = [800\delta^*, 15\delta^*, 100\delta^*]$ using the fully spectral code with a DECI awarded allocation, as each flow field has 200 million grid points. Here δ^* is the laminar boundary-layer displacement thickness. In this configuration the structure on the edge remains completely localised in both streamwise and spanwise directions. It consists of several pairs of low- and high-speed streaks (see figure 1). Similarly to the edge states in constrained domains the state goes through calm and bursting phases. This can be seen in figure 2, where the cross-flow energy

$$E_{\mathrm{cf}} = \int_\Omega (v'^2 + w'^2)\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\ , \tag{1}$$

measuring the strength of the vortices is shown. In calm phases streamwise vortices develop on one of the low-speed streaks with the other streaks slowly decaying. However as the vortices grow in strength, they break the active streak, creating a large number of vortical structures. This corresponds to the burst in the energy. These vortices regenerate new streaks and decay while being advected downstream from the core of the structure. This is reminiscent to the quasi-cyclic behaviour on the edge observed in the spatially developing edge state [1]. Thus, while being a chaotic structure the state still experiences qualitatively recurrent behaviour.

The final contribution will include the study of the effect of the Reynolds number and the path leading from the edge state to the spatially filling turbulence.

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