A MECHANISM FOR GENERATING A PACKET OF HAIRPINS - COMPARISON BETWEEN MODEL AND EXPERIMENTAL RESULTS

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Summary In this work we propose a simple mechanism, consisting of minimal flow elements, required for generating a packet of hairpin vortices. A theoretical-based numerical model is introduced and its results are successfully compared with experiments conducted in a pipe flow apparatus. The proposed scenario seems to be universal and may explain similar observations both during the late-stages of by-pass transition as well as in fully developed wall-bounded shear flows.

INTRODUCTION

In recent years it has become evident that the building blocks of wall-bounded turbulent shear layers are very similar to those observed during the late-stages of the transition process. In particular hairpin-shaped vortices, counter-rotating vortex pairs (CVPs) and streaks seem to dominate the flow. The identification of the same kind of coherent structures as part of the bypass transition and in fully developed turbulent shear flows (e.g. [1-2]) suggests that the mechanism responsible for self-sustaining process in fully developed turbulent shear flows may be very similar to those acting in the late-stage of transition.

The purpose of the present study is to propose a universal mechanism having minimal flow elements required for the generation of packets of hairpins in shear flows.

A SIMPLE THEORETICAL-BASED NUMERICAL MODEL

In order to understand the key mechanisms leading to the formation of packets of hairpins we have employed our recent developed theoretical-based method [3] which is capable of following (numerically) the evolution of finite amplitude localized (and/or periodical) vortical disturbances embedded in simple shear. The solution is carried out using Lagrangian variables in Fourier space which is convenient and enables fast computations on a regular PC.

Using this method we have shown that a sufficiently strong finite-amplitude localized vortex embedded in simple shear evolves into a single hairpin vortex whereas an elongated initial vortex can lead to formation of two (at most) hairpins at both streamwise ends of the initial vortex. Thus, streamwise variation of a long CVP is required to generate a packet of hairpins. This is accomplished by superimposing an inviscidly unstable spanwise vortex sheet which together with the lift-up by the induced velocity (of the CVP) and shear of the base flow generates packets of hairpins.

COMPARISON WITH PIPE FLOW EXPERIMENTS

In order to demonstrate the universality of the mechanism the (Cartesian) model results are compared to pipe flow experiments where a jet of water is injected perpendicularly to the pipe wall. The pipe flow facility, standing vertically, consists of two flow circuits, one for base flow and another one for disturbance. For the base flow, water is stored in an overhead tank and passes through a honeycomb and then through a smooth converging nozzle before entering the circular glass pipe having an inner radius (R_0) of 0.98 *cm*, and a total length of 230 R_0. Water exits the pipe at the bottom into a damper and then to a temperature controller. The circuit is closed by the peristaltic motor which pumps the water back into the overhead tank.

The disturbance flow is an open loop facility, wherein a water soluble dye is mixed with water and held in a small overhead tank. The mixture is injected into the base flow through a hole (with diameter of 0.8 *mm*) at a downstream distance of about 114 R_0, where the flow is close to fully developed. Flow visualization is accomplished by using a digital camera and a strong incandescent light source. Two perpendicular views of coherent structures are obtained at the same time on the camera by fixing an inclined mirror close to the pipe.

Two nondimensional parameters govern the flow: the Reynolds number (Re) and the injection velocity (Vinj) normalized by the pipe centreline velocity). In figure 1a and b, top and side views of the generated packet are shown, respectively for flow conditions of Re=2500 and Vinj =0.7. The model parameters are adjusted accordingly: the thickness of the CVP and the streamwise wavelength are estimated from flow visualization, the shear of the base flow is taken as the average shear in the cross-section of the pipe and the magnitude of the initial streamwise CVP is estimated from the injection conditions. The corresponding results of the model are shown in figure 1c and d. Finally, a 3D view of the simulated packet is presented in figure 1e.

References

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[1] Svizher, A., Cohen, J. : Holographic particle image velocimetry measurements of hairpin vortices in a subcritical air channel flow. *Phys. of Fluids.* **18**: 014105, 2006.
[2] Wu,X.,Moin,P.:Direct numerical simulation of turbulence in a nominally-zero-pressure gradient flat-plate boundary. *J. Fluid Mech* **630:**5-41, 2009
[3] Cohen, J., Shukhman, I.G., Karp. M., Philip. J.: An analytical-based method for studying the nonlinear evolution of localized vortices in plannar homogenous shear flows. *J. Comp. Phys.* **229:**7765-7773, 2010.

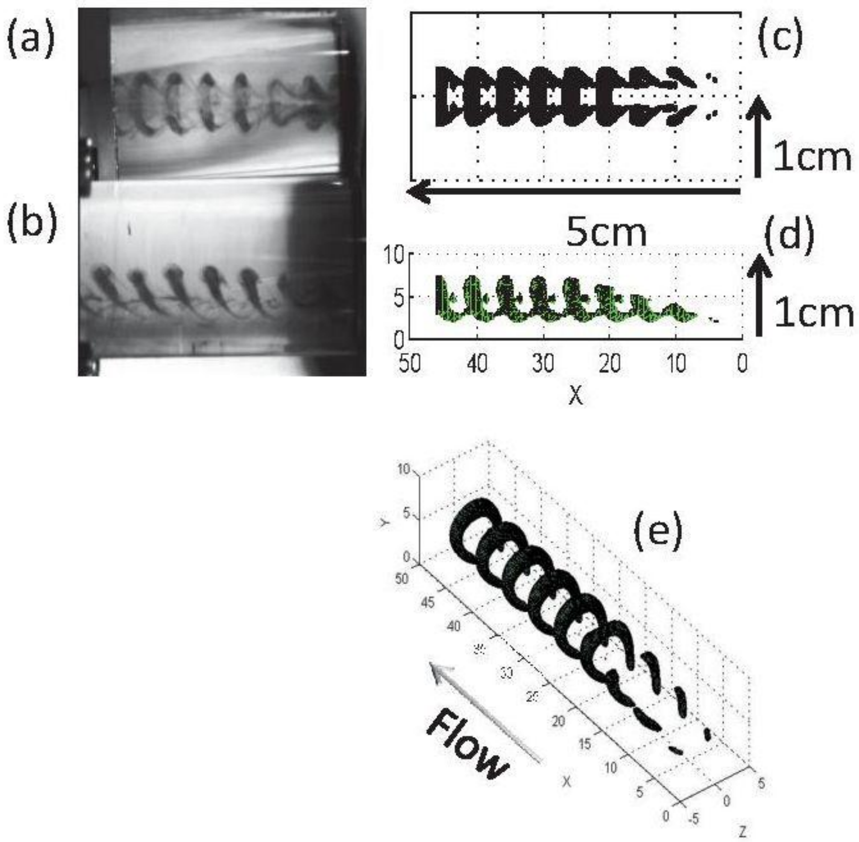

Figure 1: Generation of a packet of hairpins. (a) and (b) top and side views of pipe flow experiments for Re=2500 and Vinj=0.7; (c) and (d) corresponding numerical results using our theoretical-based model; (e) a 3D view of the packet.