ERCOFTAC
European Research Community
On Flow, Turbulence And Combustion

8th ERCOFTAC SIG 33 Workshop

Global Instabilities of Open Flows

Nice, France

June 30 – July 2, 2010

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Organisers:

François Gallaire (EPFL)
Jean-March Chomaz (LadHyX)
Ardeshir Hanifi (FOI)

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Wedensday, June 30

	13:00	**Registration**	
	13:50	**Opening statements**	
			Session 1 (Chairman: Uwe Ehrenstein)
Invited talk	14:00	**Matthew JUNIPER**	**Bypass transition in thermoacoustics**
	15:00	Jean-Christophe ROBINET	Linear And Non-linear Dynamics Of A Cavity Flow *F. Alizard, X. Merle, J.-C. Robinet, X. Gloerfelt*
	15:30	Jonathan HEALEY	Global Instability Of The Rotating-disk Boundary Layer *J. J. Healey*
Coffee	16:00		
			Session 2 (Chairman: Jonathan Healey)
	16:30	Outi TAMMISOLA	Effect Of Surface Tension On Global Instability Of Wakes *O.Tammisola, F. Lundell, D. Söderberg*
	17:00	Milos ILAK	Adjoint-based Stability And Sensitivity Analysis Of A Jet In Crossflow *M. Ilak, Ph. Schlatter, S. Bagheri, D. S. Henningson*
	17:30	Hugh BLACKBURN	Lagrangian-based methods for computing optimal boundary perturbations *H. Blackburn, X. Mao, S. Sherwin*
	18:00	Peter SCHMID	Spatial analysis of a jet in crossflow *P.J. Schmid, S. Bagheri*

Thursday, July 1

			Session 3 (Chairman: Dan Henningson)
Invited talk	9:00	**Spencer Sherwin & Philip Hall**	**Nonlinear unstable solutions and the transition to turbulence**
	10:00	Yongyun HWANG	A Self-sustaining Process At Large-scale In The Turbulent Channel Flow *Y. Hwang, C. Cossu*
Coffee	10:30		
	11:00	Paul MANNEVILLE	Transition wall-bounded flows: paradigmatic features of plane Couette flow (hydrodynamic (in)stability, laminar/turbulent coexistence, spots, …) *P. Manneville*
	11:30	Håkan WEDIN	Transitional Duct Flow *H. Wedin, D. Biau, A. Bottaro, M. Nagata, S. Okino*
	12:00	Yohann DUGUET	Edge States And Turbulence Spreading In Subcritical Shear Flows *Y. Duguet, A.P. Willis, R.R. Kerswell, P. Schlatter, D.S. Henningson, B. Eckhardt*
Lunch	12:30		
			Session 4 (Chairman: Hugh Blackburn)
Invited talk	14:00	**Dan HENNINGSON**	**Model Reduction For Flow Control**
	15:00	Fulvio MARTINELLI	Nonmodal Stability Of Plane Poiseuille Flow Of A Dielectric Liquid In Presence Of Unipolar Injection *F. Martinelli, P. J. Schmid*
	15:30	Shervin BAGHERI	Flow Analysis Using Koopman Modes *S. Bagheri, K. Chen, C.W. Rowley, I. Mezic*
Coffee	16:00		
			Session 5 (Chairman: Paul Manneville)
	16:30	Philippe MELIGA	Control of vortex breakdown in a contracting pipe *P. Meliga, F. Gallaire*
	17:00	Stefania CHERUBINI	The Breakdown Of 3D Centrifugal Global Modes In A Separated Boundary Layer *S. Cherubini, J.-C. Robinet, P. De Palma, F. Alizard*
	17:30	Oliver SCHMIDT	Linear Stability Of Compressible Flow In A Streamwise Corner *O. T. Schmidt, U. Rist*
	18:00	Jan PRALITS	Sensitivity Analysis Of The Finite-amplitude Vortex Shedding Behind A Cylinder *J. Pralits, F. Giannetti, P. Luchini*

Banquet

Friday, July 2

Session 5 (Chairman: Peter Schmid)

Invited talk	9:00	**Carlo Cossu**	**Optimal perturbations and coherent structures in turbulent shaer flow**
	10:00	Uwe EHRENSTEIN	Instability Of Averaged Low-speed Streaks In Near-wall Turbulence With Adverse Pressure Gradients *U. Ehrenstein, M. Marquillie, J.-P. Laval*
Coffee	10:30		
	11:00	Xavier GARNAUD	The application of Selective Frequency Damping to the computation of global modes of a compressible jet *X. Garnaud, L. Lesshaft, P.J. Schmid, P. Huerre, J.-M. Chomaz*
	11:30	Viktor KOZLOV	Localized Structures Of The Boundary Layer At High Free Stream Turbulence Level *M.M. Katasonov, V. V. Kozlov*
	12:00	Antonios MONOKROUSOS	Optimal Disturbances For Flow Above A Flat Plate With An Elliptic Leading Edge *A. Monokrousos, L.U. Schrader, L. Brandt, D. S. Henningson*
	12:30	Alexander KOSINOV	Natural And Controlled Disturbance Experiments To Study Linear Stability And Receptivity Of Supersonic Boundary Layer On Thin Swept Wings *A.D. Kosinov, N.V. Semionov, Yu.G. Yermolaev*

Triggering in thermoacoustics: non-normality, transient growth and bypass transition

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A stable flame placed inside an empty tube sometimes makes a humming noise and sometimes is quiet. A sufficiently large impulse can knock the system from one state to the other and back again. This is known as triggering. On an industrial scale, these thermoacoustic oscillations can be catastrophic. Consequently, in rocket engine tests, large explosions are set off inside the engine in order to test its susceptibility to triggering. Some seemingly-stable engines, however, are susceptible to triggering by disturbances of the order of the background noise level. The aim of this theoretical and numerical paper is to understand this process better by considering a toy model: a hot wire within a tube. Non-linear adjoint looping is used in order to find, by brute force, the initial perturbation that triggers to self-sustained oscillations from the lowest possible energy. This is called the 'most dangerous initial state'. The trajectory from this perturbation in state space evolves to the stable periodic solution by first growing towards an unstable periodic solution. This is analogous to bypass transition to turbulence in hydrodynamics but differs slightly because the non-linear terms do not conserve energy. The monodromy matrix around this unstable periodic solution is non-normal and its first left singular vector has similar characteristics to the most dangerous initial state. The linear stability operator around the stable fixed point at zero amplitude is also non-normal but its first left singular vector is not similar to the most dangerous initial state. At the energies required for triggering, the linear optimal around the stable fixed point has very little transient growth. This shows that triggering is achieved by maximizing non-normal transient growth towards the unstable periodic solution rather than that away from the stable fixed point. This procedure also gives the maximum amplitude of perturbations that can never lead to triggering. This paper briefly considers the implications of this for the noise characteristics that will cause triggering from low amplitudes in thermoacoustic systems.

Linear and non-linear dynamics of a cavity flow

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The emergence of unsteadiness by a flow past a cavity has been widely studied during the last fifty years because of its practical interest and because of the variety of theoretical questions [1].

The objective of the present proposal is to analyse these different physical mechanisms in an incompressible regime at low Reynolds number. In such a regime, the underlying three-dimensional space and time dynamics can be highlighted through a global modes analysis. In particular, we propose to shed light on the competitive or collaborative nature of the different global modes that take place in such a configuration.

Following previous work of Barbagallo *et al.* [2] on cavity flow, we propose to analyse an open-cavity defined by $r = 1$, and Re_L varying between 3500 and 7500 inducing a value for δ between $50 < \delta < 100$. Finally, an infinite spanwise extent is considered. The two-dimensional critical Reynolds number associated with such a case is $Re_L = 4140$. A 2D multi-domains incompressible Navier-stokes solver discretized by finite differences scheme of 6th-order is used to solve the non-linear dynamics and the base-flow in subcritical as well as super-critical regime. In the latter, a filtering strategy is employed to achieve the convergence of a stationary solution of the Navier-Stokes operator. The 2D and 3D global modes are obtained by the so-called time-stepper technique where snapshots are built by successive time integration of the Navier-Stokes operator linearized about the base flow. The Koopman modes are also obtained by a similar method from the direct numerical simulation. The instantaneous 2D flow at $Re_L = 7500$ are illustrated in Figure 1. One may observe a strong unsteadiness occurring above the cavity and along the shear layer inside the cavity. A global linear stability analysis relies the existence of the unsteadiness to unstable global modes depicted in Figures 2. These global modes are either related to the shear layer, either inside the cavity, highlighting selective noise amplifier and resonator mechanisms in competition. Moreover, because of an important coupling mechanisms, the nonlinear effects are usually dominant. To study the influence of nonlinearities, the Koopman modes are calculated and compared to global modes from linear analysis.

For the ERCOFTAC workshop, we would like to further explore the space and time dynamics of such a configuration by identifying 2D and 3D global and Koopman modes associated with the shear layer above the cavity and those with the flow inside the cavity for several Reynolds numbers. Finally, these results will be compared with 3D direct numerical simulation.

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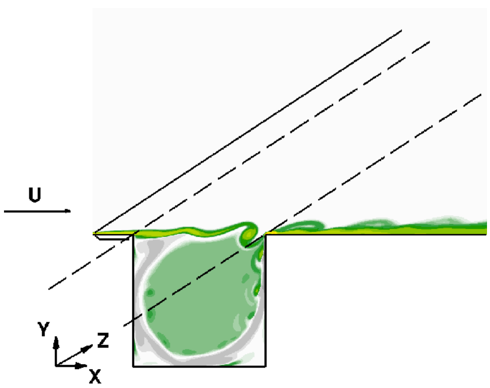

Figure 1: Instantaneous vorticity fields for $Re_L = 7500$.

References

[1] Gloerfelt, X., Cavity noise, *Von Karman Institute. VKI Lectures: Aerodynamic noise from wall-bounded flows*, 2009.

[2] A. Barbagallo, D. Sipp and P. Schmid, Closed-loop control of an open cavity flow using reduced order models. Journal of Fluid Mechanics, *J. Fluids Mech.*, **641**, 1–50, 2009.

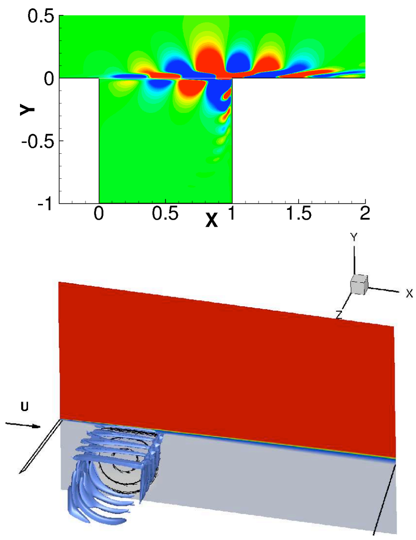

Figure 2: Spatial structure of (a) 2-D and (b) 3-D most unstable global modes.

Global instability of the rotating-disk boundary layer

J. J. Healey*

The rotating disk boundary layer has stability characteristics in common with three-dimensional boundary layers on swept wings. Close to the axis of rotation the flow is stable and laminar, further out it becomes unstable to stationary vortices and travelling waves, and at a certain distance it undergoes a transition to turbulence. It had been assumed that the instabilities were convective, and that variations in the Reynolds number, *Re*, for transition between different experiments were due to different levels of surface roughness, and vibration, of the disk. However, Lingwood[1] showed that the flow becomes locally absolutely unstable (AU) at a particular *Re* whose value is close to that observed for laminar-turbulent transition. She argued that this would cause wavepackets to slow down, and energy to build up, at this radius thereby promoting transition. Nonetheless, DNS of the linearized Navier-Stokes equations shows that wavepackets pass through the locally AU region[2], implying that the flow is globally stable. Recent experiments seem to confirm this[3], but if disturbances are large enough then a nonlinear global mode can be excited[4].

In this paper we argue that although the *infinite* rotating disk is linearly globally stable, the *finite-radius* rotating disk can be linearly globally *unstable*. All that is required is a locally AU flow at the edge of the disk, and this will excite an unstable global mode. The essential features can be illustrated using the complex Ginzburg-Landau equation with spatially varying coefficients (which describes wavepackets in weakly inhomogeneous media). Figure 1 shows solutions in the $X-T$ plane for an impulsive disturbance which is stable for $X<0$, convectively unstable for $0<X<25$ and locally AU for $X>25$, but globally stable when unbounded (a). When the disturbance hits the downstream boundary the unstable global mode is excited (b). Nonlinearity can saturate this growth and produce a steep-fronted global mode at the convective-absolute boundary (c). The position of this front has a weak dependence on the location of the downstream boundary. Remarkably, the position of the transition front in experiments shows the same dependence on the *Re* at the edge of the disk.

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[1] Lingwood, *J. Fluid Mech.* **299**, 17–33 (1995).
[2] Davies & Carpenter, *J. Fluid Mech.* **486**, 287–329 (2003).
[3] Othman & Corke, *J. Fluid Mech.* **565**, 63–94 (2006).
[4] Pier, *J. Fluid Mech.* **487**, 315 (2003); Viaud, Serre & Chomaz, *J. Fluid Mech.* **598**, 451 (2008).

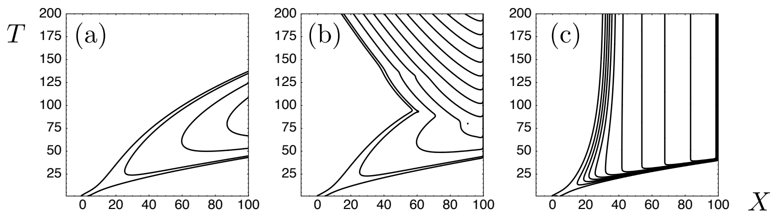

Figure 1: Contours of wave-amplitude, $A(X,T)$. (a) b.c. $A\to 0$ as $X\to\infty$: global stability. (b) b.c. $A(100,T)=0$: global instability. (c) With stabilizing nonlinearity.

Effect of Surface Tension on Global Instability of Wakes

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Here we investigate how surface tension affects the global linear instability of a 2D co-flow wake. In the model configuration, an inner fluid with low velocity and an outer with high velocity enter into a channel, introducing a wake region, which gradually disappears while a parabolic profile develops downstream (figure 1).

In addition to the three parameters (Reynolds number Re, shear ratio Λ and confinement h) considered in our previous study (Tammisola 2009), also the *Weber number* $We = \rho U_2^2 h_1/\gamma$ now enters the problem, where ρ is the density, U_2 velocity of the outer fluid at the inlet, h_1 the half width of the inner fluid at the inlet and γ the surface tension coefficient. Both fluids are constrained to have the same density and viscosity; the only effect of the interface comes from that its curvature becomes dynamically important, through the action of surface tension between the fluids.

Two wakes with different Re, Λ and h are studied in detail for varying Weber numbers. The results show that the influence of surface tension is large on the frequency, growth rate and shape of the global mode(s). Finally, we attempt to confirm and explain the surface tension effect from observations made in a local analysis of the same flow field.

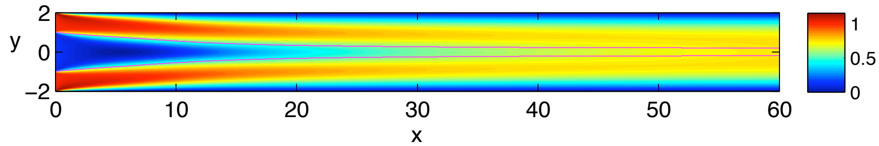

Figure 1: Streamwise base flow velocity for an example wake ($Re = 316, h = 1, \Lambda^{-1} = -1.32$). The position of the interface between the fluids is given by the magenta line.

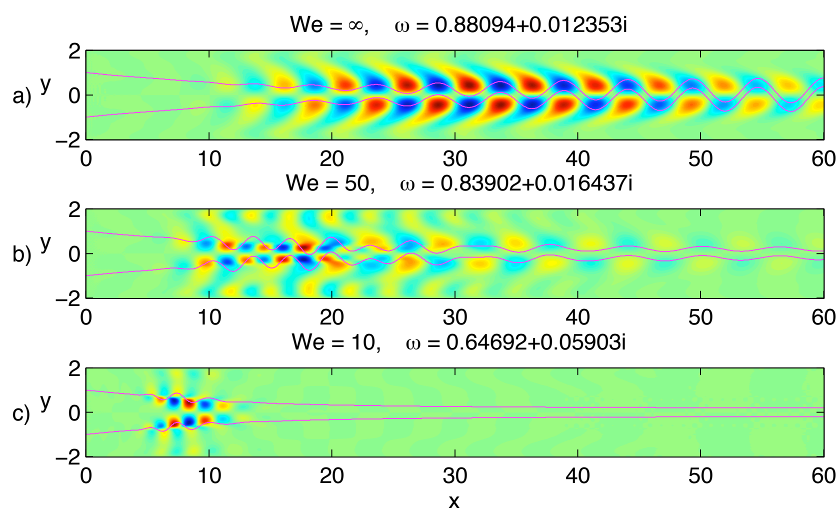

Figure 2: Real part of the streamwise disturbance velocity for the most unstable global mode of the same example wake as in figure 1, with increasing surface tension (decreasing We) from top to bottom. The eigenvalue ω is given above each figure. The disturbed position of the interface is illustrated by the magenta line, but its oscillation amplitude is only determined up to a constant.

References

Tammisola O., Linear stability of plane wakes and liquid jets: global and local approach, Licentiate thesis, KTH Mechanics, Royal Institute of Technology, April 2009

Adjoint-based stability and sensitivity analysis of a jet in crossflow

M. Ilak*, P. Schlatter*, S. Bagheri*, D. Henningson*

We compute adjoint global eigenmodes for a jet in crossflow and perform a sensitivity analysis of the flow. The global eigenmodes for the jet in crossflow at jet inflow ratio $R = 3$ were first computed by Bagheri et al[1], and it was found that the flow is globally unstable and that the unstable eigenmode with the highest growth rate has the shape of a wave packet located on top of the counter-rotating vortex pair (CVP), and is associated with instabilities on the shear layer that develops on the jet trajectory. In this work the corresponding adjoint eigenmodes are computed. We find that the leading adjoint eigenmode represents a localized structure near the wall, located slightly upstream of the jet orifice in the region where the Kelvin-Helmholtz instability, which gives rise to the shear layer, is triggered. We also study the sensitivity to body forces, which corresponds to the magnitude of the adjoint mode, and the sensitivity to localized feedback, which corresponds to the overlap of the global mode and the corresponding adjoint mode[2]. In addition, we investigate the sensitivity to base flow modifications, which is particularly useful since it indicates where in the flow passive control devices may be placed to stabilize or destabilize it.

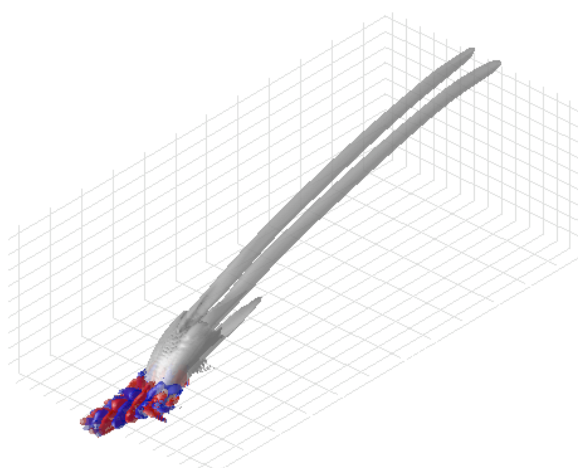

Figure 1: The λ_2 vorticity criterion for the base flow (grey), is shown together with the wall-normal velocity of the leading adjoint eigenmode (red and blue isocontours correspond to positive and negative velocities respectively).

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[1]Bagheri, S. et al, *J. Fluid Mech.*, **624**, 2009.

[2]Marquet, O. et al., *J. Fluid Mech.*, **615**, 2008.

Lagrangian-based methods for computing optimal boundary perturbations

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Xuerui Mao and Spencer J Sherwin
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Methods to compute *initial conditions* that will generate maximum linear energy growth at a given time are now well established in fluid mechanics, with a variety of methods in use. In open flows and many engineering applications however, we are often interested in the effect of perturbations to *boundary conditions*, which might be interpreted e.g. as transpiration at a wall or as velocity fluctuations that advect into a flow domain. These can be considered as either problems of flow control or receptivity.

The classical optimal initial condition problem can be stated either as an eigenvalue problem or as an optimization problem, in which a Lagrangian functional

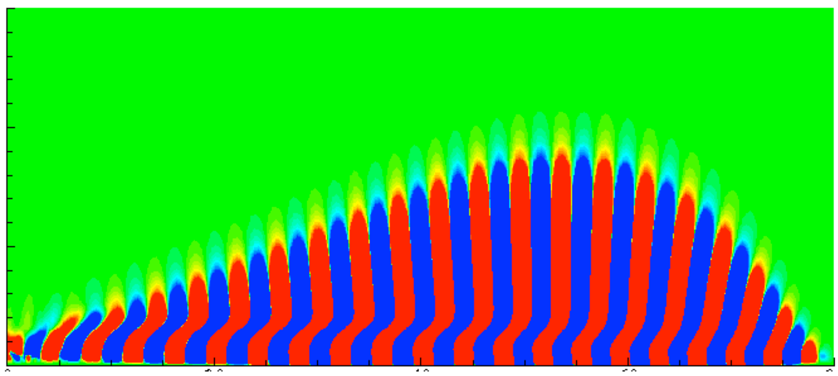
$$\mathcal{L} = \frac{(\mathbf{u}_T, \mathbf{u}_T)}{(\mathbf{u}_0, \mathbf{u}_0)} - \langle \mathbf{u}^*, \partial_t \mathbf{u} - L(\mathbf{u}) \rangle$$

is maximized at finite time T and where the first term is represents the energy growth to be maximized and the second term imposes the linearized Navier–Stokes equations $\partial_t \mathbf{u} - L(\mathbf{u}) = 0$ (and where the adjoint velocity $\mathbf{u}^*$ acts as a Lagrange multiplier). The Lagrangian can be maximized using methods discussed e.g. by Schmid (2007).

For optimal boundary perturbations (or optimal control via boundary transpiration) the methodology is extended in order to vary the ratio of norms, and more terms are included to impose initial conditions. For example in our application

$$\mathcal{L} = \frac{(\mathbf{u}_T, \mathbf{u}_T)}{T^{-1}\{\mathbf{u}_c, \mathbf{u}_c\}} - \langle \mathbf{u}^*, \partial_t \mathbf{u} - L(\mathbf{u}) \rangle - (\lambda, \mathbf{u}_0)$$

where $T^{-1}\{\mathbf{u}_c, \mathbf{u}_c\}$ represents a boundary-integral inner product of perturbation energy averaged over the time interval and the last inner product imposes a zero initial condition. The boundary perturbation can be steady or time-varying. The methodology has been applied here to inflow perturbations to a Batchelor vortex flow at swirl ratio q=3 and we see below contours of streamwise velocity perturbation for a steady inflow perturbation as the perturbation reaches the outflow boundary.



Spatial analysis of a jet in crossflow

P.J. Schmid*and S. Bagheri†

Jets in crossflow are a common occurrence in many fluid systems and thus have received a great deal of attention from experimentalists, theoreticians and computational scientists. Recently, a global stability analysis of the jet in crossflow has been reported[1] that identifies the commonly observed Kelvin-Helmholtz instability of the cylindrical shear layer as well as instabilities in the near-wall wake behind the jet exit. This temporal analysis was based on the linearized Navier-Stokes equations coupled to an iterative Arnoldi technique.

In this study, we attempt a spatial analysis of the Kelvin-Helmholtz instability based on nonlinear simulations of the jet in crossflow. In addition, we describe the spatial growth along a curved streamline emanating from the jet exit and given by the mean velocity field (see the black line in figure 1(a)). After the direct numerical simulations have reached a saturated (but oscillatory) state, flow fields projected onto $N = 111$ planes normal to the curved streamline are extracted. The flow fields are Fourier-transformed in time and velocity fields corresponding to the most dominant Strouhal number are isolated. A linear mapping between these fields is then computed using the Koopman analysis[2]/dynamic mode decomposition[3] and this mapping is subsequently analyzed using an eigenvalue decomposition. The eigenvalue correspond to a spatial wavenumber and spatial growth rate (measured along the curved streamline); from the associated eigenvectors we can reconstruct the corresponding spatial shape. Contrary to stability theory of linearized operators, these structures come with an amplitude which measures the content of the respective structure within the processed data sequence. The most dominant mode (figure 1(b)) and a representative higher mode (figure 1(c)) show a distinct vortical pattern along the flanks of the counter-rotating vortex sheet — a feature that is prevalent in the direct numerical simulations. A more comprehensive and detailed study of these structures and their spatial dynamics will be given at the ERCOFTAC-SIG meeting.

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†Department of Mechanics, Royal Institute of Technology (KTH), 10044 Stockholm, Sweden
[1]Bagheri, Schlatter, Schmid, Henningson, *JFM* **624** (2009)
[2]Rowley, Mezic, Bagheri, Schlatter, Henningson, *JFM* **641** (2009)
[3]Schmid, *JFM* (in press) (2010)

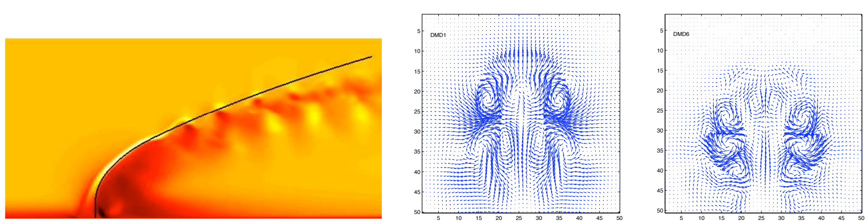

Figure 1: Spatial analysis of a jet in crossflow. (a) Snapshot from a direct numerical simulation of a jet in crossflow, including (in black) the streamline starting at the jet exit and defined by the mean velocity profile. (b) Most dominant spatial dynamic/Koopman mode. (c) Representative higher dynamic/Koopman mode.

Streamwise vortices in shear flows: harbingers of transition and the skeleton of coherent structures

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The relationship between asymptotic descriptions of vortex-wave interactions and more recent work on 'exact coherent structures' is investigated. In recent years immense interest has been focused on so-called self-sustained processes in turbulent shear flows where the importance of waves interacting with streamwise vortex flows has been elucidated in a number of papers. In this presentation it is shown that the so-called 'lower branch' state which has been shown to play a crucial role in these self-sustained processes is a finite Reynolds number analogue of a Rayleigh vortex-wave interaction with scales appropriately modified from those for external flows to Couette flow the flow of interest here. Remarkable agreement between the asymptotic theory and numerical solutions of the Navier Stokes equations is found even down to relatively small Reynolds numbers thereby suggesting the possible importance of vortex-wave interaction theory in turbulent shear flows. The formulation and asymptotic structure developed is directly applicable to flows in 2D channels of arbitrary cross-section. The minimum drag configuration associated with a fixed spanwise wavenumber is determined as a function of the downstream wavelength and this points to the crucial importance of long waves evolving on the spatial scale appropriate to the roll/streak flow. The stability of the lower branch states is also discussed and for Couette flow we show that there is a single unstable mode with growth rate proportional to the Reynolds number raised to the power $-1/2$. The instability is concentrated in a layer which surrounds the critical layer and destroys the wave leaving the roll/streak flow to decay on a $1/R$ timescale.

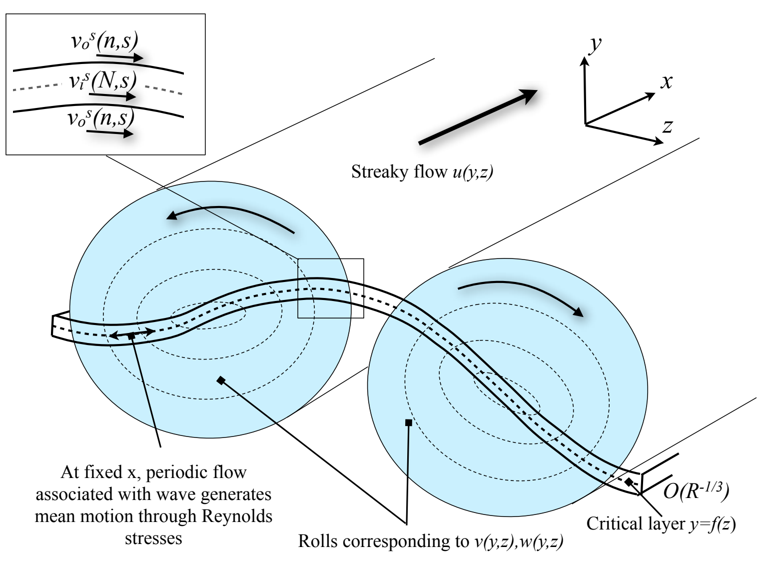

Figure 1: Sketch of critical layer intersecting rolls. The location of the critical layer varies with z where the Reynolds stresses associated with wave trapped in the critical layer generate a mean motion leading to jumps in the roll normal shear and pressure across critical layer with all other components of shear and velocity continuous.

A self-sustaining process at large-scale in the turbulent channel flow

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Abstract:

The near-wall region of wall-bounded turbulent flows has been understood as the most important place where an independent self-sustaining cycle exists [1], and the associated coherent motions in this region have been rigorously described with traveling waves [2] and/or unstable periodic orbits [3] in the phase space. On the other hand, in the outer region, turbulent motions have often been thought to be produced from the active near-wall cycles via so called the 'bottom-up' process [4]. However, recent investigations revealed that outer layer motions can experience significant non-normal amplifications [5-7]. These findings suggest that self-sustaining processes could also exist at large scale. In this study, we consider a fully-developed turbulent channel at $Re_\tau \approx 550$. We show that large-scale motions in the outer region can sustain even when smaller-scale structures in the near-wall and the logarithmic regions are artificially quenched. The self-sustaining process is found to be qualitatively similar to that in the near-wall region, and it is active only at the lengths scales larger than $L_x \times L_z \approx 3h \times 1.5h$, in good accordance with the most energetic length scales observed in the outer region.

References

[1] Jiménez, J. & Pinelli, A. 1999 The autonomous cycle of near-wall turbulence. *J. Fluid Mech.* **389**, 335.

[2] Waleffe, F. 2001 Exact coherent structures in channel flow. *J. Fluid Mech.* **435**, 93.

[3] Kawahara, G. & Kida, S. 2001 Periodic motion embedded in plane Couette turbulence: regeneration cycle and burst. *J. Fluid Mech.* **449**, 291.

[4] Adrian, R. J. 2007 Hairpin vortex organization *Phys. Fluids* **539**, 199.

[5] del Álamo & Jiménez, J. 2006 Linear energy amplification in turbulent channels *J. Fluid Mech.* **559**, 205.

[6] Pujals, G., Garcia-Villalba, M., Cossu, C. & Depardon, S. 2009 A note on optimal transient growth in turbulent channel flows. *Phys. Fluids* **21**, 015109.

[7] Hwang, Y. & Cossu, C. 2010 Amplification of coherent streaks in the turbulent Couette flow: an input-output analysis at low Reynolds number. *J. Fluid Mech.* **643**, 333.

Transitional wall-bounded flows: paradigmatic features of plane Couette flow

Paul Manneville
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We consider the transition to turbulence in plane Couette flow (PCF) as the prototype of problems arising in wall-bounded flow with non-inflectional base flow profiles. They do not experience low-R instability and, as such, are prone to direct transition via localised finite amplitudes perturbations (turbulent spots). Together with Poiseuille pipe flow in a smooth straight circular tube (PPF), PCF represent the extreme case of a system which is stable for all R. Here we present the general phenomenology of that flow and discuss elements of interpretation taken from recent theoretical/numerical approaches, namely dynamical systems theory (temporal chaos, and edge states), spatiotemporal intermittency via modelling, and numerical simulations in extended geometry relevant to experiments.

As to the phenomenology, R being defined as Uh/ν, where U is the speed of the counter-translating plates, $2h$ the distance between them, and ν the kinematic viscosity of the fluid, experiments [1] show that, upon triggering spots, immediate decay is obtained for $R<280$, decay after long transients for $280<R<325=R_g$ and sustained patchy turbulence for $R_g<R$. As R increases, turbulent patches get organised in oblique bands that progressively merge to leave room to featureless turbulence for $R\sim415=R_t$. Similar turbulent bands are also observed in counter-rotating Taylor-Couette flow [2,1], plane Poiseuille flow [3] and shear flow between close enough counter-rotating discs [4]. An analogous transition is observed in PPF (puff/slug regime) [5].

A large body of literature has been devoted to the lower end of the transitional range, around and below R_g, analysing the flow in terms of Minimal Flow Unit (periodic domain of size just sufficient to observe turbulence), which legitimates an approach in terms of low dimensional dynamical systems. The obtained phase space has complicated structure (unstable periodic orbits known as UPO, homoclinic tangle) "explaining" spots decay as the result of chaotic transients with exponentially decaying lifetime distributions [6]. The framework has further been used to find unstable exact solutions [7] expected to appear furtively as observable local structures in the flow, and unstable edge states [8] identified as germs in the laminar-to-turbulent transition.

The approach however turns to be of limited scope in view of the experimental situation where large aspect ratios are of interest. General ideas put forward by Pomeau to account for the transition [9], the analogy between a subcritical bifurcation and a 1st-order phase transition in thermodynamics, the concepts associated to growth phenomena (front propagation, critical germ), spatiotemporal intermittency viewed as a stochastic process connected to percolation, have been implemented in a reduced model showing the relevance of these ideas, but failed to account for the presence of a distinct upper transitional range with bands [10]. In contrast, bands have been obtained in fully resolved DNS of the Navier-Stokes equations, first in narrow domains specially oriented to point out their existence [11], and next in extended domains of interest to the experiments [12]. Subsequently, under-resolution understood as a modelling strategy [13] has shown that the bands were preserved provided that the cross-stream resolution was sufficient to render very large streamwise structures present in wall-bounded flows [14].

While the standard fluid mechanics approach helps us elucidate the sustainment mechanisms of turbulence (streamwise vortices, lift-up, streaks, and streak instability

[15]), no information about band formation from the first principles has been gained up to now [16]. Dynamical systems theory turned out to be valuable in stressing the complex structure of the state space far from base state. But, setting the frame in a strictly temporal context and failing to recognise that laminar-turbulent coexistence in physical space is relevant, it led to misleading and/or provocative claims about the existence of turbulence. Lessons from equilibrium thermodynamics, namely the analogy with phase transitions and R_g understood in terms of Maxwell plateau in a 1st-order phase transition, remains to be exploited further. Finally, low resolution DNS-allowing numerical experiments at low cost-shows that band formation is a robust phenomenon and raise questions about the role of the flow's cross-stream dependence (no bands if resolution below some limit) that points to the physics behind the process. These findings might be of interest for other wall-bounded flows where turbulent patterns also set in at an intermediate stage of their transitions to turbulence [2-5] and for boundary layers.

References:

[1] Bottin, PhD Thesis, 1998; Bottin et al., Europhys. Lett. 43 (1998) 171-176; Prigent, PhD thesis, 2001; Prigent et al. Physica D 174 (2003) 100-113.
[2] Andereck et al., J. Fluid Mech. 164 (1986) 155-183.
[3] Tsukahara et al., at Turbulence and Shear Flow Phenomena 4, 2005.
[4] Jarre et al. Phys. Fluids 8 (1996) 496-508, 2985-2994; Cros & Le Gal, Phys. Fluids 14 (2002) 3755-3765.
[5] Moxey & Barkley, PNAS 107 (2010) 8091-8096.
[6] B. Eckhardt et al., Phil. Trans. R. Soc. A 366 (2008) 1297-1315.
[7] e.g. Kawahara & Kida, J. Fluid Mech. 449 (2001) 291-300; Viswanath, J. Fluid Mech. 580 (2007) 339-358.
[8] Duguet et al., Phys. Fluid 21 (2009) 111701; Schneider et al., Phys. Rev. E 78 (2008) 037301.
[9] Pomeau, Ch. 4, pp. 61-96 in Bergé, Pomeau, Vidal, L'espace chaotique (Hermann, Paris, 1998); Pomeau, Physica D 23 (1986) 3-11.
[10] Lagha & Manneville, Eur. Phys. J. B 58 (2007) 433--447; Manneville, Phys. Rev. E 79 (2009) 025301 [R]; 039904 [E].
[11] Barkley & Tuckerman, Phys. Rev. Lett. 94 (2005) 014502; J. Fluid Mech. 576 (2007) 109-137.
[12] Duguet et al., J. Fluid Mech. 650 (2010) 119--129.
[13] Manneville & Rolland, Theor. Comput. Fluid Dyn. submitted, Eur. Phys. J. B, submitted, J. Stat. Phys. in preparation.
[14] Phil. Trans. R. Soc. B 365 (2007): theme issue on "Scaling and structure of high Reynolds number wall-bounded flows".
[15] Waleffe, Studies in Appl. Math. 95 (1995) 319-343.
[16] see however: Hayot & Pomeau, Phys. Rev. E 50 (1994) 2019-2221.

Transitional Duct Flow: Travelling Waves and the Edge State

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Ever since the pioneering experimental study on pipe flow in 1883 by Osborne Reynolds the question on how turbulent flow occurs and maintains itself is still an enigma for scientists, but the past fifteen/twenty years have witnessed progress on this subject. Its configurational 'twin', the square duct flow, is believed to have similar qualities as pipe flow since its laminar state is also stable to small perturbations. Hence it is conjectured that the transition scenario is a nonlinear occurrence caused by finite amplitude solutions of the Navier-Stokes equations, as suggested by earlier reports on pipe flow. An example of such solutions are travelling waves, that have no connection to the laminar flow and could provide the organising structures around which time-dependent trajectories in phase space can tangle to sustain a turbulent flow for long times. This is an interesting observation on its own but it also opens up for future possibilities to control turbulence. We present various nonlinear travelling wave solutions (TWS) that have recently been discovered.[1,2,3,4] Figure 1 on the left shows one type of TWS,[2] the most right shows an ensemble of solutions of different symmetries showing their skinfriction in relation to laminar and turbulent flows. Furthermore we discuss recent discoveries from direct numerical simulations of the edge state together with time periodic solutions. A trajectory in the edge state can be bracketed by initial conditions on the laminar and the turbulent side, *i.e.* initial conditions which eventually decay or become turbulent. Basically the edge state is represented by two pairs of vortices (see figure 1 middle). The larger outer pair is weaker, it sits above a smaller near-wall pair, which induces a strong low speed streak, symmetric around a bisector. The patterns are similar to those found in a pipe of circular cross-section.

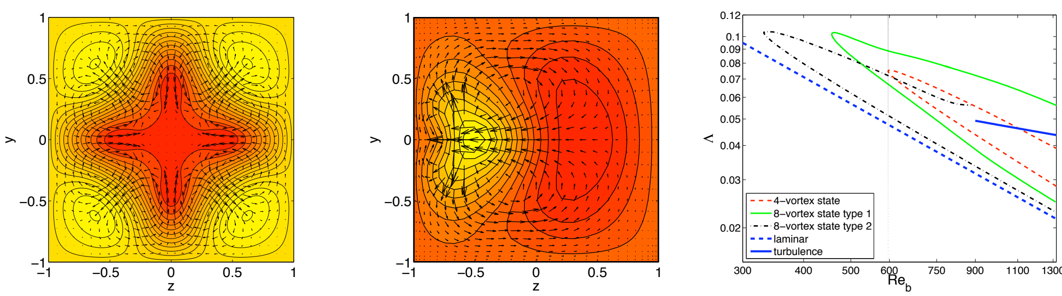

Figure 1: Two structures in square duct flow, averaged over the streamwise direction. The arrows represent the cross-stream velocity and the contour levels the streamwise velocity. Left: an 8-vortex TWS (named type 1),[2] similar to observations in turbulence. Middle: the edge state, expected to have connections to the transitional regime. Right: The skinfriction Λ as a function of the bulk Reynolds number Re_b.[2,3]

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[1]Wedin *et al.*, *Phys. Rev. Lett. E* **79**, 065305(R) (2009).
[2]Wedin *et al.*, *Advances in Turbulence XII* Proceedings of the 12th ETC, 141 (2009).
[3]Okino *et al.*, Submitted to the Journal of Fluid Mechanics (Nov. 2009).
[4]Uhlmann *et al.*, *Advances in Turbulence XII* Proceedings of the 12th ETC, 585 (2009).

Edge states and turbulence spreading in subcritical shear flows

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Transition to uniform turbulence in cylindrical pipe flow occurs experimentally via the spatial expansion of isolated coherent structures called slugs, triggered by localised finite-amplitude disturbances[1]. We study this process numerically by examining the preferred route in phase space through which a critical disturbance initiates a slug. This entails first identifying the relative attractor - edge state - on the laminar-turbulent boundary in a long pipe and then studying the dynamics along its low-dimensional unstable manifold leading to the turbulent state. The edge state is found to be spatially localised regardless of the nature of the turbulent regime[2]. A key process in the genesis of a slug is found to be vortex shedding via a Kelvin-Helmholtz mechanism from wall-attached shear layers forming at the edge states upstream boundary. Whether these shedded vortices travel on average faster or slower downstream than the developing turbulence determines whether a puff or slug (respectively) is formed[3]. An extension of these ideas to spatially developing flows, such as the Blasius boundary layer, will be discussed.

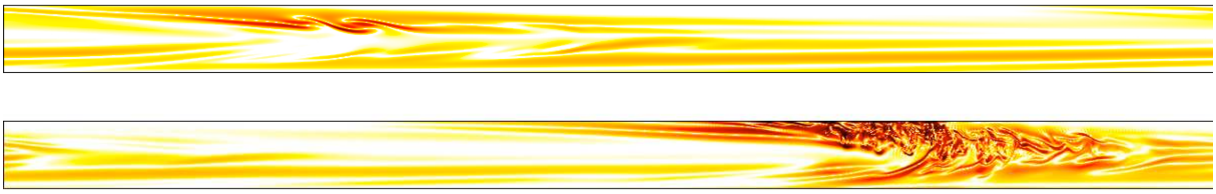

Figure 1: Direct numerical simulation of the formation of a slug in pipe flow at $Re = 4500$, starting from the instability of the corresponding edge state. Logarithmic iso-contours of the azimuthal vorticity perturbation in a meridian plane. The mean flow is from left to right.

References

1. Wygnanski, I. J., Champagne, F. H., 1973 On transition in a pipe. Part 1. The origin of puffs and slugs and the flow in a turbulent slug *J. Fluid Mech.*,**59**, 281.

2. Mellibovsky, F., Meseguer, A., Schneider, T. M., Eckhardt, B., 2009 Transition in localized pipe flow turbulence *Phys. Rev. Lett.*, **103**, 054502.

3. Duguet, Y., Willis, A.P., Kerswell, R.R., 2010 Slug genesis in cylindrical pipe flow, *submitted to J. Fluid Mech.*

Model reduction for flow control

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The dynamics and control of disturbances in the spatially evolving boundary layers are investigated from an input–output viewpoint. A set-up of spatially localized inputs (external disturbances and actuators) and outputs (objective functions and sensors) is introduced for the control design of convectively unstable flow configurations. From the linearized Navier–Stokes equations with the inputs and outputs balanced modes are extracted using the snapshot method. A balanced reduced-order model (ROM) is constructed and shown to capture the input–output behavior of the linearized Navier–Stokes equations. This model is finally used to design a feedback controller to suppress the growth of perturbations inside the boundary layer. Figure 1 shows the arrangement of sensors and actuators and figure 2 shows the reduced order controller applied to the control of a wavepacket in the Blasius boundary layer.

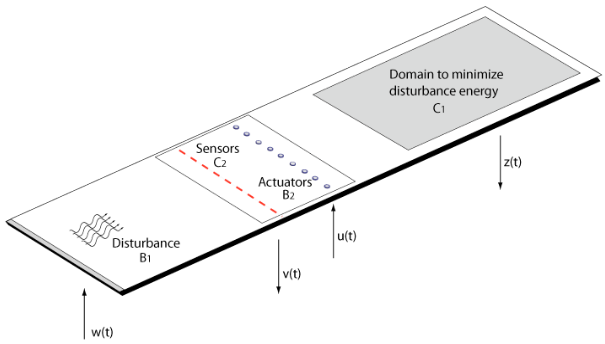

Figure 1. Input-output configurations for the TS wavepacket case. The input B1 is an optimal initial condition that triggers TS-waves, located at (30, 1, 0). The control action is provided by the input B2, constituted by a row of actuators located at x = 400. The output C2 at x = 300 contains an array of sensors used for flow estimation. The effects of the controller are quantified by C1, defined in a region spanned by 10 POD modes (here indicated with a darker gray region). All the estimation sensors are connected to all the actuators.

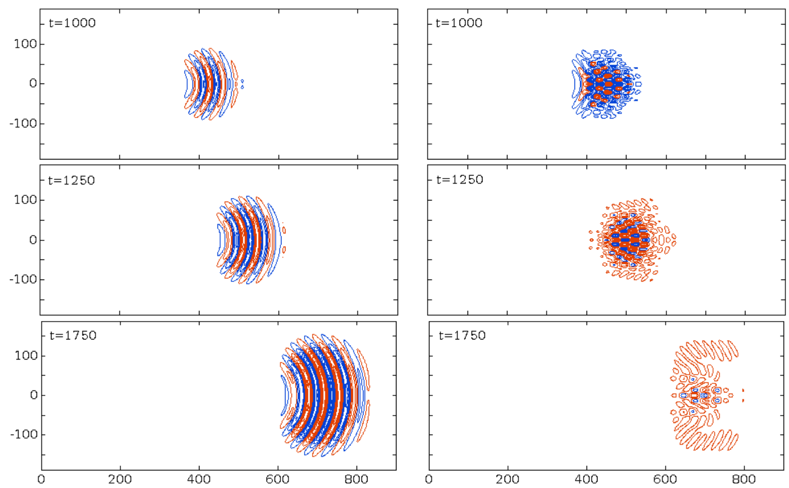

Figure 2. Evolution of a TS wavepacket at three instances of time, t = 1000, 1250, 1750, without control (left column) and with control (right column). The iso-contours of the streamwise component are shown in the xz-plane at y ≈ 1.9; red isolines indicate positive velocity, while the negative one is indicated with blue. All the plots are characterized by the same isocontour range [−1.03, 1.03].

Nonmodal stability of plane Poiseuille flow of a dielectric liquid in presence of unipolar injection

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Coulomb-driven convection in dielectric fluids has received some attention in the past due to the numerous industrial applications [1]. In particular, flows of dielectric liquids where injected ions are the main source of charge encompass those in electrostatic precipitators, EHD ion-drag pumps, EHD turbulent mixers.

Flow instabilities induced by the presence of charge injection have been studied in the last two decades [2, 3]; these studies focused primarily on planar and cylindrical geometries, pointing out the analogies with the Rayleigh-Bénard problem. However, the stability of shear flows of dielectric liquids in presence of charge injection has received considerably less attention, and a sole study [4] appears to be available in the literature.

The present work aims at significantly expanding the linear stability analysis of the three-dimensional, plane Poiseuille flow in presence of strong unipolar charge injection. The effect of charge diffusivity, neglected in previous studies, will be explicitly taken into account. The definition of a physically sound norm to quantify the disturbance amplitude will be addressed, and a nonmodal stability analysis will be presented. The effects of charge diffusivity, ion mobility and injection strength on the maximum growth and maximum growth rates will be discussed. Finally, a componentwise input-output analysis of the linearized response to perturbations on the velocity components and charge density will be presented.

References

[1] J. M. Crowley, *Fundamentals of Applied Electrostatics*, J. Wiley & Sons, New York, 1986

[2] A. Castellanos, *Coulomb-driven convection in Electrohydrodynamics*, IEEE Trans. Elec. Insul., 1991

[3] P. Atten, *Electrohydrodynamic Instability and Motion Induced by Injected Space Charge in Insulating Liquids*, IEEE Trans. Diel. Elec. Insul., 1996

[4] A. Castellanos and N. Agrait, *Unipolar Injection Induced Instabilities in Plane Parallel Flows*, IEEE Trans. Ind. Appl., 1992

Flow analysis using Koopman modes

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In this talk we present a method based on the analysis of the Koopman operator[1,2] to characterize a flow when it transitions from a steady state to a nonlinear oscillatory state – or from an unstable equilibrium to an (quasi) periodic attractor. The transition can be split into three regimes; it begins with the linear growth of small-amplitude global instabilities, followed by a transient phase where the instabilities depart from the steady solution and approach the attractor region; the transition ends with the saturation of the instabilities into a fully developed nonlinear flow evolving on an attractor. For each part, a set of global modes, referred to as the Koopman modes can be computed using the Dynamic Mode Decomposition algorithm[3]. For the first part, the Koopman modes are simply the linear global eigenmodes of the linearized Navier-Stokes equations. The Koopman modes for the transient phase are able to capture the structure of finite-amplitude disturbances and how they these disturbances modify the steady flow. These modes span the direction of the so called shift mode[4]. Finally, the Koopman modes for the fully nonlinear regime can be considered as a generalization of the time-averaged mean flow; the first mode is the mean flow, whereas other Koopman modes are harmonic averages, i.e. spatial structures that display periodic behavior in time. For example, these modes are able to identify the flow structures that oscillate with precisely the same frequency as periodic vortex shedding observed in the flow. The theory and the method are illustrated with a few examples, such as the Ginzburg-Landau equation, the cylinder flow and the fully three-dimensional jet in crossflow (see figure 1).

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[1]Mezić, *Nonlinear Dynamics*, **41(1)**, 309, (2005).
[2]Rowley, Mezić, Bagheri, Schlatter, Henningson, *J. Fluid Mech.* **641**, 115, (2009).
[3]Schmid, *J. Fluid Mech.* In press (2010).
[4]Noack, Afanasiev, Morzyński, Tadmor, Theiele, *J. Fluid Mech.* **497, 335, (2003).**

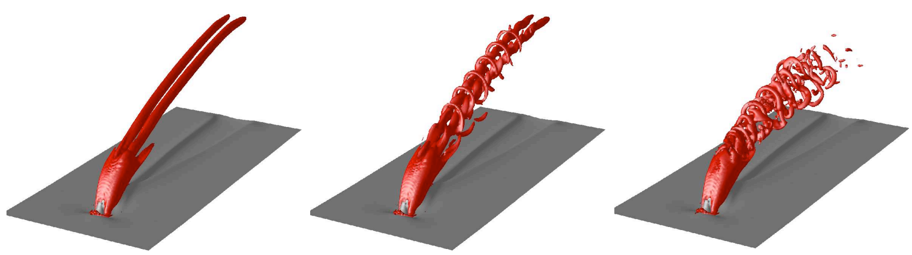

Figure 1: A jet in crossflow: The unstable steady solution (left figure) is modified by finite-amplitude disturbances (center figure) and eventually develops into a fully unsteady and nonlinear flow (right figure).

Control of vortex breakdown in a contracting pipe

P. Meliga* and F. Gallaire*

The present study investigates the vortex breakdown of the viscous, swirling jet developing in a contracting axisymmetric pipe[1]. When the swirl number, i.e. the ratio of the maximum azimuthal to streamwise velocity, exceeds a certain threshold value, such flows are known to undergo a violent transition from the so-called columnar state to the breakdown state, the latter being characterized by a large recirculation region.

We show first that breakdown occurs through a saddle-node bifurcation owing to the destabilization of an axisymmetric global mode. Above the critical swirl number, the columnar solution ceases to exist and breaks into a decelerated state, the so-obtained bifurcation diagram being in qualitative agreement with that predicted previously in the approximation of inviscid parallel flows[23].

We also aim at demonstrating the ability of adjoint-based receptivity methods to suppress vortex breakdown. To this end, we consider the effect of a small synthetic jet whose position is allowed to vary at the pipe wall, a control technique that can be easily implemented in practice. We compute first the amplitude equation governing the nonlinear amplitude of the unstable mode in the vicinity of the threshold value, which allows to approximate the structure of the bifurcated solution. The amplitude equations is then used to choose a velocity distribution that guarantees the existence of a columnar solution for swirl numbers slightly larger than the critical value. The nonlinear effect of the control is estimated by carrying out additional numerical simulations of the controlled flow, which show that the breakdown is suppressed over a large range of swirl numbers, even for a low-flow-rate jet representing only 3% of the flow rate in the inlet section (figure 1).

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[1]Lopez, *Phys. Fluids* **6**, 3683, (1994).
[2]Wang and Rusak *Phys. Fluids* **8**, 1007, (1997).
[3]Wang and Rusak *Phys. Fluids* **8**, 1017, (1997).

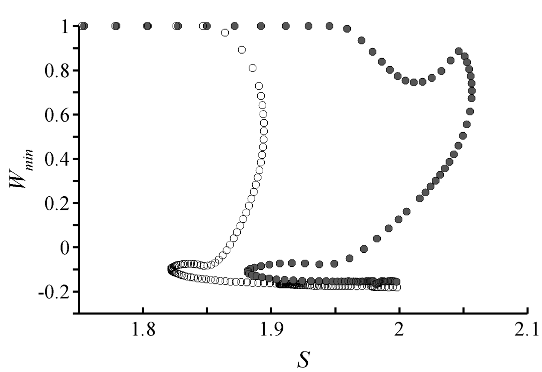
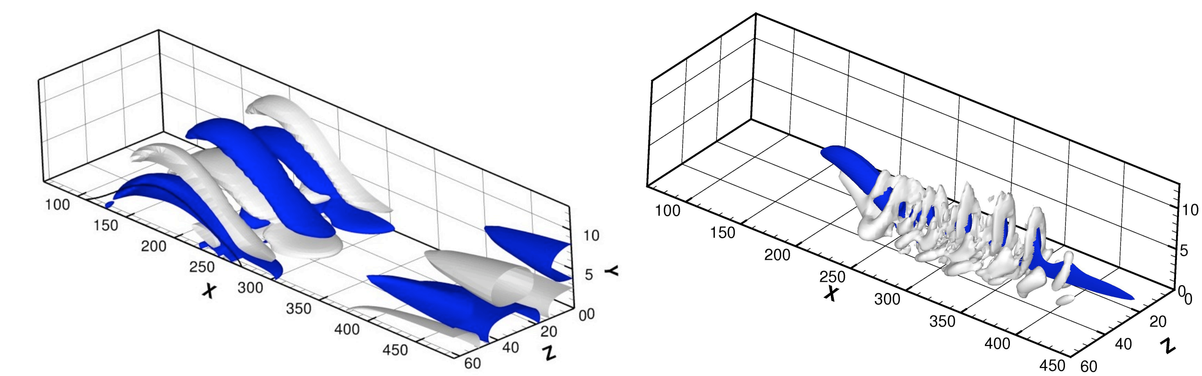


Figure 1: Minimum streamwise flow velocity in the pipe as a function of the swirl number, without control (open symbols) and with control (filled symbols).

The breakdown of 3D centrifugal global modes in a separated boundary layer

S. Cherubini[*,†], J.-C. Robinet[*], P. De Palma[†] and F. Alizard[*]

The three-dimensional stability dynamics of a separation bubble over a flat plate has been studied in both linear and non-linear conditions. Using a global eigenvalue analysis, the less stable global modes are identified, namely, an asymptotically unstable three-dimensional weakly growing mode and a marginally stable three-dimensional steady mode. Both modes seem to have a centrifugal origin. In particular, the first one appears to be originated by a Rayleigh instability, similar to the one analyzed in [1], whereas the second one, which is shown in Figure 1 (a), seems to be originated by a convective instability of Gortler type, as assessed by a spatial integration of the Gortler equations over the streamlines past the bubble.
Direct numerical simulations (DNS) show that both modes play a role in the route to transition toward the turbulent flow. In particular, an analysis of the most amplified spanwise wavenumbers at different times shows that, when the flow is perturbed with small amplitude disturbances, the unstable mode dominates the asymptotical dynamics, whereas the Gortler one is recovered during the transient. In order to investigate the mechanism of selection of the convective Gortler mode, a structural sensitivity analysis [2] has been used. It has been found that the sensitivity region is localized on the shear layer of the separation bubble. Thus, it has been conjectured that the convection of KH/TS modes along the shear layer during the early transient could be at the origin of the Gortler mode excitation.
For large amplitude perturbations, a self-sustained perturbation cycle is observed, where the Gortler mode is the *amplifier* of the perturbations induced by the *resonator* placed within the separation bubble, i.e. the unstable centrifugal mode. Transition occurs in the attached boundary layer, in a narrow spanwise-localized region, due to the breakdown of the Gortler mode. Such a transition scenario has been studied in detail: it is characterized by the formation of trains of hairpin vortices in streamwise succession, as shown by the iso-surfaces of the vortical structures in Figure 1 (b).



(a) (b)

Figure 1: Iso-surfaces of negative and positive (white and blue surfaces, respectively) spanwise vorticity for the less stable steady mode obtained by global eigenvalue analysis (a); iso-surfaces of the vortical structures (white surfaces) and of the negative streamwise perturbation (blue ones) obtained by DNS at $t = 10000$.

References

[1] F. Gallaire, M. Marquillie, and U. Ehrenstein. Three-dimensional transverse instabilities in detached boundary layers. *J. Fluid Mech.*, 571:221–233, 2007.

[2] F. Giannetti and P. Luchini Structural sensitivity of the first instability of the cylinder wake. *J. Fluid Mech.*, 581:167–197, 2007.

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Linear Stability of Compressible Flow in a Streamwise Corner

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Abstract

The stability of compressible flow in a streamwise right-angle corner formed by two perpendicular semi-infinite flat plates (Fig. 1) is investigated by means of linear stability theory. In aeronautical engineering, streamwise corner flow occurs in wing-fuselage intersection, supersonic inlet systems and numerous other places. The viscous and inviscid stability of *incompressible* corner flow has been investigated my numerous authors, among them Parker & Balachandar[2] who gave a comprehensive study of both cases. The present study addresses the stability of *compressible* corner flow. A self-similar solution first obtained by Rubin[3] and later extended to the compressible case by Weinberg & Rubin[4] is widely used as base flow for stability calculations in literature. We take a different path and obtain the base flow by implicitly marching the compressible parabolized Navier-Stokes equations in space using a Chebychev-Chebychev collocation method in the transversal planes. The base flow results agree well with the self-similar solution for the incompressible limit up to a Mach number of 2,0 while the approach allows for more flexibility concerning variations of the geometry and boundary conditions. Lowest order asymptotic cross flow solutions[1] are used for the far-field boundary conditions. The spatial linear stability analysis is based on the same spectral framework used for the calculation of the base flow. By virtue of the spectral method complete spectra of instability modes can be calculated for a given number of collocation points at a relatively low computational cost.

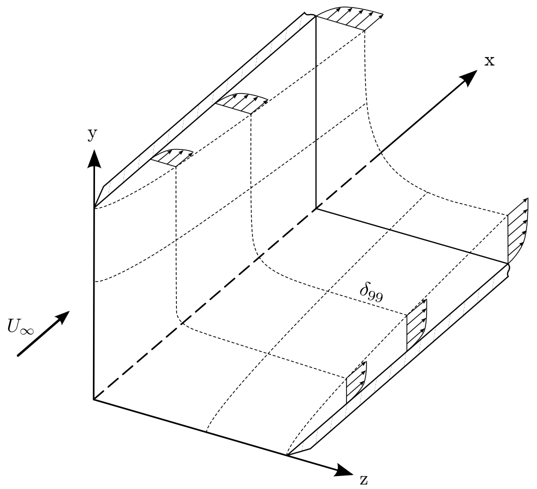

Figure 1: Corner flow configuration

References

[1] K. N. Ghia and R. T. Davis. A Study of Compressible Potential and Asymptotic Viscous Flows for Corner Region. *AIAA Journal*, 12:355–359, March 1974.

[2] S. J. Parker and S. Balachandar. Viscous and Inviscid Instabilities of Flow Along a Streamwise Corner. *Theoretical and Computational Fluid Dynamics*, 13:231–270, 1999.

[3] S. G. Rubin. Incompressible flow along a corner. *Journal of Fluid Mechanics Digital Archive*, 26(01):97–110, 1966.

[4] B. C. Weinberg and S. G. Rubin. Compressible corner flow. *Journal of Fluid Mechanics*, 56:753–774, 1972.

Sensitivity analysis of the finite-amplitude vortex shedding behind a cylinder

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In this work we study the structural sensitivity of the nonlinear period oscillation arising in the wake of a circular cylinder for super critical Reynolds numbers. The sensibility of the periodic state to a spatially localised feedback from velocity to force is analysed by performing a structural stability analysis of the problem. The nonlinear evolution equations are marched in time until a saturated periodic state is obtained. The sensitivity of the vortex shedding *frequency* and *amplitude* are analysed by evaluating the adjoint eigenvectors of the Floquet transition operator. In particular, the adjoint linearised Navier-Stokes equations are marched backward in time until a periodic solution is found. The product of the adjoint solution with the nonlinear periodic state is then used to localise the instability core. In this way, sensitivity maps can be drawn to determine the regions of the flow more sensitive to spatially localised feedbacks. Results obtained with this approach will be shown for different Reynolds numbers and compared, in order to highlight the differences, with those computed by [1] and [2] through a global stability analysis of the steady flow behind a circular cylinder and the experiments by [3]. An example is given in figure 1. for $Re = 50$ comparing the sensitivity, of the frequency and amplitude, evaluated from the periodic state and the stationary baseflow. Note that the results for the stationary baseflow coincide with the results by [2] (figure 11).

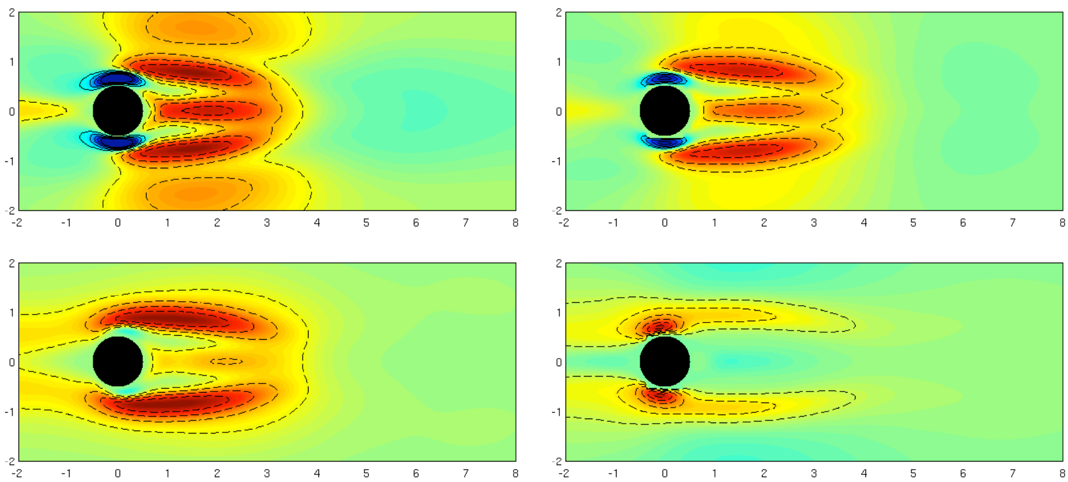

Figure 1. Sensitivity w.r.t. amplitude (top) and frequency (bottom). In each row; (left) limit cycle, (right) linear stability analysis of stationary baseflow. Negative values (dashed), positive values (solid).

References

[1] F. Giannetti and P. Luchini. Structural sensitivity of the first instability of the cylinder wake. J. Fluid Mech., 581:167–197, 2007.

[2] O. Marquet, D. Sipp, and L. Jacquin. Sensitivity analysis and passive control of cylinder flow. J. Fluid Mech., 615:221–252, 2008.

[3] P. J. Strykowski and K. R. Sreenivasan. On the formation and suppression of vortex "shedding" at low Reynolds number. J. Fluid Mech., 218:71–107, 1990.

Optimal perturbations and coherent structures in turbulent shear flows

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One of the most robust features of wall bounded turbulent shear flows is the presence of streamwise streaks. The existence of streaks in the buffer layer with a characteristic average spanwise scale $\lambda_z^+ \approx 100$, in wall units, has been known for a long time. Coherent streaky structures, however, exist also at larger scales with typical spanwise and streamwise scales $\lambda_z \approx O(h)$ and $\lambda_x \approx O(10h)$ respectively. These very large-scale streaks, also referred to as very large-scale motions or global modes or superstructures, are important because they carry a very significant fraction of the turbulent kinetic energy and of the turbulent Reynolds stress contradicting the early view that the motions at very large scale are essentially inactive. I will summarize recent investigations where it has been theoretically predicted that very large scale streamwise streaks can be amplified by a coherent lift-up effect which is able to extract energy from the mean flow at very large scale [1, 7, 2, 3, 4]. These theoretical analyses are based on generalized Orr-Sommerfeld-Squire operators that use the turbulent mean flow as base flow and the corresponding turbulent eddy viscosity in order to take into account the correct dissipation scales. The spanwise scales of both near-wall and large-scale structures are well predicted using this type of approach. The existence of the coherent transient growth of large scale streaks has been confirmed by experiments where the large scale streaks have been forced using cylindrical roughness elements [5]. Artificially forced coherent large scale streaks have also been shown to be beneficial for separation control on 3D bluff bodies [6] and for drag reduction in the turbulent pipe flow [8]. Finally, recent results proving the existence of a self-sustained mechanism at large scale [4] will be briefly summarized.

References

[1] J. C. del Álamo and J. Jiménez. Linear energy amplification in turbulent channels. *J. Fluid Mech.*, 559:205–213, 2006.

[2] C. Cossu, G. Pujals, and S. Depardon. Optimal transient growth and very large scale structures in turbulent boundary layers. *J. Fluid Mech.*, 619:79–94, 2009.

[3] Y. Hwang and C. Cossu. Amplification of coherent streaks in the turbulent Couette flow: an input-output analysis at low Reynolds number. *J. Fluid Mech.*, 643:333–348, 2010.

[4] Y. Hwang and C. Cossu. Linear non-normal energy amplification of harmonic and stochastic forcing in the turbulent channel flow. *Submitted to J. Fluid Mech.*, 2010.

[5] G. Pujals, C. Cossu, and S. Depardon. Forcing large-scale coherent streaks in a zero pressure gradient turbulent boundary layer. *J. Turb.*, 2010. In press.

[6] G. Pujals, S. Depardon, and C. Cossu. Drag reduction of a 3D bluff body using coherent streamwise streaks. *Exp. Fluids*, 2010. In press.

[7] G. Pujals, M. García-Villalba, C. Cossu, and S. Depardon. A note on optimal transient growth in turbulent channel flows. *Phys. Fluids*, 21:015109, 2009.

[8] A. P. Willis, Y. Hwang, and C. Cossu. Optimally amplified large-scale streaks and drag reduction in the turbulent pipe flow. *Submitted to Phys. Rev. E*, 2010.

[1] The presented results have been obtained in collaboration with G. Pujals, Y. Hwang and A.P. Willis (LadHyX, École polytechnique) and S. Depardon (PSA Peugeot-Citroën Automobiles).

Instability of averaged low-speed streaks in near-wall turbulence with adverse pressure gradients

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Turbulent boundary layers with adverse pressure gradients due to wall curvature are ubiquitous in many practical flows including aerodynamics of airfoils, turbomachinery or ground vehicles. Here, a channel flow with a lower curved wall has been considered. Using the numerical solution procedure documented in,[1] a database has been generated for the fully turbulent flow state at Reynolds number $Re = 12600$ (based on the channel inlet half-width), the corresponding friction velocity Reynolds number being $Re_\tau \approx 600$. Streamwise velocity streaks are known to be a key feature of wall turbulence[2] and low-speed streak structures have been extracted from our database using methods known as *skeletonization* in image processing.[3] An example of instantaneous streak-skeletons near the lower curved wall is shown in figure 1(a). Individual streaks in the wall normal plane (y, z) averaged in time and superimposed to the mean streamwise velocity have been used as basic states for a linear stability analysis. Two-dimensional modes $\hat{\mathbf{u}}(y, z)e^{i\alpha x}$ have been computed at positions along the lower curved wall as well as the upper wall. The instability onset is shown to coincide with a strong peak of turbulent kinetic energy observed in the direct numerical simulation. The shape of the (varicose) instability modes (see figure 1(b),(c)) is governed by the streak structure, while the instability is mainly associated with the inflectional mean velocity profile in the wall-normal direction. The nonlinear development of the instability mode is computed as well and the resulting structure is clearly reminiscent of the coherent vortices observed in the direct numerical simulation.

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[1] Marquillie, Laval and Dolganov, *J. Turb.* **9**, 1 (2008)

[2] Asai, Minagawa and Nishioka, *J. Fluid Mech.* **455**, 289 (2002)

[3] Palágyi and Kuba, *Graphical Models and Image Processing* **61**, 199 (1999)

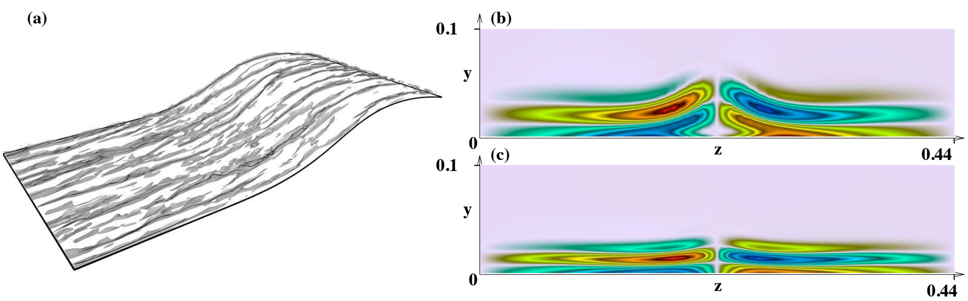


Figure 1: (a) Skeleton of instantaneous low-speed streak structure along the curved lower wall. Streamwise vorticity in the (y, z) plane of instability mode at (b) upper wall, (c) lower wall.

The application of Selective Frequency Damping to the computation of global modes of a compressible jet

X. Garnaud*, L. Lesshafft*, P.J. Schmid*, P. Huerre* and J.-M. Chomaz*

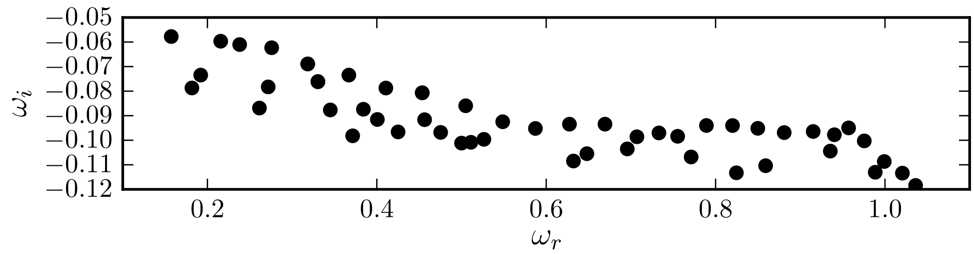
When global modes are sought over various frequency ranges, the common method of choice is to combine an Arnoldi algorithm with a "shift-invert" type of spectral transformation. Such methods require multiple successive solutions of linear systems associated with the same linear operator. In many cases, a direct LU decomposition of this operator represents an efficient strategy. For instance, this approach has been applied to dense matrices resulting from spectral discretization[1]. More recent studies take advantage of the sparsity of discretization matrices obtained with finite elements or finite differences, which allows to consider larger problems through the use of sparse solvers[2]. However, the considerable memory requirements for the LU decomposition impose severe limits for this method, making it unsuitable for compact or high-order explicit schemes, large domain sizes or three-dimensional problems. Moreover, the method requires an explicit construction of the stability matrix.

In order to avoid these problems and to allow the use of compact difference schemes, iterative solvers have been applied[3]. The shift-invert transformation typically yields poorly conditioned linear systems. Although some improvement has been achieved by use of a Cayley transformation[3], efficient preconditioning remains a difficult challenge and can be computationally prohibitive.

We present a different spectrum transformation, which does not involve the resolution of any linear system. Based of the idea of "selective frequency damping" [4], the linearized Navier-Stokes equations are coupled with a band-pass filter. Artificial damping is thus applied to modes outside a specified frequency band. Modes with frequencies within this range are then computed with a simple time-stepping technique[5].

This method does not offer the same level of flexibility as the "shift-invert" transformation, but has the clear advantages of low memory requirement and easy implementation, in particular because it is matrix-free. Moreover, it can be efficiently parallelized and promises to be suitable for three-dimensional problems.

Results will be presented for the global modes of a subsonic jet, with particular attention directed towards the aero-acoustic features.



Eigenvalue spectrum of an isothermal jet at Ma = 0.9 and Re = 100.

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[1] Akervik et al., *Eur. J. Mech. B-Fluid* **27**(5) (2008)
[2] Barbagallo et al., *J. Fluid Mech.* **641**,1–50 (2009)
[3] Mack et al., *J. Comput. Phys.* **229**(3),541–560 (2010)
[4] Akervik et al., *Phys. fluids* **18**(6) (2006)
[5] Edwards et al., *J. Comput. Phys.* **110**(1)82–102 (1994)

Localized structures of the boundary layer at high free stream turbulence level

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Abstract

Under the conditions of high turbulence level in the oncoming flow, the laminar-turbulent transition is due to the action of disturbances proceeding from the external flow on the boundary layer; as a result, in the boundary layer, streamwise-oriented (longitudinal) localized structures consisting of regions with an excess and deficit of the longitudinal velocity are formed. These structures provide preconditions for the development of high-frequency wave disturbances such as secondary instability and T-S waves, which can further transform into turbulent spots. As a result, the boundary layer flow goes over from the laminar to the turbulent state [1, 2]. This work is devoted to the study of wave packets (forerunners) formed in boundary layers in the regions that precede a drastic change in the flow velocity inside the boundary layer (fronts of longitudinal localized disturbance) [3,4].

The investigations were carried out in the subsonic low-turbulent wind tunnels T-324 and MT-324, ITAM SB RAS. Free stream velocity was in the range $4 \leq U_o \leq 8$ m/s at the turbulence level at $0.04 \leq$ Tu $\leq 2.31\%$. Test models were straight or swept wings (with sweep angle 43 and 45º). The blowing-suction method was used to introduce longitudinal localized structures into the boundary layer through the thin slot arranged in the surface parallel to the leading edge, **or from the incoming flow using thin pipe, located at 5 mm from the model nose**. The duration of the blowing-suction pulse was controlled by a high-speed electromagnetic valve synchronized with the system of signal recording. Measurements were carried out using a single-wire probe of a constant-temperature hot-wire anemometer.

The characteristics of the forerunners, affected by the free stream turbulence level, external-flow pressure gradient, the way of the longitudinal structures generation, and velocity gradients induced by the latter were investigated. In particular, it was observed that the forerunners are strongly amplified in the adverse pressure gradient flow being much influenced by local velocity gradients. The results of the study make reason to consider the forerunners as wave packets of 3D instability (T-S) waves. It was found that at downstream development of the forerunners they transform into the Λ-structures. It was shown that, the wave packets (forerunners) are exists and lead to turbulence under the high free-stream turbulence level. Moreover, a forerunners magnitude grows faster under the influence of high free-stream turbulence level.

The work was supported by the Russian Foundation for Basic Research (project no. 08-01-00027), the Council of the President of the Russian Federation for the Support of Young Russian Scientists and Leading Scientific Schools (project NSh-454.2008.1), and the Ministry of Education and Science of the Russian Federation (project RNP.2.1.2.541).

References

1. A. V. Boiko, G. R. Grek and A. V. Dovgal. The Origin of Turbulence in Near-Wall Flows. Berlin: Springer, 2002.
2. M.Matsubara, K.Takaichi, T.Kenchi. Experimental study of boundary layer transition subjected to weak free stream turbulence // Laminar-Turbulent Transition / Ed. P.Schlatter, D.S.Henningson.- Sweden: Springer-Verlag, 2009. P.277-282.
3. V. N. Gorev and M. M. Katasonov. Origination and development of precursors on the fronts of streaky structures in the boundary layer on a nonswept wing // Thermophys. Aeromech. 2004. Vol. 11, No. 3. P. 391–403.
4. V. N. Gorev, M.M. Katasonov, V. V. Kozlov and P.A. Motyrev. Experimental investigations on the forerunners of localized boundary layer disturbances at high free stream turbulence level // Thermophys. Aeromech. 2009. Vol. 16, No. 4. P. 573–581.

Optimal disturbances for flow above a flat plate with an elliptic leading edge.

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The flow around a flat plate with an elliptic leading edge is considered. The global linear stability of the resulting boundary-layer flow subject to three-dimensional disturbances is examined by means of optimization tools. The Lagrangian approach is used where the objective function is the kinetic energy of the flow perturbations and constraints involve the linearized Navier–Stokes equations. We seek the largest eigenpair of the system formed by the composite operator of the direct and adjoint propagator. This project is a continuation of previous work (Monokrousos *et al.* 2010) where here the focus is shifted towards the effect on the optimal disturbances of the inclusion of the leading edge. The procedure is also applied to find localized optimal initial conditions upstream from the leading edge.

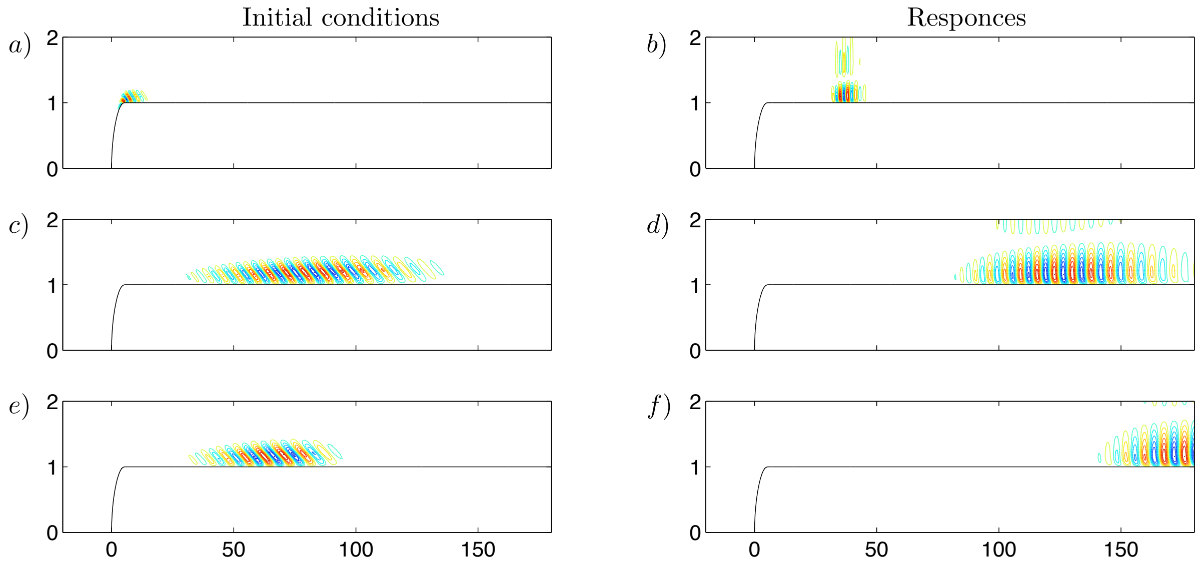

Figure 1: Optimal initial conditions and the corresponding responses. Optimisation times: $t = 60$ a),b), 120 c),d) and 250 e),f) respectively. In all figures the streamwise velocity is shown while the spatial dimentions are scaled with the half thickness of the plate.

In the figure 1 three sample results are shown. Optimal initial conditions (left-hand figures) and the corresponding responses (right-hand figures) are presented. For the case where the optimization time (T) is short (figure 1a,1b) the disturbance is localized around the junction ellipse-plate section. However as we increase T that mechanism becomes less and less efficient since the disturbace looses energy once it enters the “flat-plate” region where the effective Reynolds number (Re) of the boundary layer is low. At some point the disturbance jumps downstream (figure 1c,1d) in order to exploit the higher boundary layer Re in that region. For even larger T the initial condition moves upstream since the computational box has a finite length (figure 1e,1f). One qualitive difference from the computations without the leading egde is the case for $T = 60$ where the disturbance is exploiting the decelerated boundary layer due to the curved region upstream in order to increase the energy gain.

Monokrousos A., Åkervik E., Brandt L. and Henningson D.S, 2010, Global three-dimentional optimal disturbances in the Blasius boundary-layer flow using time-steppers. J. Fluid Mech. in press.

Natural and controlled disturbance experiments to study linear stability and receptivity of supersonic boundary layer on thin swept wings

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The paper is devoted to an experimental study of linear stability of a three-dimensional supersonic boundary layer on the swept wings at natural and controlled conditions. Existing understanding of turbulence beginning in a three-dimensional swept wing boundary layer consider four basic types of unstable wave mechanisms: (1) attachment line flow instability at the leading edge; (2) cross-flow instability of a stationary vortices; (3) cross-flow instability to travelling disturbances; and (4) Tollmien–Schlichting instability. Each of them can lead to turbulence flow. Up to now the main result for 3D boundary layer were obtained for subsonic flows [1, 2]. We should state that experiments on the linear development of controlled disturbances in a 3D supersonic boundary layer were not successfully [3]. Therefore we have been conducted a new stability experiments testing the thin swept wings at low unit Reynolds numbers. It has allowed investigating the linear disturbance evolution in supersonic boundary layer on swept wing at natural and controlled conditions. Initial amplitudes for temperature, density and velocity pulsations as well as the relative combinations of them were obtained.

The experiments were conducted in T-325 low noise supersonic wind tunnel of ITAM SB RAS at Mach 2 and unit Reynolds number $Re_1=5\times10^6$ m^{-1}. Two swept wings with $\chi=45°$were used. The first model is a symmetrical wing with 3-percent-thick circular-arc airfoil (curvature radius of R=4 m, maximum thickness is 12 mm). Second model was specially designed for controlled disturbance experiments. The test surface of the model has radius of curvature R=4 m, the bottom surface is flat (3% profile, maximum thickness is 12 mm). Source of artificial disturbances was built in the model. Controlled pulsations penetrated in boundary layer through aperture of 0.4 mm in diameter were excited by high frequency glow discharge in chamber. Disturbances in the boundary layer were measured with the help of CTA hot-wire anemometer.

Almost harmonic wave train with frequency of 20 kHz was excited in the boundary layer. Growth of the controlled disturbances was detected at linear development of the natural background pulsations. Excitations of other frequency disturbances were not found in the tested region. Nonlinearity was not observed. Experimentally confirmed, that downstream disturbances evolution on a swept wing considerably differs from the case of flat plate. In disturbance amplitude distributions over spanwise coordinate there is one maximum in cross-flow direction. Amplitude and phase spectra are asymmetrical as usually for 3D boundary layer.

Evolution of natural disturbances in supersonic boundary layer of swept wing was investigated in detail and region of linear disturbances evolution was determined. Digital time traces and statistical diagrams of natural fluctuations were obtained. Amplitude-frequency spectra of pulsations as well as mean and pulsation profiles are analyzed. Qualitative and same quantitative correspondences of natural and controlled experiments were obtained.

This work has been supported by the RFBR grants 08-01-00124, 09-01-00767.

1.W. S. Saric, H. L. Reed and E.B. White, Stability and transition of three-dimensional boundary layers, *Ann. Rev. Fluid Mech.*, Vol. 35, 2003, pp. 413-440.

2. Gaponenko V.R, Ivanov A.V., Kachanov Y.S., Crouch J.D. Swept-wing boundary-layer receptivity to surface non-uniformities, JFM, 461, 2002, P: 93-126.

3. Semionov N.V., Ermolaev Yu.G., Kosinov A.D., Levchenko V.Ya. Experimental investigation of development of disturbances in a supersonic boundary layer on a swept wing, Thermophysics and Aeromechanics, 10(3), 347-358 (2003).

8th ERCOFTAC SIG 33 Workshop
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