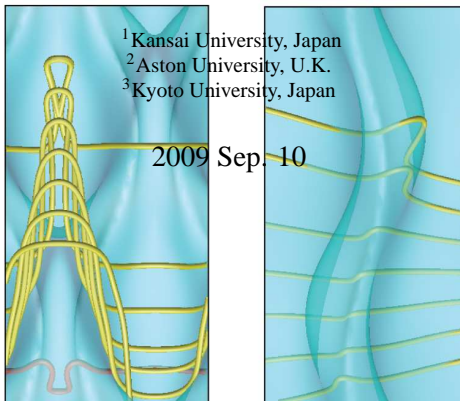


Symmetry of Coherent Vortices in Plane Couette Flow

著者	Itano Tomoaki, Generalis Sotos C., Fletcher John, Toh Sadayoshi
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Symmetry of Coherent Vortices in Plane Couette Flow

T. Itano¹, S. C. Generalis², S. Toh³, J. P. Fletcher²



Hairpin-shaped vortex

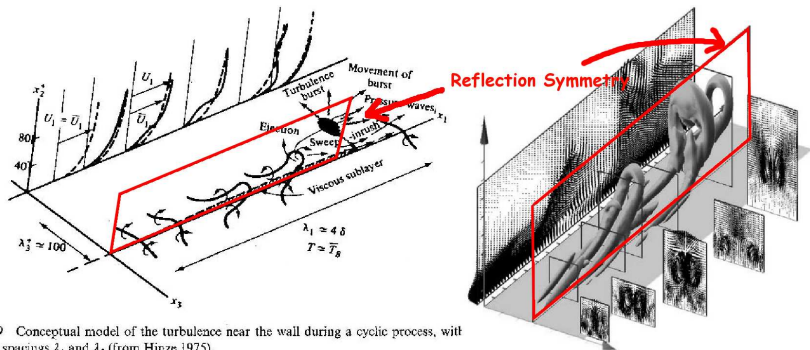


Figure 9 Conceptual model of the turbulence near the wall during a cyclic process, with average spacings λ_1 and λ_2 (from Hinze 1975).

Hinze(1975)

Adrian(2000)

- 1 one of predominant structures in wall-bounded flows
- 2 modification of shape / reflection symmetry in common

Motivation

- 1 Exact solution of plane Couette flow (PCF)

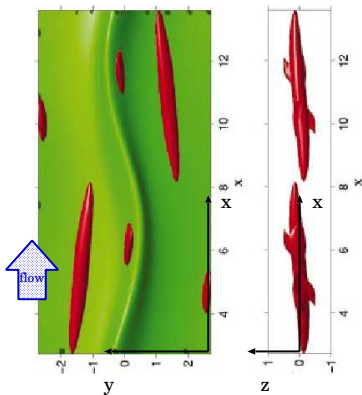
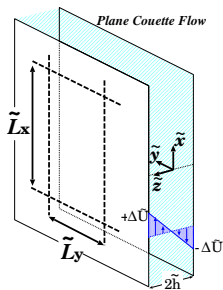


Figure: Waleffe (2003), meandering streak, $Re_{\min} = 127$

hairpin-vortex type solution exists in PCF ?

Formulation

1 configuration



2 steady / nondimensionalised equation

$$\nabla \cdot \mathbf{u} = 0, \quad (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u},$$

$$\mathbf{u}(x, y, z = \pm 1) = \pm \mathbf{e}_x,$$

periodic b.c. in x (streamwise), y (spanwise) directions.

3 Galerkin-method with Fourier and modified Chebyshev expansion

historically : The well-known solution of PCF

- Nagata(1990), Clever & Busse(1997), Waleffe(1998) → “NBW”
- Kawahara & Kida(2001) : periodic sol. embedded in turbulence
- Gibson et al.(2008), Halcrow et al. (2009)

for comparison re-calculation, one vortex line = a hairpin ?, explot !

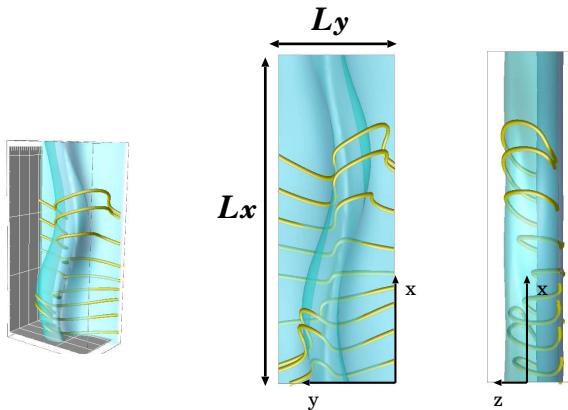


Figure: NBW at $Re = 200$ (u.b.)

new result : Hairpin vortex solution (HVS)

- Schmiegel(1999)
- I. and Generalis(2009)
- Gibson et al.(2009)

reflection symmetry \rightarrow hairpin (bundle of vortex lines)

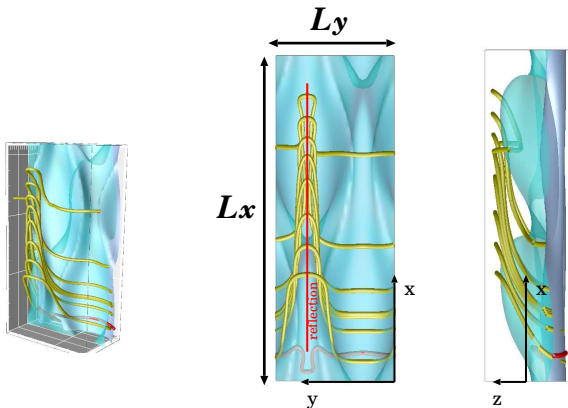
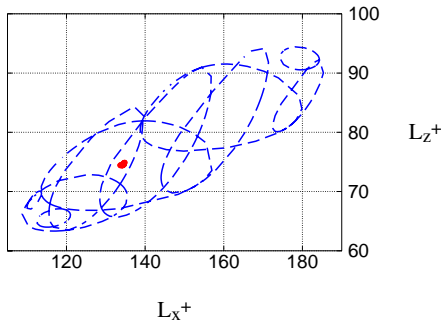


Figure: HVS at $Re = 200$ (u.b.)

#1. Streamwise and spanwise extents in wall units

streak characteristic spanwise extent $L_z^+ = 100$?

Re=139 •
Re=147 - -



- 1 $L_z^+ \approx 75$ at the minimum Reynolds number $Re_{\min} = 139$
- 2 Island HVS exists abruptly spreads out with Re increasing

#2. Multiple scales in HVS

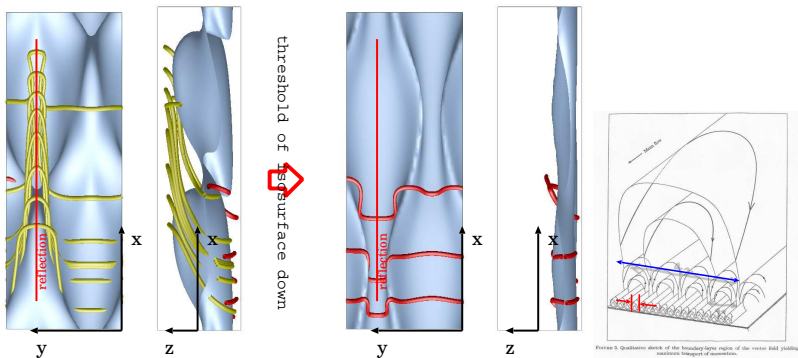


Figure: (left) $u = -0.1$ a single kink $\rightarrow u = -0.4$ two kinks ,
(right) Busse (1970)

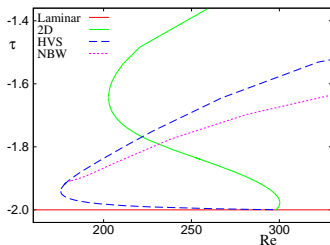
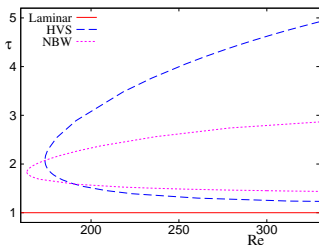
related to hierarchy of structures in turbulence ?

#3. Bifurcation of NBW from HVS

Extending the system with a parameter ϵ ($0 \leq \epsilon \leq 1$)

$$\begin{aligned}\nabla \cdot \mathbf{u} &= 0, \\ (\mathbf{u} \cdot \nabla)\mathbf{u} &= -\nabla p + \frac{6\epsilon}{Re} z \mathbf{e}_x + \frac{1}{Re} \nabla^2 \mathbf{u}. \\ \mathbf{u}(x, y, z = \pm 1) &= \pm(1 - \epsilon)\mathbf{e}_x.\end{aligned}$$

PCF : $\epsilon = 0 \rightarrow \epsilon = 1$



NBW (quaternary branch, pink) bifurcates from HVS (tertiary branch, blue) at $\epsilon = 1$ via the breaking of a reflection symmetry.

Summary

- 1 hairpin vortex solution of PCF
- 2 down to $Re_{\min} = 139$ in high resolution, $L_z^+ = 75$
- 3 Scale hierarchy of structures in HVS
- 4 NBW (derivative) bifurcates from HVS (primitive)

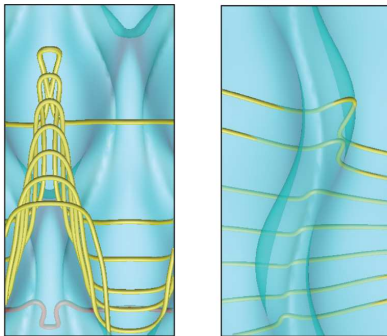


Figure: left: HVS , right: NBW