Euromech Colloquium 568

Coherent structures in fully developed turbulence

Polytechnic University of Madrid

School of Aeronautics

May 20-22, 2015

EUROPEAN MECHANICS SOCIETY

May 20. 9:00-19:00			
9:00-9:05	**Welcome and opening remarks.** J. Jiménez		
Invariant solutions I: Late transition and turbulence. **CHAIR: J. Gibson**			
9:05-9:40	S. Rawat, C. Cossu, Y. Hwang, F. Rincon	Toulouse/ Imperial	Exact coherent solutions for the filtered large scale motions in turbulent Couette flow
9:40-10:15	K. Deguchi, P. Hall	Imperial	Free-stream coherent structures
10:15-10:50	P. Hall, K. Deguchi	Imperial	Vortex-wave interactions in shear flows: classification and stability properties of solutions.
10:50-11:15	**Coffee break**		
11:15-11:50	D. P. Wall, M. Nagata	Tianjin/Oita	A localized exact coherent traveling wave in channel flow
11:50-12:25	A. Sekimoto, S. Dong, J. Jiménez	UP Madrid	Invariant solutions in homogeneous shear flow
12:25-13:00	S. Zammert, B. Eckhardt	U. Marburg/ Delft	Exact coherent structures in plane Poiseuille flow at high Reynolds numbers
13:00-14:30	**Lunch**		
Invariant solutions II: Transition. **CHAIR: M. Nagata**			
14:30-15:05	S. Altmeyer, A. Willis, F. Mellibovsky, B. Hof	IST Austria /Sheffield/UP Catalunya.	Streamwise-localized solutions with natural 1-fold symmetry
15:05-15:40	M. Avila, P. Ritter, F. Mellibovsky	Erlangen/ UP Catalunya	Coherent structures and spatiotemporal fluctuations in pipe flow
15:40-16:15	J. F. Gibson, E. Brand, T. Schneider	U. New Hampshire/ EPF Laussane	Localized exact coherent structures in plane Couette and plane Poiseuille flow
16:15-16:45	**Coffee break**		
16:45-17:20	B. Hof	IST Austria	Onset of fully turbulent pipe flow
17:20-17:55	T. Kreilos, T.M. Schneider	Laussane	Localized wall-mode and free-stream coherent structures in the asymptotic suction boundary layer
17:55-19:00	**General discussion.** **CHAIR: M. Avila**		

EXACT COHERENT SOLUTIONS FOR THE FILTERED LARGE SCALE MOTIONS IN TURBULENT COUETTE FLOW

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We investigate the nature of large-scale motions (LSM) in turbulent Couette flow. It is first shown that large-scale motions are self-sustained by verifying that they survive even when active processes at smaller scales are artificially quenched (see figure 1) in over-damped large eddy simulations as in [1, 2]. We then investigate the nature of the self-sustained large-scale motions by looking for exact solutions of the *filtered*, possibly over-damped, (LES) equations. The edge state of coherent large-scale motions is computed by edge-tracking and is found to be a non-trivial exact steady solution of the filtered equations. Newton-Krylov iterations are used to prove convergence of the steady solution and to perform parameter-continuations. By continuation to higher values of the over-damping it is shown that the lower branch edge state is connected to an upper branch solution via a saddle-node bifurcation. We have been able to compute upper branch solutions of the filtered equations at Reynolds numbers up to $Re = 2150$ using specific paths in the Reynolds number-overdamping parameter plane (see figure 2). These solutions are then continued to Navier-Stokes solutions by reducing to zero the residual stress in the LES. It is finally shown that the steady large-scale solutions of the filtered equations motions can be connected by continuation to the Nagata-Clever-Busse-Waleffe solutions of the Navier-Stokes equations.

Financial support from PRES Université de Toulouse and Région Midi-Pyrénées is kindly acknowledged.

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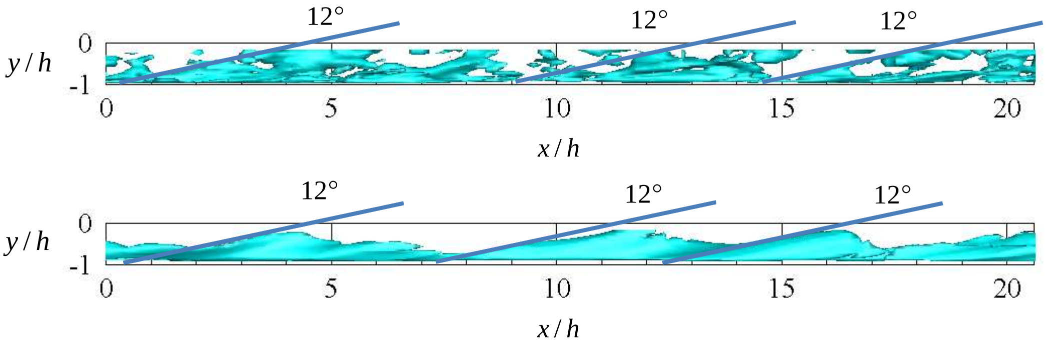

Figure 1: *Side view of snapshots of the low velocity fluctuations for the reference (top panel) and the over-damped (bottom panel) large-eddy simulations of turbulent Couette flow at Re* $= 2150$*. In the reference simulations small-scale motions are still active while they are quenched in the over-damped simulation. The surviving large-scale motions are very similar to the well-known natural ones and display the usual ramp structure observed also in other flows.*

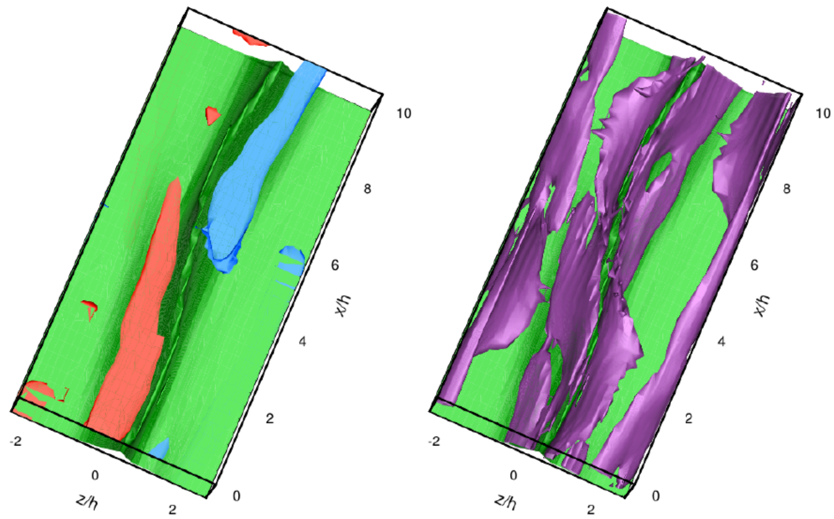

Figure 2: *Visualisation of the upper branch large-scale (LSM) steady solutions of the filtered equations (LES) obtained at Re=2150 (*$Re_\tau = 127$*). The left panel represent the large-scale coherent (i.e. filtered) streaks and quasi-streamwise vortices while the right panel shows the relative eddy-viscosity associated to the residual small-scale motions (the violet surface corresponds to* $\nu_t/\nu = 40\%$*).*

FREE-STREAM COHERENT STRUCTURES

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We first report a new kind of exact coherent structure which sits at the edge of an asymptotic suction boundary layer [1]. At a large distance from the wall, the structure is driven by the fully nonlinear interaction of tiny rolls, waves and streaks. For asymptotically large Reynolds number the interaction problem satisfies the unit Reynolds number three-dimensional Navier Stokes equations and is localized in a layer of the same depth as the unperturbed boundary layer. Then we show that the interaction problem is generic to any boundary layer which approaches its free stream form through an exponentially small correction [2] [3]. It is shown that away from the layer where it is generated the induced roll-streak flow is dominated by nonparallel effects which now play a major role in the streamwise evolution of the structure. It is shown that nonparallel effects cause the structure to persist only over intervals of finite length in any growing boundary layer. The results found shed light on a possible mechanism to couple near wall streaks with coherent structures located towards the edge of a turbulent boundary layer.

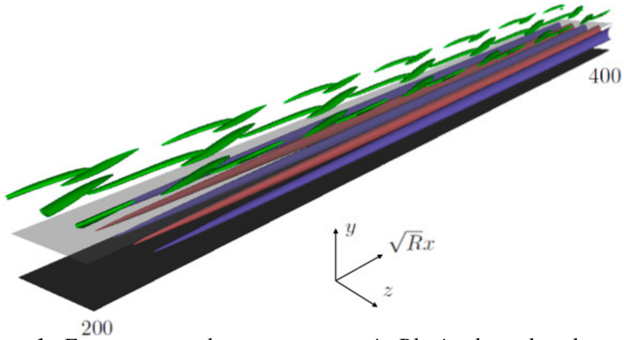

Figure 1: *Free-stream coherent structures in Blasius boundary layer flow.*

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VORTEX-WAVE INTERACTIONS IN SHEAR FLOWS: Classification and stability properties of solutions.

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In recent years it has become apparent that exact coherent structures found by numerical or asymptotic reduction of the Navier Stokes equations play a key role in both the process by which a flow becomes turbulent and the nature of fully developed turbulence. Understanding the structures therefore provides a route to both the control of transition and fully turbulent flows. The first part of the talk concerns VWI states in channels and pipes of arbitrary cross-section. Results suggest that all non-localized equilibrium states are described by the VWI equations or a second type of structure first identified for external flows by the authors. The stability of these states will be discussed and the stability properties used to classify states, which act as edge states. We will show that instabilities operate on two timescales with one directly associated with behaviour near edge states. The nonlinear states, which do not act, as edge states will be seen to have quite distinct stability properties. Control strategies associated with suction and other wall forcing methods will be discussed.

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A LOCALIZED EXACT COHERENT TRAVELING WAVE IN CHANNEL FLOW

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We detected 15 distinct travelling waves (labelled $\mathscr{G}_1, \cdots, \mathscr{G}_{15}$ in [1]) in channel flow subject to a spanwise rotation. It is found that, out of these 15 traveling waves, only two, referred to here as the TW1 flow and the TW2 flow, originating from the $\mathscr{G}_1$ tertiary flow and the $\mathscr{G}_{13}$ secondary flow, respectively, were able to be continued by homotopy to yield non-rotating channel flow solutions.

The streamwise and spanwise wavenumbers, α and β, of the TW1 and TW2 flows are optimized in order to identify the minimum value of the Reynolds number, R, at which these solutions first appear. It is noted that the TW2 flow first appears in a saddle-node bifurcation at $R = 665.3$ for $(\alpha, \beta) = (1.32, 2.89)$, reducing the lowest known Reynolds number at which exact solutions are known to exist, from the previous known minimum of 805.5 reported by [2]. The TW1 flow features one strong low-speed streak per spanwise wavelength in the streamwise component of velocity, while the TW2 flow features two such low-speed streaks. In both cases the streaks are sinusoidal and are flanked by staggered vortex structures. The TW1 flow can perhaps be regarded as an asymmetric (with respect to the channel centreplane) version of the channel flow solution found by [3], since it shares all the main features of the latter flow other than symmetry about this plane. The TW2 flow more closely resembles the MS-A flow recently presented by [2], but appears to be distinct to this latter flow since the minimum Reynolds numbers at which these two flows first appear, and the corresponding optimum wavenumbers, are markedly different.

A third flow, TW3, from which the TW1 flow bifurcates in a symmetry-breaking bifurcation, is additionally detected. This flow is characterised by a single strong low-speed velocity streak concentrated on the centreline of the channel and a much weaker single high-speed streak in each of the half channel located near the channel walls The optimum wavenumbers for TW3 appeared to be approaching the limit $\beta \to 0$. The flow structure of the solution approaching a spanwise-localised traveling wave in this limit is presented in Figure 1.

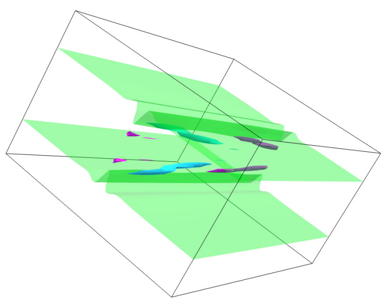

Figure 1: *The flow structure of the spamwise-localised flow. Isosurfaces of 0.7 of the minimum (maximum) of the streamwise vorticity are indicated by blue (purple). The green translucent sheet shows the isosurface of 0.5 of the maximum of the streamwise velocity.* $(R, \alpha, \beta) = (1133, 1.59, 0.50)$.

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INVARIANT SOLUTIONS IN HOMOGENEOUS SHEAR FLOW

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Homogeneous shear flow (HSF) is the most canonical flow to investigate the shear-induced turbulence and it is known that there are coherent structures, like velocity streaks and streamwise elongated vortices, similar to wall-bounded flows [1]. These coherent structures and their dynamics are considered as incomplete realizations of nonlinear invariant solutions in the incompressible Navier-Stokes equation, i.e. equilibrium solutions or periodic orbits, which have been reported in the plane Couette, Poiseuille, pipe flow, isotropic turbulence, and so on [2]. In this study, the invariant solutions such as fixed points and unstable periodic orbits (UPOs) in HSF are investigated. The direct numerical simulations (DNS) and large-eddy simulations (LES) of statistically stationary homogeneous shear turbulence are performed. The computational domain ($L_x \times L_y \times L_z$) is periodic in the streamwise (x) and spanwise (z) directions. The boundary condition is the shear-periodic in the vertical direction (y), in which the velocity is periodic between shifting points in the upper and bottom boundaries of the computational domain. Because of the periodicity in the streamwise direction, the shifting between upper and bottom boundaries due to the mean shear introduces a characteristic time period (box period, $T_s = L_x/L_y$), so that the time period of an UPO is a multiple of the box period. The nondimensional parameters are the two aspect ratios of the computational domain, A_{xz}, A_{yz}, and the Reynolds number, $Re_z = SL_z^2/\nu$, where S is the mean velocity gradient and ν is the kinematic viscosity.

Firstly, Two types of one-box-period UPOs are obtained; the one has shift-reflection symmetry as Nagata's Couette solution [3] and characterised by a staggered-aligned streamwise vortex pair (Fig. 1), and the other has a mirror-symmetric streamwise-roll pair (Fig. 2). These streamwise-vortical structure of one-box period UPOs resemble the rib vortices of the Kelvin-Helmholtz roller. The lower branch of a mirror-symmetric UPO is an equilibrium-like solution and it is an 'edge-state' on the basin boundary between laminar and turbulence. A direction along its unstable manifold represents a direct laminarization without any transient growth of the kinetic energy, and the opposite direction represents a bursting. Secondly, there are also subharmonic UPOs with several box periods. Fig. 3 shows the snapshots of

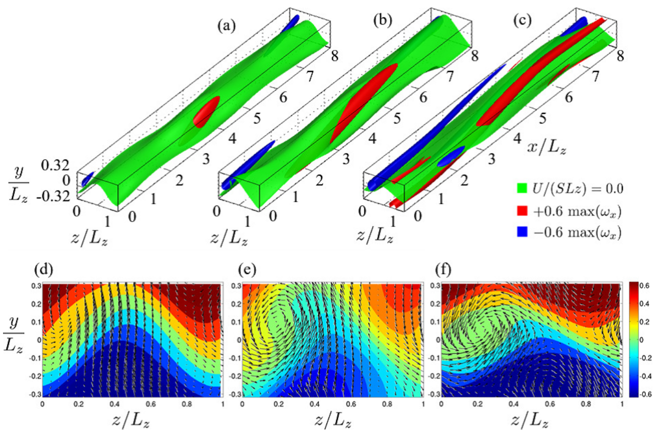

Figure 1: *One box-period UPOs with shift-reflection symmetry in DNS. The lower-branch solutions with* $(A_{xz}, A_{yz}) = (8, 0.63)$ *at (a)* $Re_z = 306$, *(b)* 592, *(c)* 1086*: (blue, red) The isosurfaces of the streamwise vorticity* ω_x, *(green) velocity streak,* $U/L_z = 0.0$. *(d-f) The corresponding total streamwise velocity* U/L_z *(contour levels are [-1:0.2:1]) and* (v, w) *(vectors) in a cross plane* $x/L_z = 0$.

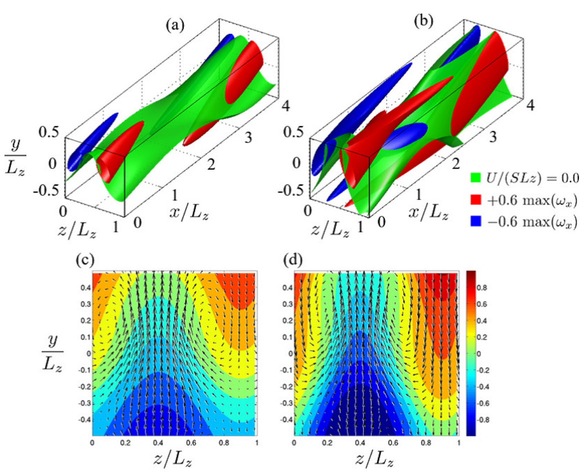

Figure 2: *The same with Fig. 1, but for the lower (a,c) and upper (b,d) branches of one box-period mirror-symmetric UPOs in DNS for* $(A_{xz}, A_{yz}) = (4, 1)$ *at* $Re_z = 240$.

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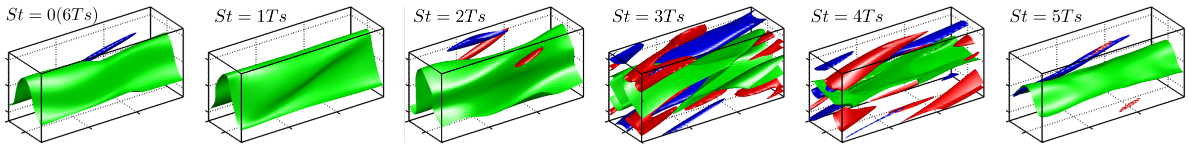

Figure 3: *Dynamic subharmonic (six box-period) UPO in DNS.* $(A_{xz}, A_{yz}) = (3, 1.33)$*,* $Re_z = 693$*. The isofurfaces are the same with Fig.1(a-c).*

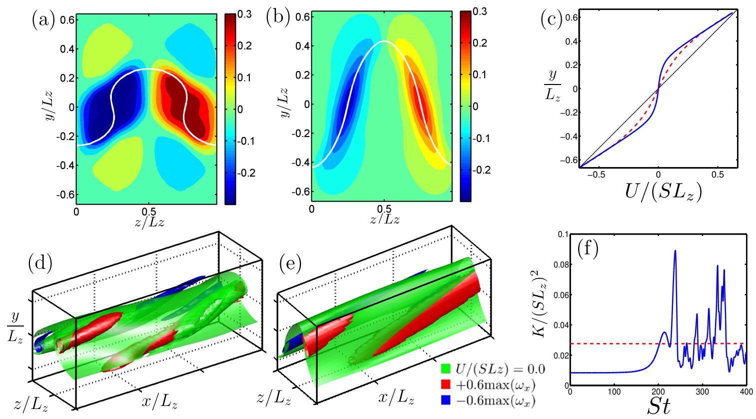

Figure 4: *Equilibrium solutions in LES. (a,d) Lower-branch (b,e) Upper branch.* $(A_{xz}, A_{yz}) = (3, 1.33)$*,* $C_S = 0.42$*. (a,b) The streamwise-averaged* ω_x/S *(contours), and the total streamwise velocity* $U/SL_z = 0.0$ *(white solid line). (c) the mean streamwise velocity of the lower- (blue thick line) and upper-branch solution (red dashed line), the black thin line is* y/L_z*. (d,e) Vortical structure for lower (d) and upper (e) branch solution. (f) The time-evolution of the kinetic energy from the lower- (blue solid) and upper-branch (red dashed line). Values are normalised by* $(SL_z)^2$*.*

a six-box-period UPO at each box-period, and it represents a regeneration cycle of streamwise vortices and a streak similar to the self-sustaining process in wall-bounded flows [4].
Lastly, equilibrium solutions are found in LES of a static Smagorinsky model with no kinematic viscosity ($\nu = 0$): the eddy viscosity is $\nu_t \equiv (C_S\Delta)^2(2\overline{S}_{ij}\overline{S}_{ij})^{1/2}$ (where $\overline{S}_{ij}$ is the grid-scale strain-rate tensor, C_S is the Smagorinsky constant and $\Delta_g = \sqrt[3]{\Delta x \Delta y \Delta z}$ is the grid scale). As in Fig. 4(a,b), both lower- and upper-branch solutions are vertically-localised, and at smaller C_S, the lower barnch exhibits a thin layer, which is similar to the canonical exact coherent structures embedded in high-Reynolds-number flows recently reported by [5]. The upper-branch is characterised by taller vortical structures.

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EXACT COHERENT STRUCTURES IN PLANE POISEUILLE FLOW AT HIGH REYNOLDS NUMBERS

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In plane Poiseuille flow (PPF) a variety of different exact coherent structures (ECS) exist. Some of these solutions are connected to the instability of the laminar profile at $Re_{crit} = 5772.22$ [1] while others appear at quite low Reynolds numbers in separate saddle-node bifurcations. For both cases, we present ECS that can be tracked numerically to Reynolds numbers far above the linear instability and discuss their properties at high Re. For our simulation we use the *channelflow*-code[4].

The edge state [2] of PPF is the symmetric travelling wave (TW_E) which initially was identified at a rather low Reynolds number of 1400 [3]. For this travelling wave it is feasible to track it to values of Re up to $3 \cdot 10^5$. We find that for high values of Re the total energy of the wave decreases as Re^{-1}. A stability analysis of the wave shows that it has one unstable direction for high Reynolds numbers. A visualization of TW_E at $Re = 25000$ is shown in 1a). In addition to TW_E, we track further travelling waves (TW) appearing in saddle node bifurcation at low Re to values of Re far above Re_{crit}.

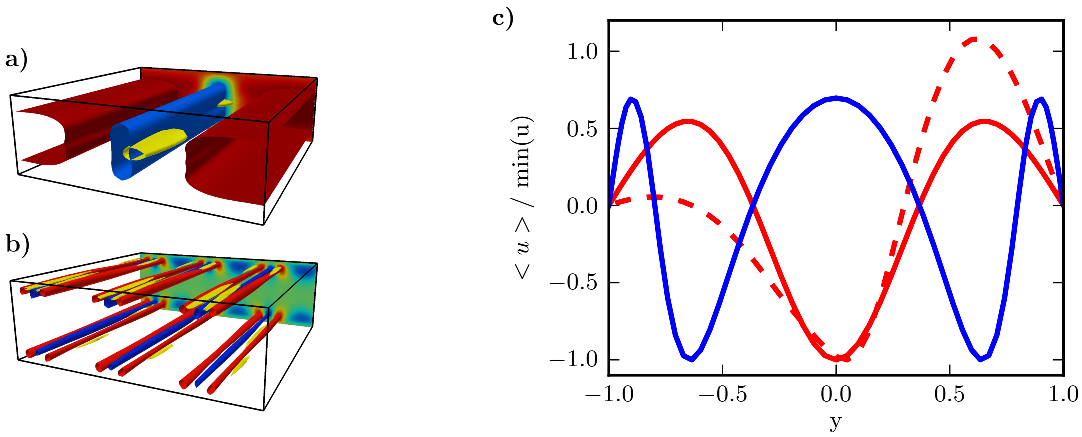

Figure 1: *In a) and b) visualizations of three-dimensional travelling wave at* $Re = 25\,000$ *are shown. The plots show iso-contours of positive and negative streamwise velocity in red and blue, respectively. Iso-contours of the Q-vortex-criterion are shown in yellow. On the back plane the streamwise velocity is color coded from the minimum value (dark blue) to the maximum values (red). The spanwise and streamwise extends of the domains is* 2π. *In c) mean velocity profiles (deviation from the laminar profile) of travelling waves at* $Re = 25\,000$ *are shown. The solid and dashed red line are the profiles for* TW_E *and another TW that appears in a saddle node bifurcation at low Re. The blue line shows the profile for TWs shown in b).*

Many ECS that bifurcate from the two dimensional Tollmien-Schlichting (TS) waves do also exist at high Reynolds numbers. In figure 1b) a visualization of a TW bifurcating from the TS-waves is shown. We study the stability and the dependence on the spanwise wavelength of these ECS. Generally, the ECS bifurcating from the TS-waves have stronger streaks and vortices close to the wall than TW_E and other ECS continued from low Re. These differences of the solutions also show up in the mean profiles of the ECS (see figure 1c). The waves bifurcating from the TS-waves

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show the strongest deviation from the parabolic profile close to the wall, while TW_E and other solutions continued from low Re show a stronger deviation for larger distances to the wall.

The persistence of these TWs to high Reynolds numbers and their spatial extension across the entire domain suggests that they will also impact large scale turbulent transport and fluctuations.

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STREAMWISE-LOCALIZED SOLUTIONS WITH NATURAL 1-FOLD SYMMETRY

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Keywords: Transition to Turbulence, Pipe Flow, Bifurcation theory.

It has been proposed in recent years that turbulence is organized around unstable invariant solutions, which provide the building blocks of the chaotic dynamics [1]. In direct numerical simulations of pipe flow we show that when imposing a minimal symmetry constraint (reflection in an axial plane only) the formation of turbulence can indeed be explained by dynamical systems concepts.

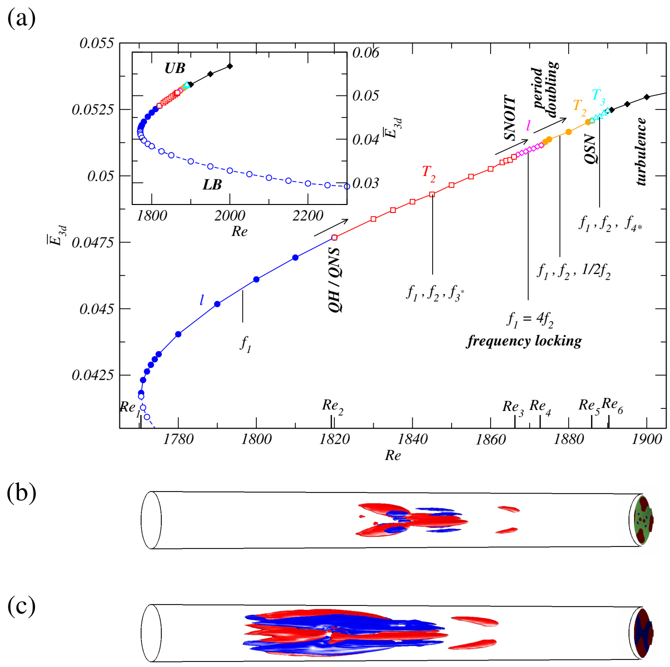

Figure 1: *(a) Variation with Re of the time-averaged three-dimensional energy $\overline{E}_{3d}$ illustrating the bifurcation sequence from limit cycle (l, i.e. a 1-torus) over 2-tori (T_2), limit cycle, and 3-torus (T_3) solutions to localized turbulence. Visualization of two localized flow states (the upper branch orbit) appearing in the bifurcation sequence: (a) limit cycle solution at $Re = 1800$ and (b) three-torus solution (T_3) at $Re = 1890$. Shown are isosurfaces of streamwise velocity at 0.3U (red) and -0.3U (blue), respectively. The laminar profile has been subtracted in all cases to highlight the three-dimensional structure of the flow and the views are shrank by a factor of 4 in the streamwise direction. 20D are shown out of a simulation domain of 40D.*

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The hypersurface separating laminar from turbulent motion, the edge of turbulence [2], is spanned by the stable manifolds of an exact invariant solution, a periodic orbit of a spatially localized structure. The turbulent states themselves (turbulent puffs in this case) are shown to arise in a bifurcation sequence from a related localized solution (the upper branch orbit). The rather complex bifurcation sequence involves secondary Hopf bifurcations, frequency locking and a period doubling cascade until eventually chaotic motion arises. Furthermore we identify several coherent structures - travelling waves - and illustrate their connection to the found localized solutions.

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COHERENT STRUCTURES AND SPATIOTEMPORAL FLUCTUATIONS IN PIPE FLOW

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[2] *Universitat Politècnica de Catalunya*

As of today no theoretical framework fully describes the onset of turbulence in shear flows. Dynamical-systems approaches suggest that invariant solutions of the Navier-Stokes equations, like traveling waves and relative periodic orbits in pipe flow, act as building blocks of the disordered dynamics. While recent studies have shown how transient chaos arises from such solutions, the ensuing dynamics lacks the strong fluctuations in size, shape and speed of turbulent spots observed in experiments.

In this talk we will show that the interaction of distinct chaotic spots emerging from invariant solutions gives rise to strong spatiotemporal fluctuations in pipe flow. While each spot features simple spatial and kinematic properties, it is only through their merging in phase space that strong fluctuations can occur. The dynamical behaviour ranges from growth and split of spots to their shrinkage and decay. The extension of this rationale to high Reynolds number flows will be discussed. Particular attention will be paid to whether such processes can account for the spatial and temporal spectra of turbulent shear flows beyond transition.

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LOCALIZED EXACT COHERENT STRUCTURES IN PLANE COUETTE AND PLANE POISEUILLE FLOW

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Coherent structures in turbulent flows can be understood mathematically as close passes to weakly unstable solutions of the Navier-Stokes equations. Much progress has been made developing this idea of "exact coherent structures" in the context of paradigmatic flows, idealized computational domains, low Reynolds numbers, and domain-filling coherent structures. For example, large numbers of weakly unstable equilibrium, traveling wave, periodic orbit, and relative periodic orbit solutions have been computed for low-Reynolds minimal flow units with periodic boundary conditions for plane Couette, plane Poiseuille, and pipe flow, and the properties of those solutions have aided our understanding of transition, intermittency, and low-Reynolds turbulence. However, there is still a huge gap between the current knowledge of exact coherent structures and the dynamics of fully-developed turbulence. In the latter, turbulence is traditionally understood to be a vast sea of mutually interacting eddies, in which patterns sometimes appear in isolation with sufficient spatial and temporal organization to arguably deserve the name "coherent structure."

So what do domain-filling, low-Reynolds, exact coherent structures in idealized computational domains have to do with localized and intermittently appearing observed coherent structures in high-Reynolds, fully-developed turbulence? The answer is not yet clear. In this talk we present recent work motivated by the desire to take at least a step or two in the direction of an answer. Specifically, we present a number of *spatially localized* equilibrium and traveling wave solutions of plane Couette and plane Poiseuille flow [1, 2]. Most of these solutions are spanwise localized and streamwise periodic, with spanwise tails that decay as $\exp(-\alpha z)$, where α is the streamwise wavenumber and z is the spanwise coordinate. The solutions exhibit highly concentrated regions of vorticity that are centered over low-speed streaks and flanked on either side by high-speed streaks. Several traveling-wave solutions of plane Poiseuille flow have vortex structures concentrated near the walls. An additional equilibrium solution of plane Couette flow is localized in both span- and streamwise directions, and has roughly the shape and structure of a minimal turbulent spot within an extended background of laminar flow.

We also present some recent extensions of the spatially localized, homoclinic snaking solutions of plane Couette flow of [3]. These solutions grow structure at their fronts in a series of saddle-node bifurcations that occur within a fixed band of Reynolds numbers. The position of this snaking region in Re depends on the streamwise wavelength, from $Re \approx 100$ at $\alpha = 1/2$ to $Re \approx 2000$ at $\alpha = 1$. The equilibria *skew* in the spanwise-streamwise plane, and the traveling waves *bend*. The bending of the traveling wave introduces non-periodicity within the solution interior and couples global properties such as wavespeed to its spanwise width. As the solution width increases and the bending lessens, the interior becomes more periodic and the properties of the traveling wave approach those of the equilibrium.

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ONSET OF FULLY TURBULENT PIPE FLOW

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Inst. Science and Technology Austria

Turbulence in pipes and other shear flows first arises in the form of localised structures, so called puffs. We will discuss how puffs first emerge starting from exact coherent structures (periodic orbits). While individual puffs are intrinsically transient, turbulence in this localised form nevertheless becomes sustained due to spatial proliferation. Nevertheless flows are spatio-temporally intermittent and it is not until somewhat higher Reynolds numbers that fully turbulent motion arises. As will be shown, the onset of fully turbulent motion corresponds to an excitability to bistability transition. Consequences for turbulence control will be discussed briefly.

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LOCALIZED WALL-MODE AND FREE-STREAM COHERENT STRUCTURES IN THE ASYMPTOTIC SUCTION BOUNDARY LAYER

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Invariant solutions have been studied mostly in wall-bounded flows but their significance for free-stream turbulence is much less explored. We will discuss two not yet reported invariant solution branches in the asymptotic suction boundary layer, a streamwise invariant parallel boundary layer. The states constructed by homotopy continuation from Couette flow are spanwise localized counterparts of the spatially periodic *wall-mode* (left figure) and *free-stream coherent structure* (right figure) identified by Deguchi and Hall [1]. Their spanwise localization allows to capture spatio-temporal features characteristic of turbulence at transitional Reynolds numbers [2] . Both new solution branches contain low- and high-speed streaks confined to the near-wall region which are also localized in spanwise direction. The two states however differ in the location of streamwise vortices associated with the near-wall streak structure. For the *wall-mode* the vortices are located close to the wall while for the *free-stream coherent structure* they are not confined to the wall but reach into the free-stream. Thus, the latter invariant solution branch directly couples free-stream and near-wall dynamics. The solution shares the near-wall topology with well known invariant states in plane Couette flow. This suggests the new states may allow to bridge the gap between well studied invariant solutions in wall-bounded flows and yet to be constructed free-stream counterparts.

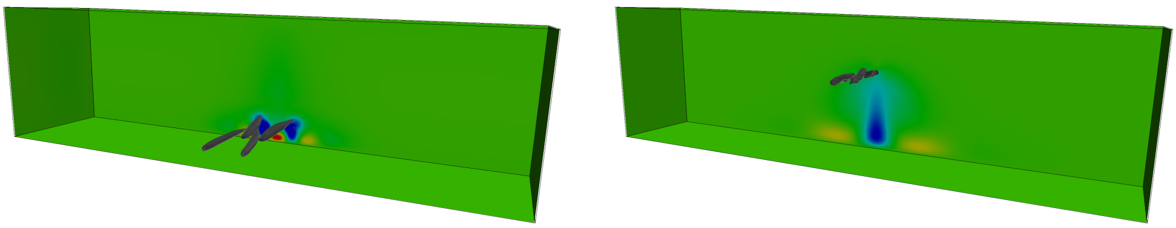

Figure 1. Wall mode (left) and free-stream coherent structure (right). Colors are downstream velocity, low- (blue) and high-speed (red) streaks. Vortices, visualized by the λ_2 criterion, are shown in gray. The two states differ in the position of the vortices, either close to the wall or outside the boundary layer in the free-stream.

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May 21. 9:00-19:00			
Reduced models. **CHAIR: D. Henningson**			
9:00-9:35	B. Eckhardt, E. Jelli, S. Zammert, M. Pausch	U. Marburg	Large scale coherent structures in turbulent flows
9:35-10:10	B. Farrell, P. Ioannou, D.F. Gayme, V. Thomas	Harvard/ Athens/ John Hopkins	A reduced nonlinear model study of roll/streak dynamics in wall-bounded shear flow turbulence
10:10-10:45	D. F. Gayme, V. Thomas, B. Farrell, P. Ioannou	John Hopkins/ Harvard/ Athens	The restricted nonlinear model as a natural minimal representation of self-sustaining turbulence in plane Couette flow
10:45-11:15	**Coffee break**		
11:15-11:50	P. J. Ioannou, B. Farrell	Athens	Structure and mechanism of turbulence in plane Poiseuille flow under dynamical restriction
11:50-12:25	J. Jiménez	UP Madrid	Direct detection of linearized bursts in turbulence
12:25-13:00	M. Pérez-Encinar, J. Jiménez	UP Madrid	Identifying Orr-like behaviour in large-scale turbulent wall-bounded flows.
13:00-14:30	**Lunch**		
Dynamics and control. **CHAIR: B. Farrell**			
14:30-15:05	S. Chernyshenko	Imperial	Coherent structures and drag reduction from linearized Navier-Stokes viewpoint
15:05-15:40	D.J.C. Dennis, F.M. Sogaro	Liverpool/ Imperial	The reorganisation of turbulent pipe flow by a drag-reducing polymer additive
15:40-16:10	**Coffee break**		
16:10-16:45	E. Öngüner, M. Dittmar, P. Meyer, C. Egbers	U. Branderburg/ LaVision	PIV measurements of turbulent structures in a horizontal pipe
16:45-17:20	R.M. Kerr	Warwick	Two steps to helicity annihilation and energy dissipation for reconnecting classical vortices
17:55-19:00	**General discussion.** **CHAIR: B. Eckhardt**		
20:30-	**Conference Dinner**		

LARGE SCALE COHERENT STRUCTURES IN TURBULENT FLOWS

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We discuss two aspects of the presence of large scale coherent structures in turbulent flows: (i) coherent structures in the asymptotic suction boundary layer and (ii) an analysis of the self-sustaining cycle in turbulent flows.

Deguchi and Hall (JFM **752**:602, 2014) recently described coherent structures in the asymptotic suction boundary layer that extend far beyond the laminar boundary layer. Analysis of their stability properties reveals that they are very unstable and hence dynamically not particularly relevant. However, their existence suggests that there could be other structures, and we will report on the results of our search for such structures. Moreover, we performed simulations in high domains in order to relate properties of the turbulent profile to the presence of the structures.

Farrell and Ioannou (JFM **708**:149, 2012) analysed the properties of streamwise rolls and streaks in wall-bounded shear flows and proposed a certain decomposition of the flow that can be used for control purposes. Adapting their approach to a low-dimensional model for shear flows allows tests and verifications of key aspects of their analysis.

A REDUCED NONLINEAR MODEL STUDY OF ROLL/STREAK DYNAMICS IN WALL-BOUNDED SHEAR FLOW TURBULENCE

Brian F. Farrell[1†], Petros J. Ioannou[2b] Dennice F. Gayme[3c] & Vaughan Thomas[3d]
[1]*Harvard University,* [2]*National and Kapodistrian University of Athens,*
[3]*Johns Hopkins University*

In wall-turbulence the roll/streak structure, which was first identified in the buffer layer, is now recognized to play a key role in the dynamics of turbulence up to and including the log layer. What is not fully understood is how this structure is maintained in the absence of an associated linear instability. The resolution of this conundrum appears to be that this structure arises from a nonlinear instability, the various proposed mechanisms for which are herein referred to as self-sustaining processes. However, once the nonlinear instability process responsible for the formation of the roll/streak is identified there remains the problem of understanding how this instability is regulated to maintain the observed statistical mean turbulent state. In this talk both of these questions will be addressed by adopting the perspective of statistical state dynamics (SSD) and specifically the reduced nonlinear (RNL) implementation of SSD to investigate the SSP instability and its regulation. The RNL system is an SSD consisting of a second order closure of the dynamics. This closure comprises the joint evolution of the streamwise constant mean flow (first cumulant) and the ensemble second order perturbation statistics (second cumulant). The RNL system is closed either by parameterizing the third cumulant using stochastic excitation or by setting it to zero. Restricting the Navier-Stokes (NS) equations to the first two cumulants retains the nonlinear interaction between the perturbation momentum fluxes and the mean flow but does not retain the explicit term expressing the streamwise varying perturbation-perturbation nonlinearity which produces a great reduction in the complexity of the dynamics. Nevertheless, RNL turbulence exhibits a close correspondence with NS turbulence including a realistic SSP. The perturbations supporting the SSP in RNL dynamics are shown to result from systematic parametric instability of the time-dependence streak. Consistently, the structure of the turbulent perturbations is found to be that of the leading Lyapunov vector of this fluctuating streak. The growth rate of this first Lyapunov vector is verified to vanish, consistent with its constituting the perturbation component of the turbulent state trajectory. This result is shown to result from a feedback mediated control process operating between the fluctuating mean flow and its associated first Lyapunov vector. In this talk it will be shown how together these results allow the SSP instability and its regulation in the turbulence of the RNL system to be characterized in great detail.

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THE RESTRICTED NONLINEAR MODEL AS A NATURAL MINIMAL REPRESENTATION OF SELF-SUSTAINING TURBULENCE IN PLANE COUETTE FLOW

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[1] *Johns Hopkins University,* [2] *Harvard University,*
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The restricted nonlinear (RNL) system is derived directly through a dynamical restriction of the Navier Stokes equations. It is comprised of a coupled system of evolution equations including a streamwise constant mean flow and streamwise varying perturbations about that mean; a decomposition motivated by the prominence of streamwise elongated structures in wall-turbulence. We first demonstrate that the streamwise constant mean flow dynamics connect experimental observations of streamwise coherence to the momentum transport that leads to shape of the turbulent (time-averaged) mean velocity profile. Next we show that the additional dynamics included in the RNL model, in particular the coupling between the streamwise constant mean and streamwise varying perturbations, lead to a system that supports self-sustaining turbulence with a turbulent mean profile and structural features consistent with DNS. We discuss RNL turbulence first in terms of the behavior of its underlying structures. In particular, we demonstrate that the structure and spectra of the rolls and streaks, which are known to play a critical role in the self-sustaining process (SSP) of wall-turbulence, show close correspondence with those observed in DNS. Figure 1 shows this correspondence in RMS streak velocity. We then demonstrate that once in the self-sustaining state, RNL turbulence naturally collapses to a minimal system supported by a small number of streamwise varying perturbations interacting with the mean. Moreover, we demonstrate that a realistic RNL SSP can be maintained as few as one streamwise-varying perturbation interacting with the mean flow. The resulting 'band-limited' RNL system constitutes an analytically and computationally attractive reduced order model for studying wall-turbulence.

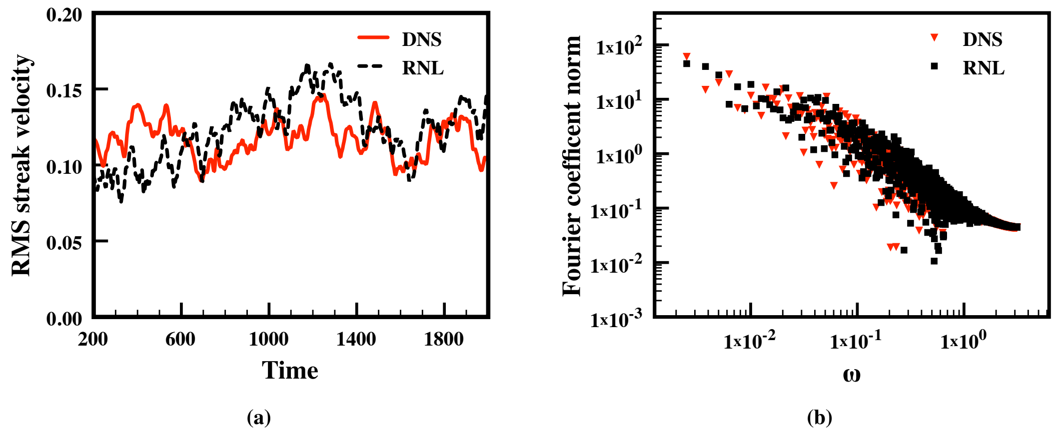

Figure 1: *(a) RMS streak velocity ($U_s := \sqrt{\int_0^{L_z}\int_{-\delta}^{\delta}(U-[U])^2\ dy\,dz}$, where the square brackets indicate a spanwise average) versus time for the DNS (red solid line) and the RNL simulation (black dashed line, L_z is the spanwise extent of the channel and δ is the half-width of the channel). (b) The corresponding temporal Fourier spectrum for the DNS (red triangles) and the RNL simulation (black squares).*

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EUROMECH COLLOQUIUM 568, MAY 20–22, 2015
COHERENT STRUCTURES IN FULLY DEVELOPED TURBULENCE
SCHOOL OF AERONAUTICS, U. POLITÉCNICA MADRID, SPAIN

STATISTICAL DYNAMICS OF THE TURBULENT STATE IN WALL-BOUNDED TURBULENCE

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[2] *Harvard University*

Statistical state dynamics (SSD) has recently been applied to study wall-bounded turbulence [1]. SSD dynamics [2] had been previously applied primarily to study homogeneous isotropic turbulence (cf. [3]). Remarkably, to obtain an accurate approximation of the full dynamics of wall-turbulence it suffices to retain only the first two cumulants of the flow, which provides a Gaussian approximation to the full SSD which will be referred to as the S3T or CE2 system. When applied to anisotropic flows S3T theory reveals a variety of new phenomena that are intrinsic to SSD including bifurcations with no counterpart in the dynamics of individual realizations. These bifurcations are found to connect with the underlying dynamics of the large scale coherent structures that dominate anisotropic turbulence and that provide the mechanism sustaining the turbulent state.

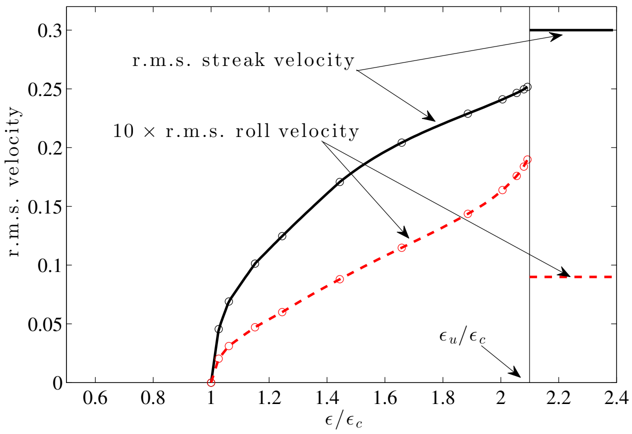

Figure 1: *Typical S3T bifurcation diagram for the Couette problem. Shown are the RMS streak velocity (solid) and* $10\times$ *the RMS streamwise roll velocity (dashed) as a function of the perturbation forcing amplitude,* ϵ*. For* $\epsilon/\epsilon_c < 1$*, the spanwise homogeneous state is S3T stable. At* ϵ_c *the spanwise uniform equilibrium bifurcates to an equilibrium with a streamwise roll and streak. Stable streamwise roll and streak equilibria extend up to* $\epsilon_u/\epsilon_c = 2.1$ *beyond which the streamwise roll and streak transitions to a time-dependent state which can self-sustain and the amplitudes of the roll and streak become independent of* ϵ*. Shown for reference are the r.m.s. velocities of the streak and roll in the self-sustaining state. The Reynolds number is* $R = 400$*,* $L_x = 1.75\pi$ *and* $L_z = 1.2\pi$*.*

A representative bifurcation structure for Couettte flow under increasing levels of externally imposed spanwise homogeneous random excitation is shown in Fig. 1. For low levels of excitation the flow state is spanwise constant and very close to the laminar Couette profile. At a critical excitation level the spanwise symmetry of the mean flow is broken and spanwise inhomogeneous equilibria with roll/streak form emerge. The velocity of the streak and the associated roll circulation increase with excitation amplitude (cf. Fig. 1) until the roll/streak equilibria disappear through a saddle-node bifurcation and the S3T system transitions to a time-dependent state. This turbulent state continues to be dominated by large scale roll/streak structures but these exhibit chaotic time dependence. Surprisingly, this system remains turbulent when the external excitation is removed while spontaneously undergoing reduction in complexity to a turbulent state supported by a small set of structures. This naturally simplified system provides a powerful tool for study of the mechanism maintaining the turbulent state.

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Analysis of the S3T roll/streak bifurcation from the spanwise homogeneous state reveals that the crucial phenomena supporting the instability is that streak perturbations distort the turbulent field in such a way as to result in Reynolds stress divergence configured to induce rolls that though the lift-up mechanism reinforce the original streak perturbation. Illustration of this universal mechanism is shown in Fig. 2. This phenomena is fundamental to shear turbulence because in fully developed turbulence it is this collocation of streaks with their roll forcing that maintains the turbulent state.

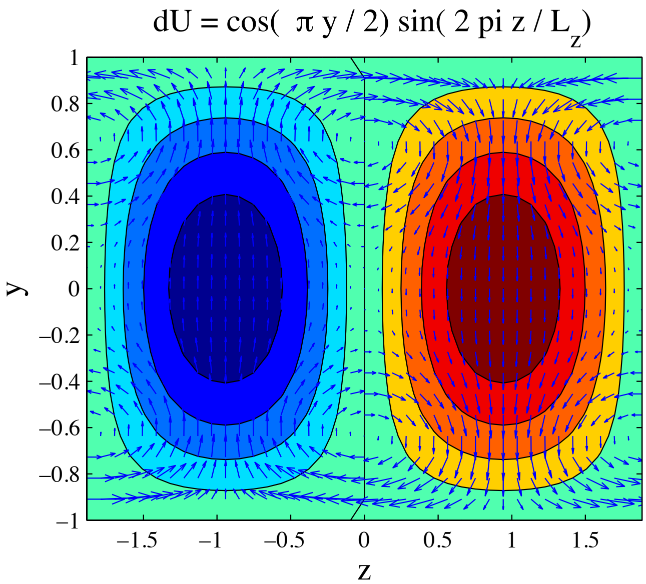

Figure 2: *The rate of change of streamwise roll acceleration induced by a streak perturbation to a Couette flow that is maintained turbulent by stochastic forcing. Distortion of the turbulence by the streak perturbation induces Reynolds stresses that force roll circulations supporting the streak via the lift-up mechanism. Shown are contours of the imposed streak perturbations, $\delta U = \cos(\pi y/2)\sin(2\pi z/L_z)$, with $\delta U > 0$ in $z > 0$, and vectors of the resulting rate of change of roll acceleration, $(\dot{V}, \dot{W})$. The Reynolds number is $R = 400$, $L_x = 1.75\pi$ and $L_z = 1.2\pi$.*

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DIRECT DETECTION OF LINEARIZED BURSTS IN TURBULENCE

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The relevance of linear transitional mechanisms in fully turbulent shear flows, and in particular of the Orr-like inviscid transient amplification of disturbances, is explored in the context of the prediction of bursting behavior. Although the logarithmic layer of wall-bounded turbulence is used as the primary example, most conclusions should apply to other flows with linearly stable mean profiles that are dominated by large-scale streamwise-velocity streaks and intermittent bursts of the cross-shear velocity. When the linearised problem is solved in the limit of small viscosity, it has previously been shown that statistical properties, such as the bursting time- and length-scales, the energy fluxes between components, and the mean inclination angles, are consistent in linear and nonlinear systems. The question addressed here is whether the individual structures predicted by the linearised solution can be detected in fully nonlinear simulations, and whether the linearized approximation can be used to predict their evolution. It is found that strong bursting of the largest scales is well described linearly, comprising about 65–70% of the total time, but that weaker fluctuations are not. It is also found that adding an eddy viscosity does not substantially improve predictions.

Funded by the ERC Multiflow project.

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IDENTIFYING ORR-LIKE BEHAVIOUR IN LARGE-SCALE TURBULENT WALL-BOUNDED FLOWS

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Orr-like bursts of the wall-normal velocity have been analysed elsewhere in the form of individual Fourier modes in direct numerical simulations of turbulent channels in domains small enough to be minimal for the logarithmic layer. As in the case of individual structures in full-size turbulence, those bursts have vertical dimensions of the same order as the horizontal ones, and span the logarithmic layer. In those simulations, the first few Fourier modes can be interpreted as individual structures, but the same is not true in large-scale simulations, whose vertical dimensions are much smaller than the box size. Structures are then expected to be intermittent both in space and in time, and individual Fourier modes spread them over the whole box. Here we present a method based on wavelet projections that addresses both spatial and spectral locality. Using continuous wavelets as filters, active flow regions are identified by their strong local intensity. A local optimum wavelength and wavefront inclination is then computed for each active region, and used to trace the Orr-like behaviour. The method will be presented, as well as preliminary results for both tests and real turbulence simulations at Reynolds numbers up to $Re_\tau = 2000$.

Funded by the ERC Multiflow project.

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COHERENT STRUCTURES AND DRAG REDUCTION FROM LINEARIZED NAVIER-STOKES VIEWPOINT

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Linearized Navier-Stokes equations (LNSE) were recently demonstrated to be a useful tool in studies of fully-developed turbulent flow past oscillating wall in the regime with drag reduction. Using LNSE, it turned out to be possible to predict the dependence of streak angle on time [1] and to predict the relative drag reduction as a function of the oscillation period and the longitudinal wavenumber [2,3]. Together with earlier results on developed turbulent flows this demonstrates the applicability of LNSE to developed turbulence. The proposed talk will address the question of the relationship between coherent structures and drag in the light of these recent results.

A widely-accepted view of this relationship is that the mechanism by which turbulence sustains itself is crucially dependent on coherent structures. An immediate consequence of such a notion is that drag reduction is achieved by destroying or inhibiting structural coherence. (Note that until carefully thinking over the recent results, the author himself shared this common opinion.) In the talk it will be argued, however, that the way and the nature of the predictions of structures and drag reduction by LNSE-based approaches contradict this viewpoint. The cited results indicate that the coherent structures are modified by wall oscillations via changing the filtering properties of the LNSE operator, so that the shape of the optimal structures, that is the structures most easily passing through the LNSE operator, changes. The observed structures (streaks) have the properties of these optimal structures. The same analysis shows, however, that the amplification of the optimal structure by the LNSE filter is increased by wall oscillations, while the drag decreases. At the same time the predictions of drag reduction, also made on the basis of LNSE, show that the drag is not linked to the optimal coherent structure that is the structure observed in the actual flow. Instead, in [2] drag is linked to the structure that is observed in the flow past the non-oscillating wall (which structure is not observed in the flow with drag reduction), while in [3] it is linked to the broadband amplification by the LNSE operator.

The above arguments pose a question of verifying the implications of these new results by analysing the available data obtained by direct numerical simulations, or by new direct numerical simulations specifically designed for this purpose.

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THE REORGANISATION OF TURBULENT PIPE FLOW BY A DRAG-REDUCING POLYMER ADDITIVE

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[1] *University of Liverpool*
[2] *Imperial College London*

Recently, the presence of a set of distinct organisational states has been identified in Newtonian turbulent pipe flow at Reynolds number, $Re_D = U_b D/\nu = 35000$ (where U_b = bulk velocity, D = pipe diameter and ν = kinematic viscosity), through the decomposition of the two-point spatial correlation of the streamwise velocity fluctuations (R_{uu}) by azimuthal wavenumber (k_θ) [1]. States with dominant azimuthal wavenumbers corresponding to k_θ = 2,3,4,5,6 were discovered and each state was characterised by the frequency and longevity of its occurrence. The state corresponding to $k_\theta = 3$ was found to be the most common and coherent. Each of the states were characterised by alternating positive and negative fluctuations of the streamwise velocity (u) around the pipe azimuth, which were related to a series of alternately-rotating quasi-streamwise vortices. The overall picture was reminiscent of a set of non-linear travelling wave solutions previously identified at Reynolds numbers an order of magnitude lower [2, 3].

Since Toms [4] first observed that a small amount of polymer added to the pipe flow of a Newtonian fluid leads to a significant decrease in skin friction, the phenomenon of drag reduction by additives has been extensively researched. The effect of the polymer on the mean velocity profile, the turbulence structure and the large-scale turbulent motions have been investigated, both experimentally and numerically, in a variety of wall-bounded flows [5, 6, 7, 8, and many others]. In this work we examine the effect of the polymer on the organisational state of the flow, which is found to be dramatic, significantly changing the probability of certain states occurring and increasing the coherence of the favoured states.

The experiments were performed in the Very Large Scale Pipe Flow (VLSPF) facility at the University of Liverpool. This facility consists of a 23.3m long pipe constructed of a series of borosilicate glass sections with an internal diameter of 100mm. The turbulent flow at $Re_D = 10000$, is investigated using a high-speed, stereoscopic particle image velocimetry technique in which the measurement plane (located 22m from the pipe inlet, corresponding to $220D$) is perpendicular to the streamwise velocity, providing all three components of velocity across the entire pipe cross section with good temporal resolution. The VLSPF is filled with approximately 750 litres of ordinary tap water for the Newtonian flow case and a semi-dilute (225ppm), visco-elastic, shear-thinning, aqueous solution of polyacrylamide (PAA) for the non-Newtonian (drag-reduced) case. PAA has a high molecular weight and presents a non-rigid structure ideal for high drag reduction. Indeed, the drag-reduction achieved by the addition of the polymer is 62%.

All of the wavenumber states found previously at $Re_D = 35000$ (k_θ = 2,3,4,5,6) [1] are also found at $Re_D = 10000$ with and without the polymer. However, in the case of the polymer solution there is a significant change. The $k_\theta = 2$ shows a very strong coherence and the higher wavenumber states are rarely observed. Figure 1 shows an example of the variation of the wavenumber states in the streamwise direction for both the water and polymer solution. The axial coherence of each of the states is demonstrated by this figure. Although this is just one example it is highly representative of the trend throughout the entire dataset (which consists of the equivalent of $240R$ of fluid passing the measurement plane for the polymer and $280R$ for the water). The percentage of instances of $k_\theta = 2$ increases from 19% for the water to 33% for the polymer and is the most common state of the flow. (For water $k_\theta = 3$ is the most common state.) The middle panel of figure 1 is the correlation (R_{uu}) corresponding to the flow state for each streamwise location. This clearly shows several examples of transitions between states, which are far more common in the water than in the polymer solution. The bottom panel is the corresponding instantaneous streamwise velocity fluctuation, which enables the visualisation of the large-scale structures that are responsible for the pattern in R_{uu} shown in the middle panel, and are therefore key in determining the wavenumber state of the flow. The increased azimuthal extent (width) of the coherent structures in the flow with the polymer is particularly clear in this plot, but the improved axial coherence of these structures is also evident.

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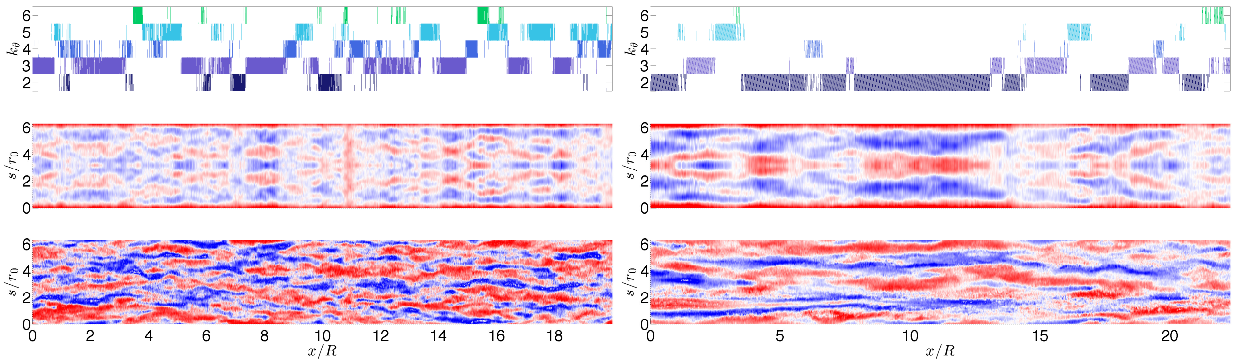

Figure 1: *An example of the axial coherence of the wavenumber states for water (left) and aqueous polymer solution (right). Top: Variation of azimuthal wavenumber (k_θ) with axial distance (x), showing significant axial coherence of the wavenumber states. Middle: The corresponding correlation map at $r_0/R = 0.75$ showing the correlations that lead to the state allocation and also the transitions between wavenumber states (red indicates $R_{uu} > 0$, blue $R_{uu} < 0$, white $R_{uu} \approx 0$ and s is arclength, i.e. $s = r_0\theta$). Bottom: The corresponding instantaneous velocity fluctuations, where red indicates $u > 0$, blue $u < 0$ and white $u \approx 0$.*

It is interesting to note that the "edge-state" (the invariant state embedded in the edge of chaos that neither decays or becomes fully turbulent) identified in numerical simulations at Reynolds numbers near transition [9], would be classified as $k_\theta = 2$ in our system and the conditional average of all $k_\theta = 2$ instances does resemble the edge state [1, 9]. Thus, it appears that the polymer is increasing the proportion of time the turbulent flow spends in states similar to this edge-state. Given that the addition of the polymer also corresponds to a large decrease in drag, these could potentially be low-drag states, which would present an interesting target for flow control strategies.

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EUROMECH COLLOQUIUM 568, MAY 20–22, 2015
COHERENT STRUCTURES IN FULLY DEVELOPED TURBULENCE
SCHOOL OF AERONAUTICS, U. POLITÉCNICA MADRID, SPAIN

PIV MEASUREMENTS OF TURBULENT STRUCTURES IN A HORIZONTAL PIPE

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In last decades the so called large scale motions (LSM), which are composed of detached eddies with wide range of azimuthal scales in the outer layer, are identified. Advanced versions of LSMs, the very large-scale motions (VLSM), have radial scales. The VLSMs are concentrated around a single azimuthal mode and make a smaller angle with the wall compared to the LSM. These mentioned phenomena are investigated at high Reynolds numbers in the pipe facility Cottbus-Large Pipe at BTU Cottbus-Senftenberg (CoLa-Pipe) (Figure 1) which provides a bulk Reynolds number of $\mathrm{Re}_b \leq 1.5 \times 10^6$. Previous studies at the Department of Aerodynamics and Fluid Mechanics provide an outline for conditions of fully developed turbulent flow state with natural as well as artificial transition. Considering these fully developed flow conditions at CoLa-Pipe, current investigations are primarily focused on the structures in boundary layer in terms of LSM and VLSM by using hot wire anemometry and PIV (Particle Image Velocimetry). As being a high Reynolds number pipe facility, for CoLa-Pipe slightly different PIV setups (Figure 2) are necessary in comparison the other pipe facilities. Considering the phenomena "‘the higher the Re-number the larger the turbulent structures"’ large laser planes are expected in axial streamwise direction. This step is mandatory for capturing turbulent properties at high velocity ranges. Obtaining turbulent structures at high Reynolds numbers optically with PIV requires long laser plane setups in axial direction. Taylor's hypothesis and proper orthogonal decomposition (POD) are used to capture instantaneous fluctuations and turbulent structures. The main aim of this work will be analyzing the lengths of structures at bulk Reynolds numbers range of $\mathrm{Re}_b \approx 10^4$ to 10^5 in terms of their wavelengths and comparing with those of low Reynolds numbers regions considering different measurement techniques.

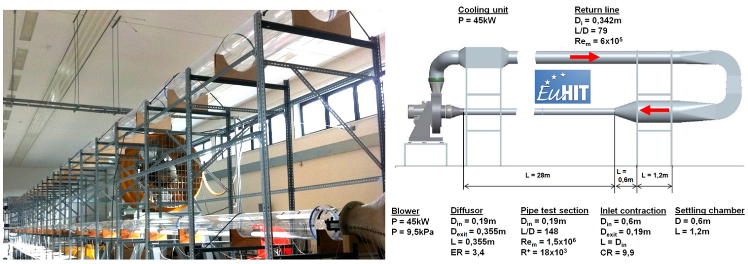

Figure 1: *Cottbus-Large-Pipe (CoLa-Pipe), a unique wall-bounded flow test facility*

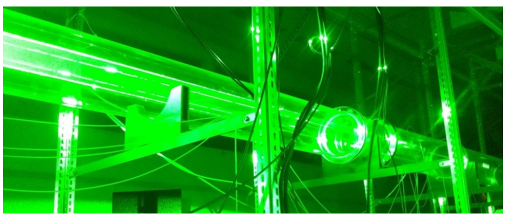

Figure 2: *Streamwise PIV configuration / Cottbus-Large-Pipe (CoLa-Pipe)*

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TWO STEPS TO HELICITY ANNIHILATION AND ENERGY DISSIPATION FOR RECONNECTING CLASSICAL VORTICES

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Traditional tools for describing coherent vortical structures, the interactions between them and how they reconnect include tracing vortex lines, determining the circulation about these lines and the vorticity magnitude, which is closely related to the dissipation of kinetic energy. A new tool that modern diagnostics is to describe their topology by using the helicity, the scalar product of the velocity and vorticity, and the closely related linking number between structures.

Prior to a new vorticity linking experiment that starts with a trefoil knot [2], helicity could only be determined numerically because only simulations could provide both the velocity and vorticity simultaneously on a mesh. And prior to a new set of simulations using vortices with stable internal cores [1], it has been difficult to tie the calculated helicity to observable structures [3]. Given these new capabilities, quantitative comparisons between the topology of experimental structures and similar simulated structures are now possible.

This presentation will present the first such comparisons by looking at the surprising claim that the linking number of the experimental trefoil knot is preserved by reconnection. An observation that at first seems to contradict all other numerical simulations and experiments showing changes in the helicity during reconnection events. The new simulations will show that the helicity is temporarily preserved as twisting, with the topological linking is converted into writhe. Then, in the simulations the twist self-dissipates resulting in finite changes in the helicity, the associated linking number and even the global energy.

What roles might these helicity diagnostics play in addressing these questions: 1) Could there be a finite-time singularity of the Navier-Stokes equations with a finite viscosity in a finite-domain, as defined by the Clay Foundation. 2) The physical question of whether there is an energy dissipation anomaly in the limit of zero viscosity. Which is implicitly assumed in any engineering or geophysical model of turbulent flows that uses eddy viscosities.

The first arises in the dynamics of the initial partial reconnection, when there is a finite change in the circulation about the original vortices at the point of reconnection, a local property, but no changes in either the global energy or helicity. This step seems to be a necessary condition for the formation of the next step and there are indications that this can only happen if the domain surrounding the initial vortex structures is infinitely large.

For the second question, is there finite energy dissipation as the viscosity goes to zero, seems to be associated with a final change in topology, when the writhe and twist created in the first step is annihilated.

Two sets of new calculations will be presented. In one set are extensions of the anti-parallel reconnection work of Kerr (2013) to higher resolution and higher Reynolds numbers that show how the circulation and local maxima of higher-order derivatives of the velocity have singular scaling. Helicity in the symmetric quadrants of the geometry over this period grows slowly as it is transported across the planes of symmetry. Then helicity changes little as the reconnected and unreconnected parts of the original vortices twist around one another. Finally, this twisting reaches a breaking point and there are rapid changes in both the helicity and total energy.

The new configuration will be calculations of the helical trefoil with initial writhe+twist number $Wr = 3$ that evolves into figure 1, then of updated versions of the anti-parallel reconnection from Kerr (2013). These show that while the initial reconnection might briefly create coils with the same total helicity, the experimental analysis was stopped before the transition to the second step, too early to see a sharp change in the helicity as seen in Holm and Kerr and in the new calculations. Based upon this, if the experimental analysis could be continued, then the trefoil experiment as well as their linked ring experiment and all the simulations would agree that shortly after reconnection, very sudden and finite changes in the helicity do appear. An observation that would demonstrate that there can be sudden changes in measurable, macroscopic properties even if small, but finite, changes in the global energy are not measurable.

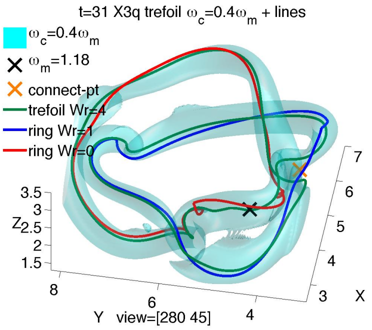

Figure 1. Vorticity isosurface plus three closed trajectories at $t = 31$. The **green** trajectory roughly follows the original trefoil with additional twists and $Wr = 4$. The closest approach, the "reconnection point", of the two halves of this trefoil is indicated by the **orange cross** where due to an extra twist, the vortex lines are locally anti-parallel. For the linked rings of **Red** $Wr = 0$ and **blue** $Wr = 1$ plus linking ($Wr = 2$) equals that of the original trefoil: $\sum Wr = 2 + 1 + 0 = 3$.

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May 22. 9:00-15:00			
Structures in turbulent flows: Observational evidence. CHAIR: D. Gayme			
9:00-9:35	Y. Bengana, Y. Hwang	Imperial/ UPMC	Self-similar bursting of minimal attached eddies in turbulent channel flow
9:35-10:10	A. Lozano-Durán, J. Jiménez	UP Madrid	Time-resolved evolution of coherent structures in turbulent channels
10:10-10:45	P. Schlatter, R. Örlü, D. Henningson	KTH	On hairpin vortices in turbulent boundary layers
10:45-11:15	**Coffee break**		
11:15-11:50	X. Wu, P. Moin	RMC Ontario/ Stanford	Careful visualization of accurate DNS database reveals turbulent spot in the near-wall region of fully turbulent boundary layer
11:50-12:25	A. Shahirpour, J. Sesterhenn, C. Egbers	U. Branderburg/ TU Berlin	Numerical investigation of turbulent pipe flow structures and their dependence on wall temperature
12:25-13:30	**General discussion. CHAIR: P. Schlatter**		
13:30	**Closing remarks and Lunch**		

SELF-SIMILAR BURSTING OF MINIMAL ATTACHED EDDIES IN TURBULENT CHANNEL FLOW

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Very recently, we have performed a numerical experiment designed to simulate only the energy-containing motions at a prescribed spanwise length scale using their self-sustaining nature [1]. The computed statistical structure of the energy containing-motions at each of the length scale have been found to be self-similar with respect to the spanwise length scale, proportional to the distance from the wall. More strikingly, the statistical structure was found to be remarkably similar to that given in the original theory of Townsend, demonstrating the existence of the attached eddies as energy-containing motions contributing to the logarithmic layer. The present study is an extension of this work specially to understand the 'dynamics' of the self-sustaining attached eddies, each of which is composed of a streak and streamwise vortices aligned.

An over-damped LES to isolate the self-sustaining attached eddies at a given spanwise size L_z is performed, while maintaining their minimal computational box (i.e. $L_x/L_z \simeq 0.5$). It is found that the self-sustaining attached eddies exhibit the process remarkably similar to the bursting of the self-sustaining near-wall motions: i.e. the streak is amplified via lift-up effect and subsequently experiences breakdown involving regeneration of the streamwise vortices. Examination of the correlation time scale of this physical process reveals that the self-sustaining minimal attached eddies are 'dynamically self-similar' with the bursting time scale, $T \simeq 2L_z/u_\tau$. This time scale retrieves well-known near-wall bursting time scale $T^+ \simeq 200$ at $L_z^+ = 100$ [2], while it yields $T \simeq 3h/u_\tau$ for the largest attached eddies composed of minimal VLSMs and LSMs at $L_z \simeq 1.5$. Comparison of this time scale with that of the full simulation in the same box is made, showing that this dynamic self-similarity also persists in 'real' flows. In the final presentation, more details of the self-similar bursting of the attached eddies will be presented: e.g. examination of the lift-up effect and streak instability of the attached eddies in comparison with full simulations, and effect of the Reynolds number.

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TIME-RESOLVED EVOLUTION OF COHERENT STRUCTURES IN TURBULENT CHANNELS

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U. Politécnica de Madrid

The study of coherent structures in turbulence assumes that there is a group of coherent regions in the flow that are important enough to explain the dynamics of the whole flow. Of course, defining those regions is not trivial and its relevance compared to the rest of the flow is not guarantee and has to be proved.

Attempts to describe wall-bounded turbulence in terms of coherent motions date at least to the work of Theodorsen (1952), who proposed a horseshoe vortex as the central structural element. A seminal contribution was the attached-eddy model proposed by Townsend (1961) for the logarithmic layer and further developed by Perry et al. (1982). In such a model, wall turbulence was considered to be dominated by a forest of self-similar horseshoe wall-attached vortices of different sizes, leaned in the streamwise direction, and legs extending to the wall. Followed by the rapid improvements of the experimental techniques and with the advent of DNS, a new iteration of the horseshoe vortex emerged called the *hairpin-packet paradigm*. Originally proposed by Adrian et al. (2000), the model conceived wall-bounded turbulence as a set of several hairpin vortices organized in coherent packets that grow from the wall into the outer region, as the sketch shown in figure 1(a), and with lifetimes much longer than their characteristic turnover times.

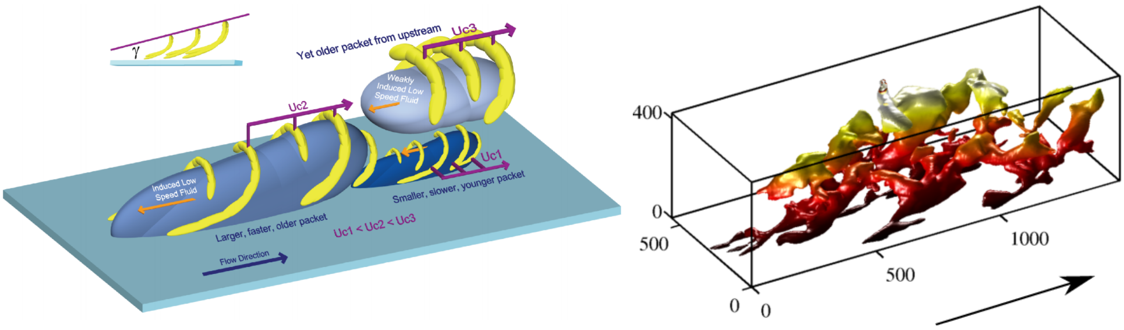

Figure 1: *(a) Hairpin-packet paradigm imagined by Adrian el al. (2000). (b) Example of a three-dimensonal ejection colored with the distance from the wall by Lozano-Durán et al. (2012). The axis are scaled in wall units and the arrow indicates the streamwise direction.*

An alternative model has been recently proposed by Lozano-Durán et al. (2012) extending previous works by del Álamo et al (2006) and Flores et al. (2010), in which the logarithmic layer is explained in terms of ejections, sweeps and clusters of vortices. These structures are intrinsically turbulent and complex objects, as the example shown in figure 1(b), in contrast to the simpler hairpins.

The goal of the present talk is to present a new multiscale structural model for the logarithmic layer of wall-bounded turbulence and to validate or refute the models above.

In order to accomplish this, a novel approach is proposed based on the temporal tracking of three-dimensional coherent structures in a time-resolved direct numerical simulation of a turbulent channel at $Re_\tau = 4200$ (Lozano-Durán et al. 2014). By making use of the time-resolved data, we extend the structural time-dependent analysis to the logarithmic layer in terms of three-dimensional clusters of vortices, sweeps and ejections.

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The eddies are identified as connected regions of intense tangential Reynolds stress and discriminant of the velocity gradient, and tracked in time. Once their evolutions are properly organized, they provide the necessary information to characterize eddies from birth to death. Eddies are born at all distances from the wall, although with higher probability near it, where the shear is strongest. Most of them stay small and do not last for long times. However, there is a family of eddies that become large enough to get attached to the wall while they reach into the logarithmic layer. They can be considered the best candidates for Townsend's attached eddies found until now. They are geometrically self-similar, with sizes and lifetimes proportional to their distance from the wall. Eddies associated with ejections move away from the wall with $dy/dt = u_\tau$, and their base attaches very fast at the beginning of their lives. Conversely, sweeps move towards the wall at $-u_\tau$, and attach later. In both cases, they remain attached for $2/3$ of their lives. In the streamwise direction, eddies are advected and sheared by the local mean velocity.

The model proposed above shares a few properties with the hairpin's packet paradigm, like being consistent with the logarithmic velocity profile and the self-similar nature of the structures involved. Nevertheless, the results reveal crucial differences that make the two models no longer compatible. These differences will be discussed.

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CAREFUL VISUALIZATION OF ACCURATE DNS DATABASE REVEALS TURBULENT SPOT IN THE NEAR-WALL REGION OF FULLY TURBULENT BOUNDARY LAYER

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Zero-pressure-gradient flat-plate boundary layer (ZPGFPBL) beneath a continuous flow of freestream nearly-isotropic turbulence (FST) has been computed with direct numerical simulation (DNS) on 4 billion grid points. The boundary layer's momentum thickness Reynolds number develops from 80 to 3000, with a corresponding FST decay from 3 to 0.8 percent. The present DNS distinguishes from several previous bypass transition simulations in that the current skin friction coefficient overlaps with the Blasius solution over an extended region prior to breakdown, and agrees very well with turbulent ZPGFPBL experimental data over an extended fully-turbulent region after the completion of transition. In particular, the agreement with the Melbourne data by Erm and Joubert is excellent over an extended region. The present DNS distinguishes from other DNS turbulent boundary layer work in that the current turbulent boundary layer deveops from an upstream clean bypass transition process with no compromises in the streamwise boundary condition such as recycling. In the turbulent boundary layer, profiles of the rate of dissipation for turbulence kinetic energy are consistent with the scaling argument of the -1 power law within the inertial sublayer. The DNS dissipation profiles obey this -1 power law even at the very low Reynolds number $Re_\theta = 670$ near the completion of transition.

After a thorough evaluation and validation of the statistics including frequency spectra, a detailed and careful visualization of the DNS database was conducted using the swirling strength vortex identifier. In the bypass transition region, the study reveals vortex dynamics of the bypass transition in the narrow sense that has not been achieved in previous studies. We define bypass transition in the narrow sense here as a superposition of the ZPGFPBL, in its freestream, with the simplest possible turbulent flow – initially homogeneous isotropic turbulence of (mildly) finite amplitude. The visualized bypass transition process differs from the streak growth, streak secondary instability, and streak breakdown scenario reported in many previous bypass transition studies. Streaks are present, but they are not dynamically important in this breakdown process since here they occur downstream of infant turbulent spots. It is therefore quite possible that a subcategory of boundary layer bypass transition in the narrow sense might be modeled as the secondary instability of natural transition with merely the TS-wave being circumvented. In the fully turbulent boundary layer region above $Re_\theta = 2500$, along the wall-normal direction, several layers of hairpin-dominated vortex structures are identified. Above $y = 0.7\delta$, the preponderance of hairpin forest is quite obvious, and the individual hairpin vortices are large and can can be easily followed in time for a relative long period. Between $0.2\delta < y < 0.6\delta$, the hairpin structures still dominate but are often tangled and twisted, and are less clean then those in the upper layer. The life span is also shorter. It is very interesting to find, through careful, objective and patient visualization study, a layer of hairpin dominated vortex structures in the near-wall region below $y < 0.2\delta$. These near-wall structures are much smaller, and have a much shorter lifespan then those in the outer layer. Furthermore, we identified turbulent spot like concentrations of strong vortex structures surrounded by relatively weaker and quieter boundaries below $y < 0.1\delta$. These localized concentrations of strong but tiny hairpin vortices have a vague apparent similarity to the transitional turbuent spot. The similarity is first reflected in how they spread and grow with space-time; the similarity is also reflected in their common trailing tails in the form of a narrow hairpin street. We believe this is the first time that the concept of "turbuelent turbulent-spot" has been identified and observed in the near-wall region of fully-turbuent, zero-pressure-gradient turbulent boundary layer.

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NUMERICAL INVESTIGATION OF TURBULENT PIPE FLOW STRUCTURES AND THEIR DEPENDENCE ON WALL TEMPERATURE

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It has been more than a century since the significance of wall bounded turbulence has been realized and in the meantime it has remained an attractive topic for both experimental and numerical studies. Among canonical forms of wall turbulence, pipe flow has received special attention due to its industrial and practical relevance. In this regard the goal of reducing energy losses finds even more grounds while dealing with turbulent flows where dissipation plays a decisive role in causing energy losses. This fact, together with the increasing interest in physics of turbulent pipe flow at high Reynolds numbers have motivated construction of experimental facilities, enabling investigations at highly turbulent regimes. The same motivation has triggered countless numerical studies in terms of Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) as a result of recent advances in high performance computing. Study of coherent structures at high Reynolds numbers remain to be under focus to this day with the aim of reaching a deeper understanding about their nature. Large Scale Motions (LSM) are described as packets of individual eddies and are claimed to have streamwise scale of 2-3 pipe radii [1]. On the other hand Very Large Scale Motions (VLSM) are interpreted differently by various scientists as joint series of vorticity packets [1] or as meandering superstructures [2] with stream wise length scale of 8-16 pipe radii. At this stage many key questions are still under dispute concerning identification and scaling of such structures.

In spite of vast range of experimental and numerical data available, many of the fundamental questions regarding structure and scaling of wall turbulence and coherent structures are yet to be answered. Such uncertainties become even bolder at higher Re numbers and answering them gets more essential and more demanding at the same time. This constraint is far more limiting in terms of numerical simulations owing to extremely high computation time needed to resolve all the flow structures. The present research aims to shed light on a number of such controversies in ranges of Reynolds numbers for which sufficient numerical data does not exist. Furthermore, majority of numerical studies in the past have been concentrated on isothermal wall boundary condition whereas in this study effect of temperature changes in the wall has been also taken into consideration.

In the first part of present study, LES has been performed for turbulent viscous flow in a pipe at four different regimes ranging from bulk Reynolds number of $Re_b = 5300$ to $Re_b = 37700$ (Fig. 1). Stream wise periodic length of $25R$ is selected for a pipe of radius R. Mean flow features, streamwise turbulence intensities and kinetic energy budget of mean flow and turbulent fields are compared with DNS data by El Khory et al. [3] to validate the results.

In the second part, DNS of turbulent pipe flow is performed at a range of bulk Reynolds numbers starting from $Re_b = 4 \times 10^4$ to provide flow properties comparable with the experimental results from CoLa-Pipe (Cottbus Large Pipe) [4]. In the first place the investigations are aimed at numerical study of recent areas of focus including scaling of wall turbulence (mean flow features, turbulence fluctuations) as well as scaling and identification of LSMs and VLSMs. Furthermore and more prominently, effect of wall temperature changes in all the mentioned flow features and structures are to be clarified. Various thermal wall boundary conditions (adiabatic, isothermal) are simulated and their influence on the size and interaction of structures are to be investigated in detail. Gained results from the present study are to be compared to experimental data from CoLa-Pipe.

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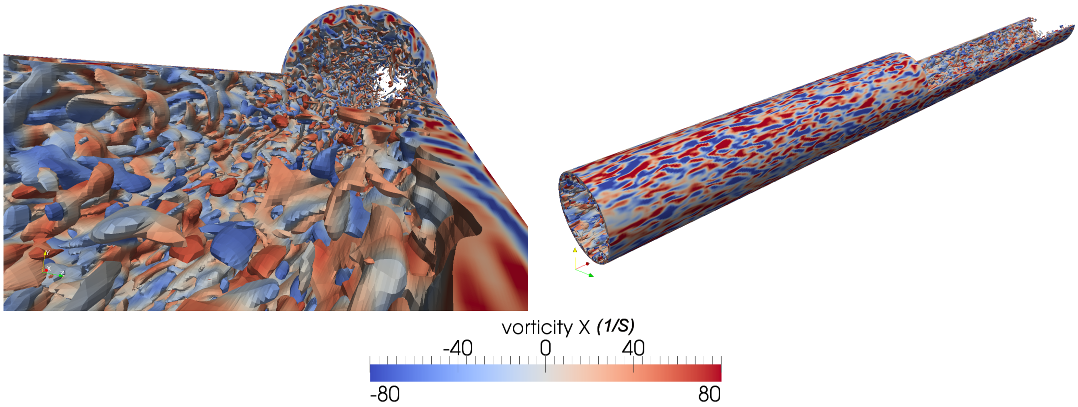

Figure 1: *LES of turbulent pipe flow at* $Re_b = 11700$ *(shear Reynolds number of* $Re_\tau = 360$*) - Vorticity iso-surfaces colored by streamwise vorticity magnitude*

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