The evolution of key coherent structures in homogenous shear flows

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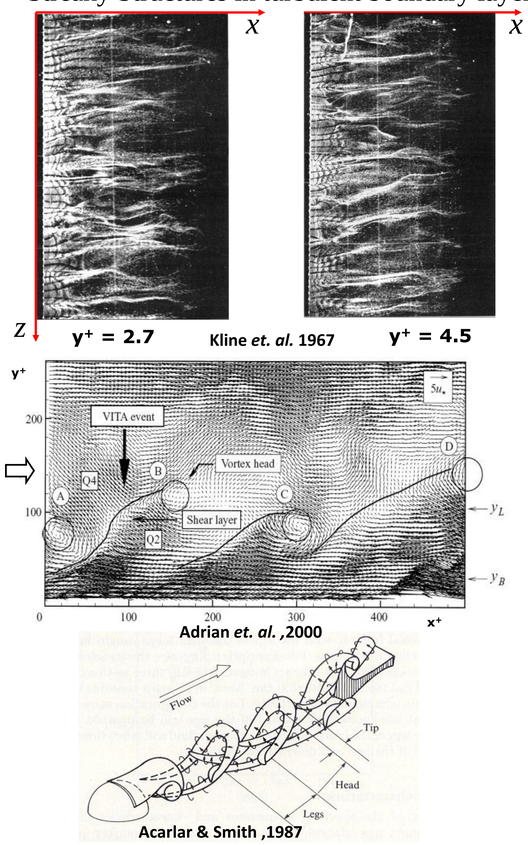
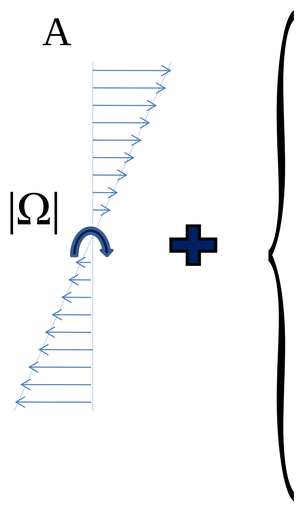
Coherent Structures

Turbulent shear flows are governed by well-organized coherent structures. The structures appear also during several transition scenarios. Our aim is to present a model for their formation.

Streaky Structures in turbulent boundary layer





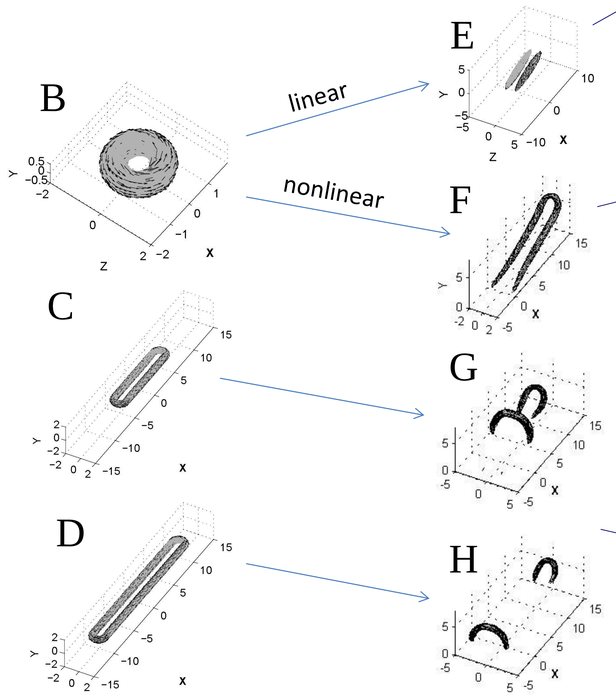


Figure 1. Coherent structures in turbulent boundary layers
Top: Streaky structures along the streamwise direction, near the wall
Middle: 4 hairpins organized in the streamwise direction
Bottom: Illustration of a packet of hairpins generated by a hemispherical bump

Figure 2. Interaction between homogenous shear and localized disturbances

Mathematical Method

Due to the localization of the disturbance the flow is assumed to have a linear dependence on the coordinates (first term in the Taylor series expansion), i.e. the baseflow contains homogenous shear:

$$\vec{V}=\left(-\tfrac{1}{2}(\Omega+\sigma)\,y,-\tfrac{1}{2}(\sigma-\Omega)\,x,0\right)\ ,\ \vec{\Omega}=(0,0,\Omega)$$

Using Fourier transform and Lagrangian variables, the disturbance vorticity equation is transformed to a set of ordinary differential equations, which are solved numerically using Euler's method (detailed in Cohen *et. al.* 2010). The solution is obtained within minutes on a standard computer.

Counter Rotating Vortex Pairs (CVPs)

Pair of elongated streamwise vortices, generating streaks of high/low velocity.
<u>Our model</u>: linear interactions between shear and localized disturbance.

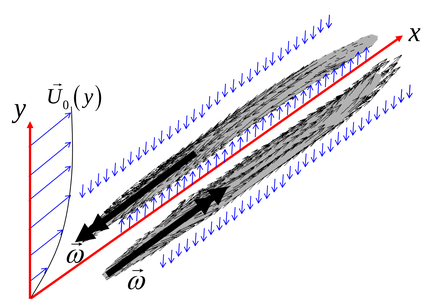


Figure 3. Counter Rotating Vortex Pair (CVP)

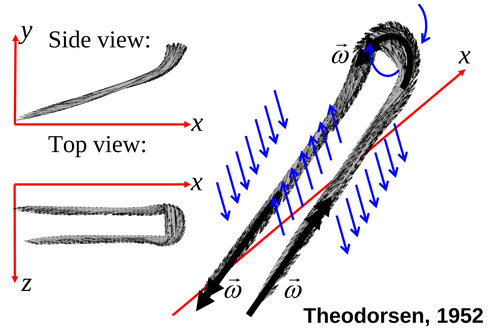


Figure 4. Hairpin (horseshoe) vortex

Theodorsen, 1952

Hairpins

Its associated velocity field consists of an upstream and outward induced velocity between the hairpin 'legs' and vortex flow around its 'head', resulting in significant mixing which is a major characteristic of turbulent shear flows.
The hairpin is inclined at 45° to the main flow and therefore can act as a pump transporting momentum in the cross-flow direction.
<u>Our model</u>: nonlinear interactions between shear and localized disturbance (sufficiently high initial magnitudes).

Two Hairpins

Elongated disturbances lead to 2 hairpins → hairpins result from streamwise variation.

Packet of Hairpins

<u>Our model</u>: replacing the elongated disturbance by the combination of a CVP and a wavy spanwise vortex sheet.
Verified with pipe flow experiment.

Summary

A simple universal model explaining the formation of coherent structures has been developed and verified successfully with experiments.

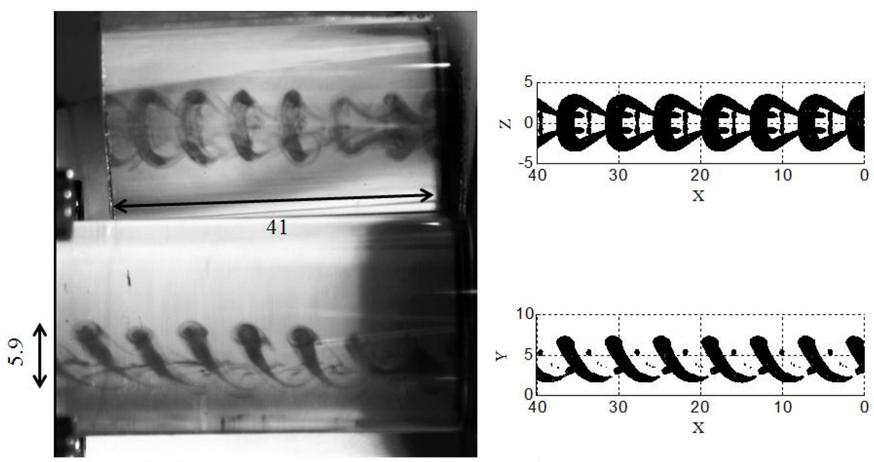


Figure 5. Comparison between a packet of hairpins generated in pipe flow experiment using cross-stream jet injection and our model

Acknowledgments

This research is supported by the Israeli Science Foundation under Grant No. 1394/11.

References

Cohen, J., Shukhman, I.G., Karp, M., and Philip, J., "An analytical-based method for studying the nonlinear evolution of localized vortices in planar homogenous shear flows", J. of Computational Physics, Vol. 229 (20), 2010, pp. 7765-7773