ERCOFTAC
European Research Community
On Flow, Turbulence And Combustion

7th ERCOFTAC SIG 33 - FLUBIO Workshop

Open Issues in Transition and Flow Control

Santa Margherita Ligure, Italy

October 16-18, 2008

Marie Curie Fellowships

7TH ERCOFTAC SIG33 - FLUBIO WORKSHOP ON *OPEN ISSUES IN TRANSITION AND FLOW CONTROL*

October 16

	09:00	10:55	**Registration with welcome coffee and croissants**	
	10:55	11:00	**Opening statements**	
			Session 1 (Chairman: Dan Henningson)	
Invited talk	11:00	11:45	**J.M. Chomaz** LadHyX	Linear and nonlinear stability of real flows: the global approach
	11:45	12:05	**M. Nagata** Kyoto University	The Sliding Couette Flow Problem
	12:05	12:25	**D. Rodríguez &** V. Theofilis School of Aeronautics, UP Madrid	Direct-Adjoint Solutions Of Boundary-Layer Flows
	12:25	12:45	**A. Monokrousos**, E. Akervik, L. Brandt & D.S. Henningson Linné Flow Centre, KTH	Optimal Initial Perturbations And Optimal Forcing Using Adjoint Based Methods For The Flat Plate Boundary Layer
	12:45	13:05	**S. Cherubini**, JC Robinet & P. De Palma Politecnico di Bari & Arts et Métiers, ParisTech	Recovering Flapping Frequency In A Separated Flow
Lunch	**13:05**	**14:30**		
			Session 2 (Chairman: Ulrich Rist)	
	14:30	14:50	**P. Schlatter**, L. Brandt, R. de Lange & D.S. Henningson Linné Flow Centre, KTH Mechanics	On Streak Breakdown In Bypass Transition
	14:50	15:10	**D. Tempelmann**, A. Hanifi & D.S. Henningson Linné Flow Centre, KTH Mechanics	Optimal Disturbances And Receptivity Of Three-Dimensional Boundary Layers
	15:10	15:30	**L.U. Schrader**, L. Brandt & D.S. Henningson Linné Flow Centre, KTH Mechanics	Leading-Edge Effects On The Receptivity Of Two- And Three-Dimensional Boundary-Layer Flow
	15:30	15:50	**F. Giannetti,** S. Camarri & P. Luchini DIMEC, Università di Salerno	An Adjoint-based Analysis Of The Secondary Instability Of The Wake Of A Circular Cylinder
Coffee	**15:50**	**16:10**		

Session 3 (Chairman: Paolo Luchini)

	16:10	16:30	J. Hoepffner & **L. Brandt** Paris VI & KTH Mechanics	Stochastic Approach To The Receptivity Problem
	16:30	16:50	**M.M. Katasonov**, V. N. Gorev & V. V. Kozlov ITAM, Novosibirsk	Wave Forerunners Of Localized Structures On Straight And Swept Wings At A High Free Stream Turbulence Level
	16:50	17:10	**F. Alizard**, U. Rist & J.C. Robinet IAG Stuttgart Universität, SINUMEF ENSAM Paris	Linear Stability Of A Streamwise Corner Flow
	17:10	17:30	**V. Kozlov** ITAM, Novosibirsk	Actual Problems Of The Subsonic Aerodynamics in Shear Flow Control
	17:30	17:50	**R. S. Donelli**, F. De Gregorio Fabrizio & P. Iannelli CIRA, Capua	Flow Separation Control by A Trapped Vortex Cavity
	17:50	18:10	**S. Hein** & E. Schülein DLR, Gottingen	Transition Control By Suction At Mach 2

October 17

Session 4 (Chairman: Jean-Marc Chomaz)

Invited talk	09:00	09:45	**B. Eckhardt** University of Marburg	Dynamical systems and shear turbulence
	09:45	10:05	**H. Wedin**, D. Biau, A. Bottaro & M. Nagata DICAT; Università di Genova & Kyoto University	Nonlinear Flow States In A Square Duct
	10:05	10:25	**V.V. Kozlov**, G.R. Grek, G.V. Kozlov, A.M. Sorokin & Yu.A. Litvinenko ITAM, Novosibirsk	Coherent Structures Of The Laminar And Turbulent Jets
	10:25	10:45	**Y. Duguet &** P. Schlatter Linné Flow Centre, KTH	Edge States And Puff-like Turbulent Regimes
	10:45	11:05	**G. Pujals**, C. Cossu & S. Depardon LadHyX	Optimal perturbations in zero pressure gradient turbulent boundary layers
Coffee	**11:05**	**11:25**		

Session 5 (Chairman:Viktor Kozlov)

	11:25	11:45	**P. Orlandi** Meccanica e Aeronautica, Università “La Sapienza”, Roma	The DNS Of The Reynolds Experiment "On The Circumstances which Determine Whether The Motion Shall Be Direct Or Sinuous"
	11:45	12:05	**B. Selent** Institut für Aero- & Gasdynamik, Uni Stuttgart	DNS Of Jet In Crossflow On A Flat Plate Boundary Layer

	12:05	12:25	S. Bagheri , P. Schlatter , P. Schmid & **D. Henningson** Linné Flow Centre, KTH Mechanics	Global Stability of a Jet in Crossflow
	12:25	12:45	**A. P. Willis** & C. Cossu LadHyX	Optimal Growth In The Turbulent Pipe
Lunch	**12:45**	**14:00**		
	14:00	15:30	**Discussion on trends in stability and transition, organisers: B. Eckhardt and J.M. Chomaz**	
Coffee	**15:30**	**15:50**		

Session 6 (Chairman: Bruno Eckhardt)

Invited talk	15:50	16:35	**C. Rowley** Princeton University	Reduced order models for flow control
	16:35	16:55	**E. Åkervik**, S. Bagheri, L. Brandt & D.S. Henningson Linné Flow Centre, KTH Mechanics	Low-dimensional Model For Control Of The Blasius Boundary-layer By Balanced Truncation
	16:55	17:15	**J. Weller**, E. Lombardi & A. Iollo Institut de Mathématiques de Bordeaux	Robust Reduced Order Models Of A Wake Controlled By Synthetic Jets

	17:15	**Ferryboat to Portofino**
	18,45	**Cocktail in Portofino**
Banquet	19:30	**Ferryboat to San Fruttuoso di Camogli**
	20:00	**Wokshop dinner "da Giovanni"**
	22:30	**Ferryboat back to Santa Margherita Ligure**

October 18

Session 7 (Chairman: Clarence Rowley)

Invited talk	09:00	09:45	**P. Luchini** Università di Salerno	Optimal feedback control applied to transition and turbulence
	09:45	10:05	**U. Rist**, H. Günes & S. Cadirci IAG Stuttgart and Istanbul Technical University	Qualitative And Quantitative Characterization Of A Jet And Vortex Actuator
	10:05	10:25	**G.R. Grek**, G.V. Kozlov, A.M. Sorokin & Yu. A. Litvinenko ITAM, Novosibirsk	Control Of A Round Jet By Modification Of The Initial Conditions At Nozzle Exit
	10:25	10:45	**T. Bewley**, J. Cessna & C. Colburn UC San Diego	EnVE: A Consistent Hybrid Ensemble/variational Estimation Strategy For Multiscale Uncertain Systems
Coffee	**10:45**	**11:05**		

			Session 8 (Chairman: Paolo Orlandi)	
	11:05	11:25	**J. Pralits**, T. Bewley & P. Luchini DIMEC, Università di Salerno and UCSD	Feedback Stabilization Of The Wake Behind A Steady And A Rotating Cylinder
	11:25	11:45	**K. Baysal** & U. Rist IAG Universität Stuttgart	Identification And Quantification Of The Interaction Between Shear Layers And Vortices
	11:45	13:15	**Discussion on trends in control and ROM, organisers: P. Luchini and C. Rowley**	
	13:15	13:30	Closing	
Lunch	**13:30**			

The sliding Couette flow problem

Masato Nagata
Department of Aeronautics and Astronautics
Graduate School of Engineering
Kyoto University

The sliding Couette flow, categorised by Joseph (1976), is a flow between concentric cylinders of radii a and b ($b > a$), where the inner cylinder is pulled with an axial speed U relative to the stationary outer cylinder. It is known that the linear critical Reynolds number based on the axial speed U and the gap width b-a is infinite so that secondary flows, if they exist, must bifurcate abruptly from the laminar state. The absence of linear instabilities similarly occurs in the problems, such as plane Couette flow, pipe Poiseuille flow and flow in a square duct, which have been extensively explored with success in recent years. As far as the author knows finite amplitude solutions in the sliding Couette flow have not been found yet.

In this short paper we analyse both linear and nonlinear instabilities of the sliding Couette flow in the limit of narrow gap. Following Masuda, Fukuda & Nagata (2008) we apply a uniform rotation Ω in the streamwise direction in order to provoke rotational instabilities. The idea is to see whether bifurcated flows developed with increasing Ω may be sustained in the subcritical region and even exist as Ω is reduced back to zero.

We show numerically that the critical Reynolds number approaches the global stability limit determined by energy theory in the limit of large rotation rate. A nonlinear analysis indicates that secondary flows bifurcating at a moderate rotation rate are characterized by three-dimensional spiral vortex structures. Attempted continuation of the secondary flow branch to the zero rotation rate will be discussed.

References

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DIRECT-ADJOINT EIGENSOLUTIONS OF BOUNDARY-LAYER FLOWS

D. RODRIGUEZ AND V. THEOFILIS
School of Aeronautics, Universidad Politécnica de Madrid, Pza. Cardenal Cisneros 3, E-28040 Madrid, Spain
dani@torroja.dmt.upm.es

Abstract

The instability characteristics of boundary-layer flows are studied in the scope of the BiGlobal theory. This methodology studies the behavior of small, three-dimensional (two directions resolved simultaneously and the third taken as periodic) perturbations of a basic flow by numerical solutions of partial-derivative-based eigenvalue problems (EVP) (e.g. Theofilis 2003). The related adjoint problem studies the receptivity of the basic flow to these perturbations, through the solution of an analogous EVP (e.g. Hill 1992, Gianetti and Luchini 2007).

This linear instability approach is employed here to study the instability and receptivity characteristics of boundary-layer flows. Wave-like eigenmodes, such as Tollmien-Schlichting wave have been recovered for both the Poiseuille and the self-similar Blasius basic flows using the BiGlobal methodology (figures 1 and 2). The eigenvalues corresponding to these wave-like eigenmodes are accurate with the results from the local approach (Mack 1976), filling the gap existing between the Orr-Sommerfeld/Squire problem and the BiGlobal approach. The effect of permitting the boundary-layer growth is studied hereafter, when the use of OS equation is not justified. The mild-nonparallel nature of the boundary-layer flows under a constant pressure gradient is expected to change the eigenvalues, but not the structure of the eigenspectrum, so the same families of modes are to be recovered. Fully non-parallel flows are studied with the inclusion of a laminar separation bubble. Kelvin-Helmholtz instability due to the shear-layer is then the dominant issue, and is also recovered with the boundary-layer modes (Theofilis 2007). Finally, the enclosed, reversed flow region within the bubble originates the existence of global modes (figure 3). Those global modes (Theofilis *et al.* 2000) are by far different from the wave-like eigenmodes, mainly on the receptivity properties. The study of the receptivity properties of this global modes seems to be of prime importance on controlling the behavior of the laminar separation bubbles.

Figure 1: Amplitude function of the real part of the streamwise disturbance velocity, $\hat{u}(x, y)$, for the first mode of the A-family (Mack 1976) at $Re = 7500$. Two complete periods are shown.

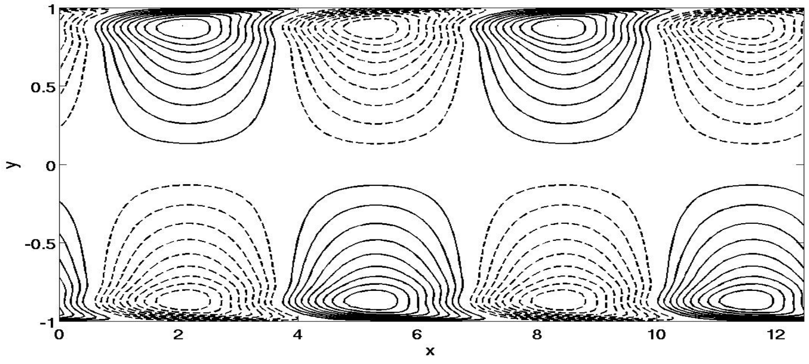


Figure 2: Amplitude function of the real part of the streamwise disturbance velocity, $\hat{u}(x,y)$, for the first mode of the Tollmien-Schlichting mode at $Re = 580$ and $\alpha = 0.179$ (Mack 1976). Ten complete periods are shown.

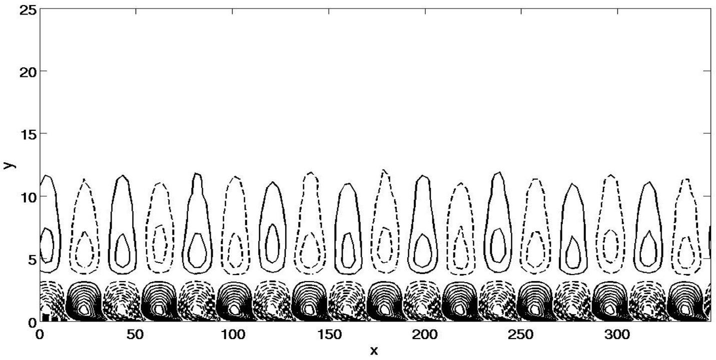
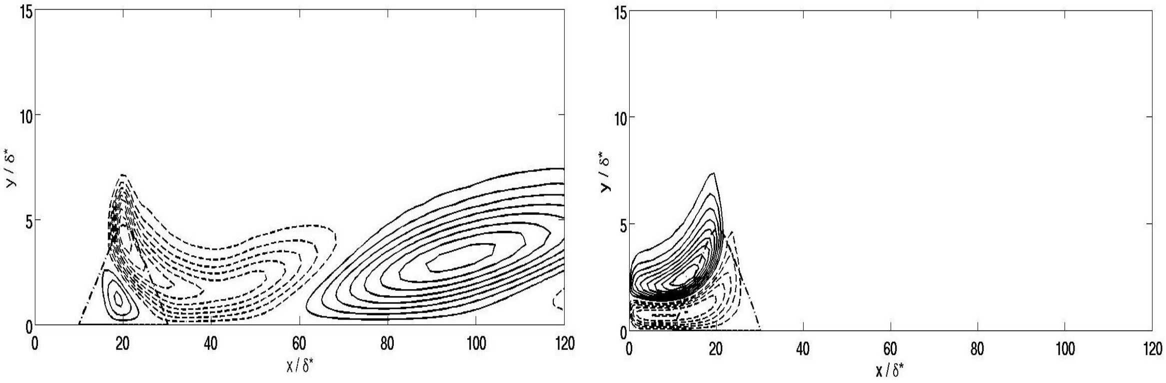


Figure 3: Amplitude functions of the real part of the direct (left) and adjoint (right) streamwise disturbance velocities, $\hat{u}(x,y)$, for the least stable travelling global mode at $Re_{\delta^*} = 50$ and $\beta = 0.25$.



Acknowledgments

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Optimal initial perturbations and optimal forcing using adjoint based methods for the flat plate boundary layer.

A. Monokrousos, E. Åkervik, L. Brandt, and D. S. Henningson
Linné Flow Centre, KTH Mechanics, SE-100 44 Stockholm, Sweden

Adjoint-based iterative methods are employed in order to compute optimal disturbances in the case of linear perturbations in a spatially growing boundary layers. The Lagrangian approach is used where an objective function is chosen and constraints are assigned. We are looking for stationary points of the Lagrange function with respect to the different design variables where optimality is fulfilled, equivalent to finding the leading eigenpair of composite direct and adjoint Navier-Stokes evolution operator. To this purpose power iterations as well are Krylov subspaces are used, both matrix-free methods, where the state is marched forward in time with a normal DNS solver and backward with the adjoint solver until a chosen criterion is fulfilled.

The adjoint-based optimisation is first applied to find the initial conditions yielding maximum disturbance energy at a given time and spanwise wavenumber. The problem is initialised with a random field, usually noise. The direct and adjoint Navier-Stokes equations are integrated until the action of the combined forward and backward time marching corresponds to pure stretching of the initial condition, i.e. $p_0 = \lambda q_0$, with q_0 being the initial perturbation and p_0 the final field from the adjoint solution while λ is a scalar. At convergence q_0 is the optimal disturbance and also an eigenvector of the operator $\mathcal{H}^\dagger\mathcal{H}$ where $\mathcal{H}$ corresponds to the direct DNS and $\mathcal{H}^\dagger$ to the adjoint: $\mathcal{H}^\dagger\mathcal{H}q_0 = \lambda q_0$. A similar procedure can be applied to find the optimal forcing. The objective function is then the integral of the energy in time, while in the governing equations there is an additional time periodic forcing term.

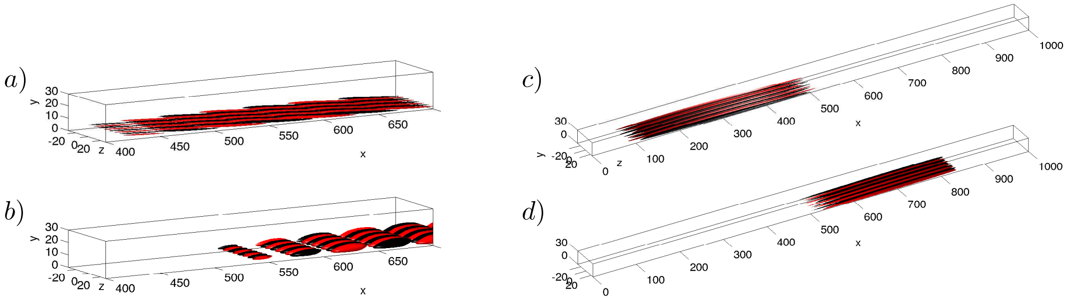

Figure 1: Optimal initial conditions and corresponding flow responses. *a*) Optimal perturbation (streamwise velocity) and *b*) optimal response (streamwise velocity) for final time $t = 200$, *c*) optimal perturbation (wall-normal velocity) and *d*) optimal response (streamwise velocity) for final time $t = 600$.

In the figure 1 two cases of optimal initial condition and the corresponding response are presented. The left-hand figures show the results for the case where the optimisation time is short (200 time units). In this case we see the effect of the Orr mechanism where upstream leaning structures lead to propagating oblique wave packets. The right-hand figures show results for a longer optimisation time (600 time units). In this case most of the energy of the initial perturbation resides in the wall-normal and spanwise velocity components, while in the flow response is the streamwise velocity that has most of the energy. We thus observe significant component energy transfer due to the non-normality of the system.

Recovering flapping frequency in a separated flow

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

The transient dynamics of a separated boundary layer over a flat plate is investigated by means of linear global eigenvalue analysis and DNS simulations with the aim of seeking the typical frequencies associated to two-dimensional instability. Time-marching integration[1] of the two-dimensional incompressible Navier-Stokes equations is used to perform the time dependent simulations and, in conjunction with a Newton continuation procedure, to compute the base flows. The separation is obtained through the imposition of a suction and blowing normal velocity profile at the upper boundary. Linear asymptotic instability of the base flow has been found to appear at $Re_c = 213$, the Reynolds number being defined as $Re = U_\infty \delta^*/\nu$, where δ^* is the displacement thickness of the Blasius profile at the inlet of the domain. Simulations have been performed for Reynolds number equal to $Re_{sub} = 197$ (subcritical) and $Re_{sup} = 220$ (supercritical). In both cases, it is known that the non-normality of the Navier-Stokes operator could lead to a transient growth of the energy[2], $E(t)$. The linear evolution of the energy associated to the optimal initial condition has been computed by the global model (see Figure 1(a)). As expected[3], at short time a very large amplification of the perturbations is observed in the separated zone, whose peak increases with the Reynolds number reaching a value of $E(t)/E(0) \sim 10^{12}$ for $Re = Re_{sup}$. After the algebraic growth phase, the normalized energy curve follows the amplification rate of the least stable mode. Moreover, we found a modulation affecting the asymptotic trend, due to the interaction of the two least stable modes. Such a modulation can be identified with the flapping frequency, which is known to be a typical feature of separated flows[4].

In order to compare the non-linear transient behaviour with the linear one, the linearly optimal perturbation is superposed on the base flow with an amplitude of order 10^{-4}. For $Re = Re_{sub}$, after a transient growth of the perturbations, followed by a short plateau[5], the flow relaxes to the stationary solution, (see Figure 1(a)) whereas for $Re = Re_{sup}$ the energy gain exhibits a non linear saturation, leading the flow to a self-sustained state[6], as shown in Figure 1(b) . In order to seek for the typical frequencies of the two flows, we compute a Fourier transform in the time domain of the streamwise velocity fluctuations within the separation region. In both spectra, we recover the same main frequencies (see Figure 1(c)), the higher ones being typical of TS and KH waves, the lower one being recognizable as the flapping frequency f, resulting from the interaction of the most unstable modes. Indeed, defining d as the distance on the real axis between the least stable modes, it has been found that $f \approx 0.001 \approx d/(2\pi)$. It is worth to notice that the low frequency disappears for long times, leading to a periodic state characterized by TS and KH waves. Finally, one can notice a slow increasing of the flapping frequency with the Reynolds number, and consequently with the bubble size, which suggests that the beating could be linked to some extent with an upstream-downstream propagation of perturbations between the reattachment and the separation point of the bubble.

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[*] SINUMEF Laboratory, Arts et Métiers ParisTech, 151, Bd. de l'Hôpital 75013 Paris, France.

[†] DIMEG, Politecnico di Bari, Via Re David 200, 70125 Bari, Italy.

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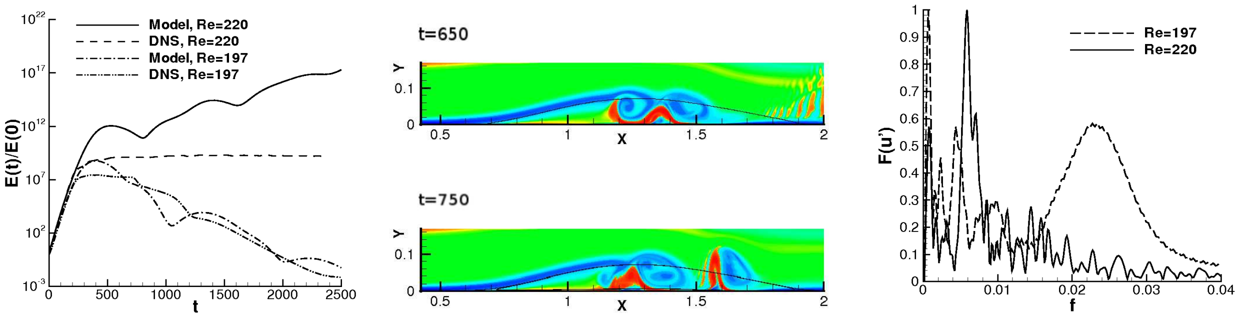

(a) (b) (c)

Figure 1: (a) Energy gain of the perturbations obtained by global model and DNS; (b) vorticity fields for $Re = Re_{sup}$ at times $t = 650$ and $t = 750$; (c) Fourier spectra of the streamwise velocity fluctuation.

On Streak Breakdown in Bypass Transition

Philipp Schlatter[1], Luca Brandt[1], Rick de Lange[2] and Dan S. Henningson[1]

[1]Linné Flow Centre, KTH Mechanics, Stockholm, Sweden
[2]Mechanical Engineering, Eindhoven University of Technology, The Netherlands

Recent theoretical, numerical and experimental investigations performed at the Department of Mechanics, KTH Stockholm, and the Department of Mechanical Engineering, Eindhoven University of Technology, are reviewed, and new material is presented to clarify the role of the boundary-layer streaks and their instability with respect to turbulent breakdown in bypass transition in a boundary layer subject to free-stream turbulence. The importance of the streak secondary-instability process for the generation of turbulent spots is clearly shown. The secondary instability manifests itself as a growing wave packet located on the low-speed streak, increasing in amplitude as it is dispersing in the streamwise direction. After a sufficiently long period of growth the flow locally breaks down and a turbulent spot is formed.

The material that will be presented includes qualitative and quantitative data pertaining to temporal sinuous secondary instability of a steady streak, impulse responses both on a parallel and a spatially developing streak (see Figure 1a), the two-mode model of bypass transition suggested in Ref. [4] (see Figure 2), and finally full simulations (see *e.g.* Ref. [1], a snapshot is provided in Figure 1b) and experiments of bypass transition [3]. In all the flow cases considered, similar characteristics in terms of growth rates, group velocity and wave lengths, but also three-dimensional visualizations of the streak breakdown have been found. The wave length of the instability is about an order of magnitude larger than the local boundary-layer displacement thickness δ^*, the group velocity about 0.8 of the free-stream veloctiy U_∞ and the growth rate on the order of a few percent of U_∞/δ^*. The characteristic structures at the breakdown are quasi-streamwise vortices, located on the flanks of the low-speed region arranged in a staggered pattern.

These findings are in contrast to those presented recently by Durbin and Wu [2], who instead propose a Kelvin-Helmholtz instability mechanism for the breakdown, both in the model of bypass transition [4] and in bypass transition itself. Their interpretation seems to originate from the fact that they are mainly considering two-dimensional plane views of the flow. Corresponding three-dimensional views and associated animations clearly support the view put forward in the present contribution.

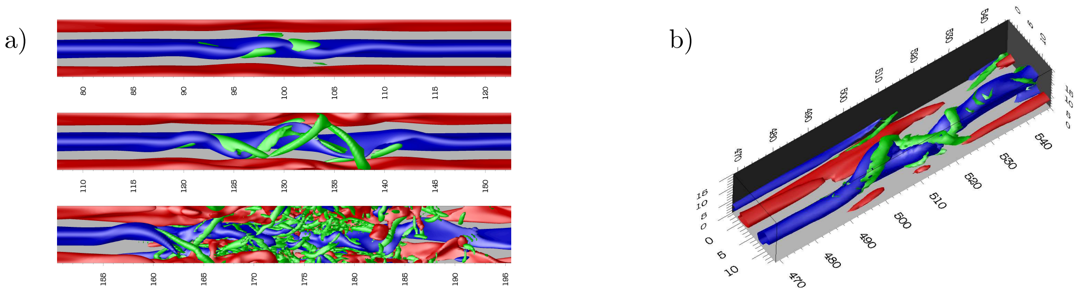

Figure 1: a) Top view of the flow development for a nonlinear impulse response on a spatially evolving streak at three time instants. b) Snapshot of a sinuous streak instability prior to the formation of a turbulent spot taken from DNS of bypass transition [1]. Low-speed streaks are indicated by blue isocontours, red corresponds to high-speed streaks, and green to vortical structures (λ_2 criterion).

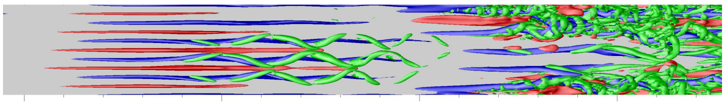

Figure 2: Three-dimensional top view of the flow structures pertaining to the model problem of bypass transition proposed in Ref. [4]; Transition is induced by two free-stream modes only. A spanwise oscillation of the low-speed streaks with each of the wiggles closely connected to an intense vortical motion can clearly be identified; in a similar pattern as seen in the visualisations in Fig. 1. Colors see Fig. 1.

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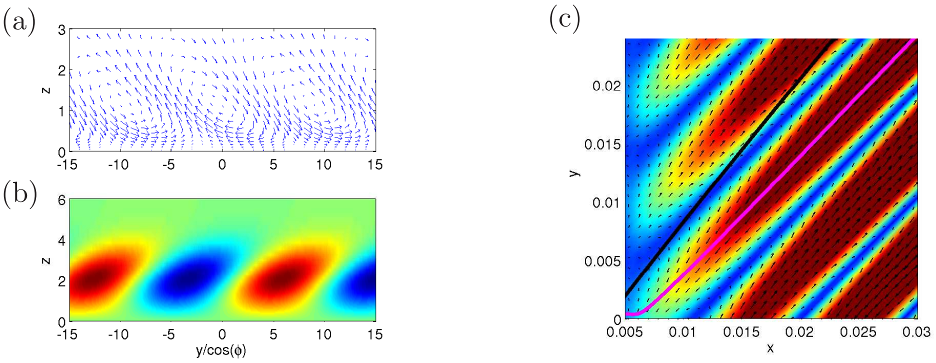
Optimal Disturbances and Receptivity of Three-Dimensional Boundary Layers

David Tempelmann[1], Ardeshir Hanifi[1,2], Dan Henningson[1]
[1] Linné Flow Center, KTH Mechanics, SE-100 44 Stockholm, Sweden
[2] Swedish Defence Research Agency, FOI, SE-164 90 Stockholm, Sweden

It is commonly known that significant differences exist between free-stream turbulence levels in free flight and those in the wind tunnel. To be able to predict the performance of wings based on wind tunnel measurements one should know how free-stream turbulence effects the flow and with it the boundary layer. Therefore a receptivity model is needed.

As a first step towards this aim we compute the initial disturbances of a Falkner-Skan-Cooke boundary layer which are associated with the maximum energy growth. Starting with the linear, incompressible disturbance equations the intention is to derive a parabolic set of equations to be able to follow the growth of the disturbances as they evolve in space. Therefore an appropriate scaling is needed which allows to identify higher order terms that can be neglected. It is well known that disturbances tend to be aligned with the outer streamline in three-dimensional boundary layers. Thus, we assume disturbances which are periodic in spanwise and weakly varying, non-oscillatory along the curved path of the disturbance. To apply the correspondent scaling we need to express the disturbance equations in a curvilinear coordinate system. Introducing normal modes, applying the scaling and neglecting terms of orders higher than Re_δ^{-1} leads to a parabolic set of equations. Transforming the equations back to the cartesian coordinate system reveals that they are similar to the parabolised stability equations if the streamwise wavenumber is set to $\alpha = \tan(\phi)\beta$, where ϕ is the angle between the tangent of the disturbance path and the direction normal to the leading edge. Adjoint based optimisation is then carried out to compute the optimal disturbances. These take the form of tilted vortices in the cross flow plane and evolve into streaks of alternating high and low speed stream wise velocity which are almost elongated with the outer streamline. When entering the super-critical domain of the flow the streaks evolve into cross-flow modes and experience exponential amplification.



(a) Vector plot of initial disturbance in crossflow plane; (b) Streamwise velocity of downstream response of optimal disturbance.

(c) Development of streaks close to initial position; Outer streamline (black) and real path of disturbances (pink)

To check the validity of this approach the energy growth of the optimal disturbance is compared to results from a Direct Numerical Simulation. Furthermore a parameter study is performed where the spanwise wavenumber, the pressure gradient , the Mach number and the downstream position for which the energy is optimised are varied. The work is performed within the framework of the EU-project TELFONA.

Leading-Edge Effects on the Receptivity of Two- and Three-Dimensional Boundary-Layer Flow

Lars-Uve Schrader, Luca Brandt and Dan S. Henningson
Linné Flow Centre, KTH Mechanics, Stockholm, Sweden

The early stages of transition to turbulence are initiated by the action of external perturbations on the boundary layer, which may reside at the wall, e.g. surface roughness, or in the free stream, like acoustic or vortical disturbances. The response of the boundary layer to such kind of pertubations may be characterised by the occurence of exponentially growing eigenmodes, e.g. Tollmien-Schlichting (TS) waves, or of nonmodal instabilities such as streaks. The study of the early phase of the boundary-layer response to external forcing is the matter of *receptivity analysis*.

It is known that boundary-layer receptivity to free-stream disturbances is enhanced in particular in regions of rapid streamwise mean-flow variations. It can therefore be expected that the boundary layer is receptive especially at the leading edge and in regions of high surface curvature. This talk will deal with the receptivity to free-stream perturbations of two- and three-dimensional boundary layers evolving on unswept and swept flat plates with elliptic leading edges. Figure 1 shows the response of the boundary layer on a two-dimensional aerodynamic body to an acoustic (a) and a vortical free-stream disturbance (b). The body consists of a flat plate attached to an elliptic leading edge of aspect ratio 20:1 (a) and 6:1 (b).

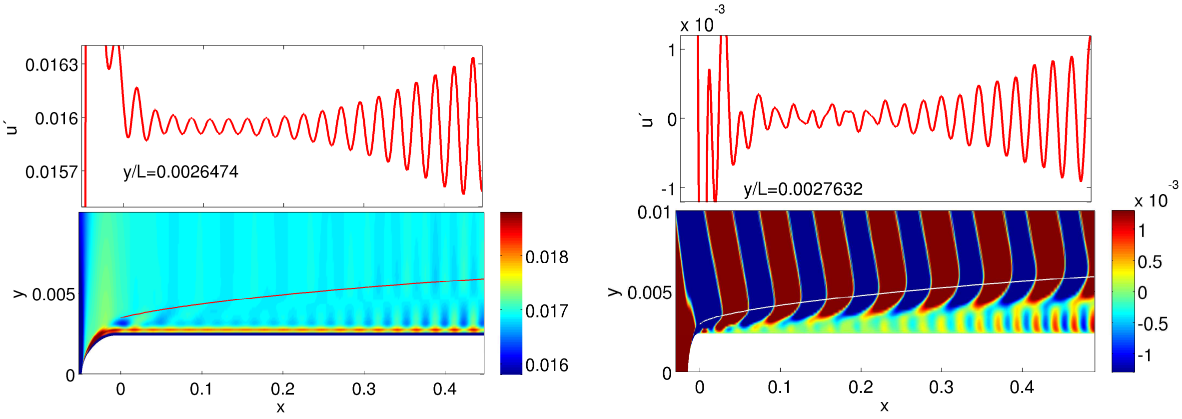


Figure 1: Boundary-layer response to two-dimensional free-stream perturbations. (a) Planar acoustic free-stream wave, frequency $\omega = 96$; elliptic leading edge of aspect ratio 20:1. (b) Spanwise free-stream vorticity, frequency $\omega = 96$, wall-normal wavenumber $\gamma = 240$; elliptic leading edge of aspect ratio 6:1. The figures are not at their true aspect ratio.

In both figures the formation and growth of TS instability inside the boundary layer is observed. Especially figure 1(b) also shows scale reduction from the large characteristic length of the free-stream disturbance to the smaller length scale of the boundary-layer instability, being known as a key element for receptivity to free-stream perturbations. Scale reduction relies on strong streamwise mean-flow changes, and thus, the observed receptivity is a leading-edge effect.

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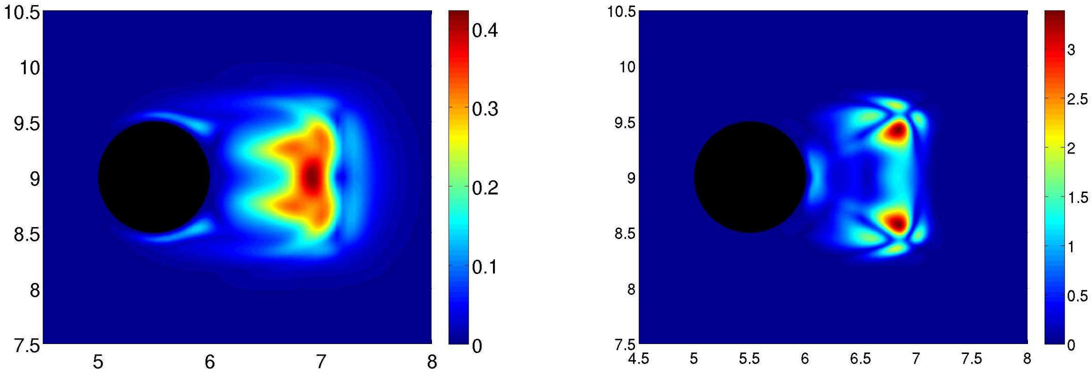
An adjoint-based analysis of the secondary instability of the wake of a circular cylinder

F. GIANNETTI*, S. CAMARRI†, P. LUCHINI*
*Dipartimento di Ingegneria Meccanica , Università di Salerno, 84084 Fisciano (SA), Italia
†Dipartimento di Ingegneria Aerospaziale , Università di Pisa, 56122 Pisa (Pi), Italia
fgiannetti@unisa.it, s.camarri@ing.unipi.it, luchini@unisa.it

The secondary instability of the wake of a circular cylinder is a well known phenomenon and has been widely studied in the last decade. (see, for instance, Barkley & Henderson (1996)). At Reynolds number (based on the cylinder diameter) $Re \simeq 189$ the two-dimensional von Kármán street becomes linearly unstable to three-dimensional perturbations. A Floquet linear stability analysis shows the existence of two separate bands of synchronous unstable modes: the first one (mode A) appears at $Re \simeq 189$ and is characterized by a spanwise wavelength of about 4 cylinder diameters, while the second one (mode B) develops for $Re > 259$ and has a shorter spanwise length-scale (about 1 diameter). Several physical mechanisms have been proposed to explain the transition to a three-dimensional flow. Some authors, for example (see Thompson et al. 2001), suggest that mode A is related to an elliptic instability of the vortex cores while mode B is associated with an instability of the braid regions.

Recently, Barkley (2005), carrying out the Floquet stability analysis on several restricted subdomains, showed that only a small region of the flow behind the cylinder plays a role in the development of the secondary instability. A similar behavior was also observed by Giannetti & Luchini (2007) in the case of the first instability of the cylinder wake. Using the properties of the adjoint operators and plotting the product between the adjoint and the direct unstable mode, they were able to identify the core of the instability (*the wavemaker*) which is localized in two small lobes symmetrically placed across the separation bubble.

In this work, we generalize the approach described in Giannetti & Luchini (2007) in order to treat a periodic base flow. In particular, the sensitivity of the Floquet exponent to a generic structural perturbation of the linearized equations is carried out by evaluating both the direct and the adjoint eigenfunctions of the Floquet transition operator. A spatial sensitivity map is then built in order to precisely identify the region of the flow where the instability is triggered. This approach is used in the present work to analyze both mode A and B (a typical example of the results obtained with



(a) Mode A (b) Mode B

Figure 1: Sensitivity map (spectral norm) of the Floquet exponent to structural perturbations of the Floquet transition operator: (a) mode A at $Re = 200$ and wavenumber $k = 1.6$; (b) mode B at $Re = 259$ and $k = 7.6$.

this procedure is given in figure (a) and (b)). Moreover, as in Barkley (2005), a Floquet stability analysis is also performed on restricted domains in order to confirm the results obtained through the use of the adjoints. Finally, the sensitivity of the Floquet exponent to a variation of the periodic base flow is investigated by solving a forced adjoint equation. Implications for a possible control strategy of the secondary instability will be discussed.

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Stochastic approach to the receptivity problem

Jérôme Hœpffner[†] and Luca Brandt[‡]

Transition to turbulence is due to the growth of unstable disturbances which finally break down to turbulence. Despite the fact that the initial linear amplification of these perturbations can now be accurately estimated, numerous investigations have shown that, owing to the nature of the instabilities typically arising in a most of the shear flows typically encountered, the transition depends strongly on the external perturbation environment. The entrainment process of ambient disturbances and the flow response to a general disturbance environment is described by the receptivity theory.

To gain physical understanding in the receptivity problem and to help identifying the mechanisms at work in relevant configurations, a stochastic approach is proposed. The stochastic analysis is pursued to examine the flow behaviour in the presence of external disturbances of chaotic nature. The method can be used to examine the receptivity of flows to external noise whose statistical properties are known or can be modelled. This approach allows improvement of predictions of the flow behaviour based only on the behaviour of unstable modes and optimal growth theory. The exact optimal perturbations are seldom encountered in practical configurations. This can be viewed as a natural "experimental" approach: The flow systems is considered in its realistic environment.

The stochastic approach was recently applied to the case of by-pass transition in two-dimensional boundary layers under free-stream turbulence[1]. A stochastic initial condition is considered where the free-stream perturbations are described by the spatial correlations of isotropic homogeneous turbulence, however without any dominant time scale. The spatial correlation of the excited flow at later times can be computed by the numerical solution of a Lyapunov equation. It is shown that free-stream turbulence has the necessary features to excite secondary energy growth, thus playing a central role in the transition to turbulence.

To reproduce as accurately as possible the main features of the ambient erratic disturbances, thus improving the prediction of the flow response, both the spatial and the temporal correlations of the external excitations are now considered. This is motivated by the observation that flow systems are not only sensitive to the space scales of the perturbations, but also to their time scales. In particular, in the case of incoming inflow conditions, the time and the space behaviour are strongly related since perturbations are convected by the mean flow.

The analysis will initially consider the relatively simpler case of a two-dimensional parallel channel and boundary layer flow with and without inflow/outflow conditions. The case of a stochastic forcing[2] will be revisited for time correlated forcing, and a stochastic inflow condition will be considered. The time/space correlated excitations are characterised by dominant time and space scales; when examining the flow response, the aim is also at better understanding the relation between an optimal forcing/initial conditions and the behaviour of the flow when randomly forced by a correlated signal.

[†] Department of Mechanical Engineering, Keio University, Tokyo, Japan.

[‡] Linné Flow Centre, KTH Mechanics, SE-100 44 Stockholm, Sweden.

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Wave forerunners of localized structures on straight and swept wings at a high free stream turbulence level

M.M. Katasonov, V. N. Gorev, V. V. Kozlov

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, Novosibirsk, Russia

Abstract:
In recent years the longitudinal localized vortex disturbances, so called “streaky structures”, or “puffs” appearing in boundary layers under the effect of external flow turbulence are of much interest [1]. At present day, investigations performed under "natural" conditions do not provide an exhaustive answer to the questions posed, because, in boundary layers, disturbances arise at random and it is hardly possible to trace the behavior of a particular disturbance. In the studies aimed at the comprehensive investigation of localized longitudinal structures, the structures are artificially modeled. In this work wave packets (forerunners) occurring in the regions preceding a drastic change of flow velocity inside the boundary layer at the localized disturbances fronts are in focus [2]. Their characteristics and dynamics have been studied experimentally in straight and swept wing boundary layers under the low and high free stream turbulence level.

The investigations were carried out in the subsonic wind tunnel. The velocity of the oncoming flow was U_∞= 5 m/s. The high level of free stream turbulence (Tu = 0.79 and 2.31%U_∞) was generated from grid located at the beginning of the wing tunnel test section. The tested models were straight and swept wing airfoils with chords c_1 = 290 mm and c_2 = 410 mm respectively. The models were set at zero angle of attack at the middle of the test section. The blowing-suction method was used to introduce disturbances into the boundary layer through the 40 mm width slot on the model surface. The duration of the blowing 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.

By applying the blowing (suction) pulse onto the boundary layer a localized disturbance (streak) are appeared. Together with localized disturbance also an a high frequency wave packets (forerunners) are observed, see figure 1. As a result of dispersion, the rectangular pulse front spreads generating a broad spectrum, the most unstable ones oscillations being enhanced by the boundary layer. It was found that, developing downstream in the boundary layer, the forerunners transform into Λ-structures and lead further downstream to turbulence through the formation of turbulent spots.

It was shown that, the wave packets (forerunners) are exists and lead to turbulence under the high free-stream turbulence level. Moreover, an 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, MK-101.2007.1), and the Ministry of Education and Science of the Russian Federation (project RNP.2.1.2.3370).

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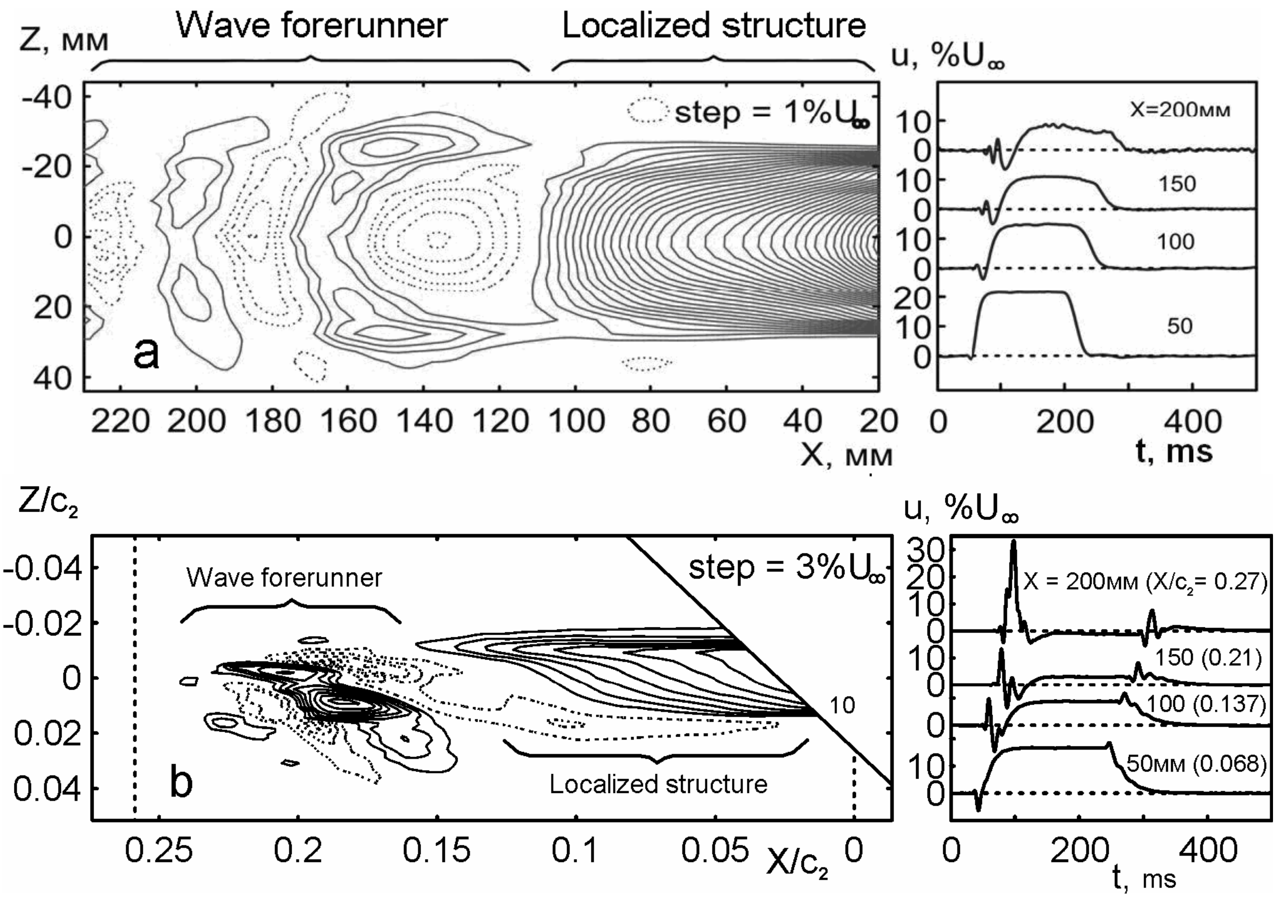

Figure 1: *Hot-wire anemometer visualization of the disturbances in the boundary layer. Contour lines of equal velocity fluctuations (left) and time traces (right). a) straight wing; b) swept wing. The suction method was used to generate the localized disturbance.*

Linear stability of a streamwise corner flow:

ALIZARD Frédéric[+*], RIST Ulrich[+], ROBINET Jean-Christophe[*].

*SINUMEF Laboratory, Arts Métiers ParisTech, 151, Bd. de
l´Hôpital 75013 Paris, France
+IAG Laboratory, Universität Stuttgart, Pfaffenwaldring 21 70569
Stuttgart, Deutschland

The linear stability of an incompressible flow along a streamwise corner formed by the intersection of two perpendicular flat plates is considered. The difficulty of the theory to identify the experimental predictions [1] and the fully three dimensionality of the flow make this problem a perfect candidate for a development of a generalized spatial stability theory.

The base flow is thus computed from a solution of the 3D self similar boundary layer equations with a Newton Solver based on the library NITSOL (Figure 1). The perturbation is written in the wave form as follows:

$$\mathcal{Q}\left(x,y,z,t\right)=\left[\mathbf{u},p\right]\left(x,y,z,t\right)=\hat{\mathcal{Q}}\left(x,y,\epsilon Z\right)e^{i\left(\mathcal{F}-\Omega_r t\right)} \text{ where } \epsilon \ll 1 \tag{1}$$

$$\frac{\partial}{\partial z}\mathcal{F}=\alpha \tag{2}$$

with $\Omega_r \in \Re$ the pulsation and $\alpha \in C$, where $-\alpha_i$ represents the spatial amplification rate and α_r the wave number of the zeroth order in ϵ.

The spatial stability problem of the zeroth order in ϵ, resulting from the introduction of the perturbation (1) into the linearized Navier-Stokes equations, leads to a large non-linear eigenvalue problem (3) solved using companion matrices and an Arnoldi Shift and Invert procedure.

$$\mathcal{L}\left(\alpha,\Omega_r,Re\right)\hat{\mathcal{Q}}=0 \text{ with } \mathcal{L}=\mathcal{A}_0+\mathcal{A}_1\alpha+\mathcal{A}_2\alpha^2 \tag{3}$$

where Re is the Reynolds number.

The spectrum and the eigenfunctions, given in Figures 2 and Figures 3 respectively, illustrates thus two different types of spatial modes: one reminiscent to the classical Tollmien-Schlichting modes, composed of different transverse wave numbers and a specific one strongly localized in the corner: the corner mode.

A spatial analysis, based on the eigenvalues of the spatial operator and a PSE marching procedure [2] taking into account the non-parallel effects for the first order in ϵ, will thus be performed on these two families and more particularly on the corner mode in order to quantify their influence on this specific flow. The influence of an adverse pressure gradient and the angle of the corner could be considered.

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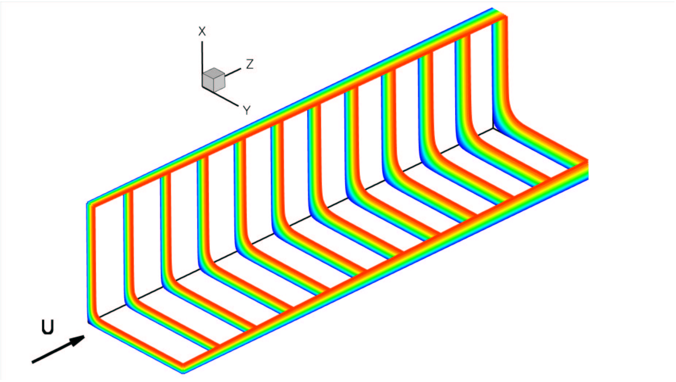

Figure 1: Streamwise component of the corner flow resulting from the self similar 3D boundary layer equations. The development of the boundary layers along the two flat plates can be observed.

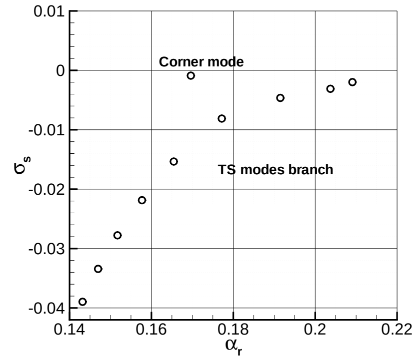

Figure 2: Spatial analysis performed at a Reynolds number $Re = 450$ and the streamwise coordinate $z = 250$. The pulsation is fixed to $\Omega_r = 0.08$. The spectrum is illustrated where $\sigma_s = -\alpha_i$ represents the spatial amplification rate and α_r the streamwise wave number.

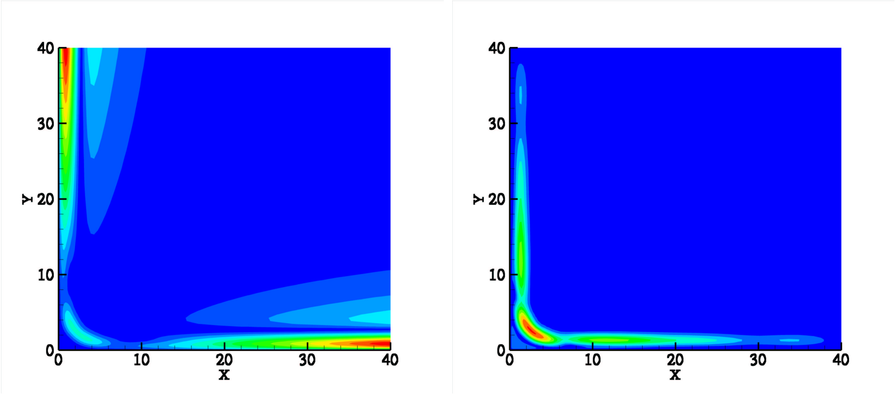

Figure 3: Illustration of the real part of the streamwise component of the perturbation of the TS mode (left) and the corner mode (right), at $Re = 450$, $z = 250$ and $\Omega_r = 0.08$.

ACTUAL PROBLEMS OF THE SUBSONIC AERODYNAMICS IN SHEAR FLOW CONTROL

V.V. Kozlov
Khristianovich Institute of Theoretical and Applied Mechanics,
Novosibirsk, 630090 RUSSIA

Optimization of aerodynamics of modern and perspective air vehicles needs the solution of several fluid mechanics problems. They are related to studying the flow phenomena occurring close to a body surface with further elaboration of new methods to control local and global flow characteristics. As a result, it becomes possible to increase lift of wings, reduce drag of the vehicles and their acoustic radiation. As a whole, flow control is aimed at improvement of economy and operational functionality of air vehicles of different destination.

A phenomenon which is crucial for the near-wall flow pattern is hydrodynamic instability one can observe in two- and three-dimensional attached and separated boundary layers. Amplification of the laminar flow disturbances results, finally, in transition to turbulence, generation of vortex structures close to the body surface, and has a strong effect on formation of separated flow regions. Thus, solution of the aerodynamic problems is integrated to studying various aspects of flow instability.

The paper focuses on exploration results obtained recently on this topic from the standpoint of the main, by the author sight, problems of fluid mechanics involved in progress of commercial aviation. They include flow laminarization on lifting surfaces, control of flow separation on small-scale air vehicles, modification of turbulent flow over blades of compressors and turbines, control of instability and acoustic radiation of jets. Wind-tunnel data on basic properties of shear flows and the associated fluid mechanics phenomena are reported which contribute to fundamental knowledge on the subsonic aerodynamics and can be used in solving the above problems.

Flow separation control by a trapped vortex cavity.

R.S. Donelli, F. De Gregorio, P. Iannelli,
Italian Aerospace Research Centre (CIRA), Capua (CE), 81043, Italy

This paper presents the experimental and numerical campaign aimed to investigate the potential benefits obtainable using a trapping vortex cell system on a high thickness airfoil to control flow separation.

To ensure a high lift–to–drag ratio, wing of modern airplanes are thin and streamlined. However, the tendency to design commercial aircraft of ever-larger dimensions, or innovative configuration as Blended-Wing-Body airplanes requests innovative solution in the field of wing structures. In order to carry a larger load having thick wing would be beneficial. The drawback of this type of airfoils is a low efficiency due to a high value of the drag coefficient. These airfoils are characterised by early flow separation phenomenon even for small incidence angle. Nowadays many research activities are aimed to investigate active or passive system dedicated to flow control. The capacity to influence the flow separation on the aerodynamic/control surface of an aircraft is a crucial aspect in term of safety, manoeuvrability and efficiency. At the end of 2005, VortexCell2050, an European funded research project, has been launched with the scope of investigate the possibility to control the flow separation using trapped vortex cavities and active control.

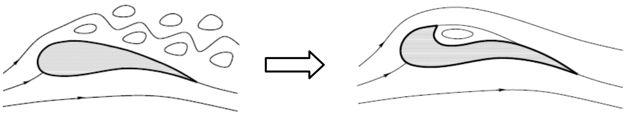

Figure 1: Trapped vortex concept

Basic concept of the trapped vortex cavities is shown in figure 1. The flow otherwise separated is forced to remain attached by an intense vortex anchored in the cavity. As preliminary activity, a 2D model has been numerically investigated, designed and built in order to present clear and stable separation. In order to maintain low the cost of the basic investigations, the measurements have been performed in the CT-1 open wind tunnel having test section sizes of 305x305x600 mm^3 and maximum speed of 55 m/s.

Furthermore, the necessity to mount the instrumented trapped cavities and to simulate a Reynolds' number up to one million requested to build a model with a chord length of at least 350mm. For fulfil the above-mentioned specifications and to be able to install the model in the small CT-1 WT avoiding blockage problems, the model has been mounted on the bottom of the wind tunnel. Figure 2 (left side) shows the model mounted on the bottom wall of the test section and the colour map of the velocity field intensity magnitude measured by PIV technique. The design of the model foresaw removable component for allocating on the upper surface of the airfoil different flow control systems.

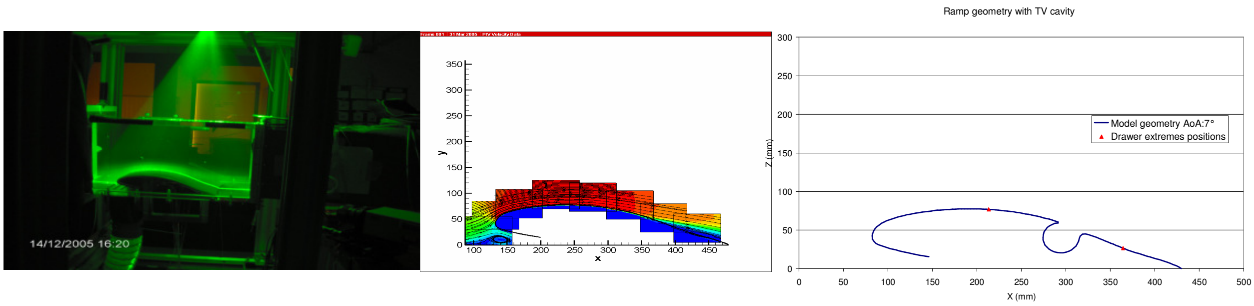

Figure 2: Experimental set-up and velocity field obtained by PIV data – Geometry of the cavity mounted on the model.

An extensive experimental and numerical test campaign has been performed for investigating the aerodynamic characteristics of the test article and in particular the flow separation behaviour for different test conditions without the flow control system by using PIV measurements and based RANS approaches solvers. Once the behaviour of the model ramp has been investigated, a trapping vortex cavity has designed, built and installed on the model (figure 2 on the right). The cavity has been equipped with a blowing and suction system in order to try to stabilise the vortex in the cavity. The suction system is formed by more then 900 passing holes located in the cavity with a diameter of 1mm, the suction holes are grouped in three different group in order to applying different mass flow. The blowing system is formed by more than 125 hole with same diameter. Four flow meters are mounted in order to measure the suctioning and blowing mass flow from the vortex cell. The cavitity has been equipped with 17 pressure taps distribuited around the circumference and long the span of the cavity in order to monitor the flow field behaviour. All the trapping vortex cavity has been built with fully trasparent material in order to allow the PIV measurements inside the cavity. The influence of the trapped vortex cell on the 2D airfoil model has been investigated. Numerical and experimental results have been compared and a description of these investigations and on the stabilization of the flow separation will be presented.

Transition Control by Suction at Mach 2 (SUPERTRAC project)

By S. Hein, E. Schülein

DLR, Bunsenstraße 10, D-37073 Göttingen, Germany

Stefan.Hein@dlr.de

Abstract

Different concepts of laminar flow control for supersonic swept wing flows are currently investigated in the EU project SUPERTRAC (SUPERsonic TRAnsition Control) (D.Arnal *et al.* (2006)). For subsonic and transonic flight Mach numbers the feasibility and potential benefits of laminar flow control by suction have been evaluated and demonstrated in several wind tunnel and flight experiments already. For supersonic flows, however, comparable experience and knowledge is not available yet. Therefore, in SUPERTRAC work package 3 experimental and numerical studies on laminar flow control by suction for a infinite swept wing configuration at Mach 2 were performed. The Ludwieg Tube Facility (RWG) at DLR Göttingen with a test section of 0.34m x 0.35m were used for these experiments. Hence, a rather small wind tunnel model was required and the measurements had to be performed at relatively high freestream unit Reynolds numbers which introduced some additional complexity for the design of the wind tunnel model. Therefore, a comprehensive numerical trade–off analysis was required in preparation of the wind tunnel experiments to define a wind tunnel model and test conditions which meet the different and partly conflicting requirements best. N-factor computations have been performed for different freestream conditions, relative profile thicknesses and sweep angles of the wing. Both sharp and blunt leading edges were considered. Moreover, the suction rates, the position and the downstream extend of the suction panel were varied systematically. The work was shared between the project partners. These numerical data were used to select a suitable model configuration for the RWG experiments. Finally, a biconvex profile with sharp leading edge and a relative thickness of 13 percent was chosen. The measurements have been performed for sweep angles of 20 and 30 degrees. Suction was applied between 5 and 20 percent chord through a suction panel made from sinter material of relatively high porosity. With this setup a significant delay of transition by suction could be achieved in the experiment.

Results from the preparatory numerical study, the wind tunnel experiment and the subsequent numerical analysis of the experimental data will be presented. The latter is still in progress, but e.g. should provide information on the dependence of the transition N-factor on the suction rate.

The work presented is part of the European research project SUPERTRAC under contract No. AST4-CT-2005-516100. The authors are grateful to all SUPERTRAC partners for their contributions to the results discussed.

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Nonlinear Flow States in a Square Duct

Håkan Wedin[1], Damien Biau[1], Alessandro Bottaro[1], Masato Nagata[2]

[1]*University of Genova, Italy;* [2]*University of Kyoto, Japan*

The transition from laminar to turbulent flow in a square duct is an intriguing problem of hydrodynamics. The laminar profile of the flow in a square duct is linearly stable and it is hence conjectured that transition to turbulence is caused by the emergence of finite amplitude solutions of the Navier-Stokes equations. Recent evidence on circular pipe flow suggests that these alternative solutions, in the form of travelling waves and with no connection to the laminar flow, provide the skeleton around which time-dependent trajectories in phase space can orbit, preventing relaminarization of the flow for long times. Here we present nonlinear solutions or 'self-sustaining-states' to the Navier-Stokes equations, obtained with an approach initiated by Fabian Waleffe. The nonlinear flow that emerges when using such states as initial conditions in direct numerical simulations is studied.

Coherent structures of the laminar and turbulent jets

V.V. Kozlov, G.R. Grek, G.V. Kozlov, A.M. Sorokin and Yu.A. Litvinenko

Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Division of the Russian Academy of Sciences,
Institutskaya st. 4/1, Novosibirsk, 630090 Russia

Abstract:

Smoke visualization and hot-wire measurements of the laminar and turbulent round and plane jets were carried out at a constant mean velocity in the jet core of $U_0 \approx 5$ m/s. The turbulent flow regime was induced by a sand paper placed close to the nozzle exit. It is known [1], that the downstream evolution of laminar round jet with a classical mean velocity profile at the nozzle exit is associated with origination of ring vortices. Results of smoke visualization of the laminar and turbulent round jets are presented in figure 1 where one can observe the ring vortices in both cases. In spite of the mean velocity profile at the nozzle exit of turbulent jet weakly differs from that of the laminar jet, i.e. it is only approaching the shape of turbulent profile, the velocity fluctuations intensity clearly demonstrates the turbulent state of flow (see comparison of the velocity fluctuations profiles for the laminar and turbulent jets in figure 1). Thus, it is shown that coherent structures such as ring vortices can exist both in the laminar and turbulent round jets.

Completely different situation with the coherent structures is found in the plane jet. In this case, the ring vortices are not observed. However, sinusoidal oscillations of the entire plane jet [2] become visible in the case of parabolic mean velocity profile at the nozzle exit, see figure 2. Smoke visualization of the plane jet in the absence of acoustic forcing demonstrates that the laminar jet is subjected to the sinusoidal disturbances while the turbulent jet is not (see figure 1). At the same time, the sinusoidal oscillations both of the laminar and turbulent jets occurring under acoustic excitation at the frequency of 30 Hz are clearly observed in the flow visualization of figure 2. The coherent structures (i.e. cylindrical vortices of the sinusoidal vortex street) are well seen at visualization of the laminar plane jet subjected to acoustic forcing. On the other hand, acoustic excitation of the turbulent jet results in sinusoidal oscillations of the entire jet while the cylindrical vortices are destroyed by turbulence. Mean and fluctuations velocity profiles of the laminar and turbulent plane jets are presented in figure 2. Comparison of the mean velocity profiles (see figure 2, top-right) demonstrates that the laminar plane jet has a parabolic mean velocity profile at the nozzle exit which results in its sinusoidal instability. Otherwise, the turbulent mean velocity profile is the typical for a turbulent jet at the nozzle exit. Comparison of the fluctuation velocity profiles (see figure 2, bottom-right) demonstrates that the oscillations intensity of turbulent jet in its shear layer is almost thirty times and in the core of jet is more than ten times higher than the oscillations intensity in the laminar jet.

Thus, it is found that sinusoidal oscillations of the entire plane jet result in origination and downstream evolution of the coherent structures (i.e. cylindrical vortices penetrating fully the jet cross-section) at every half-period of the oscillations both of the laminar and turbulent jets.

This work was supported by the Russian Foundation for Basic Research (grant no. 08-01-00027), the Ministry of Education and Science of the Russian Federation (project RNP 2.1.2.3370) and by the grants of President of the Russian Federation (NSh-454.2008.1 and MK – 420.2008.1).

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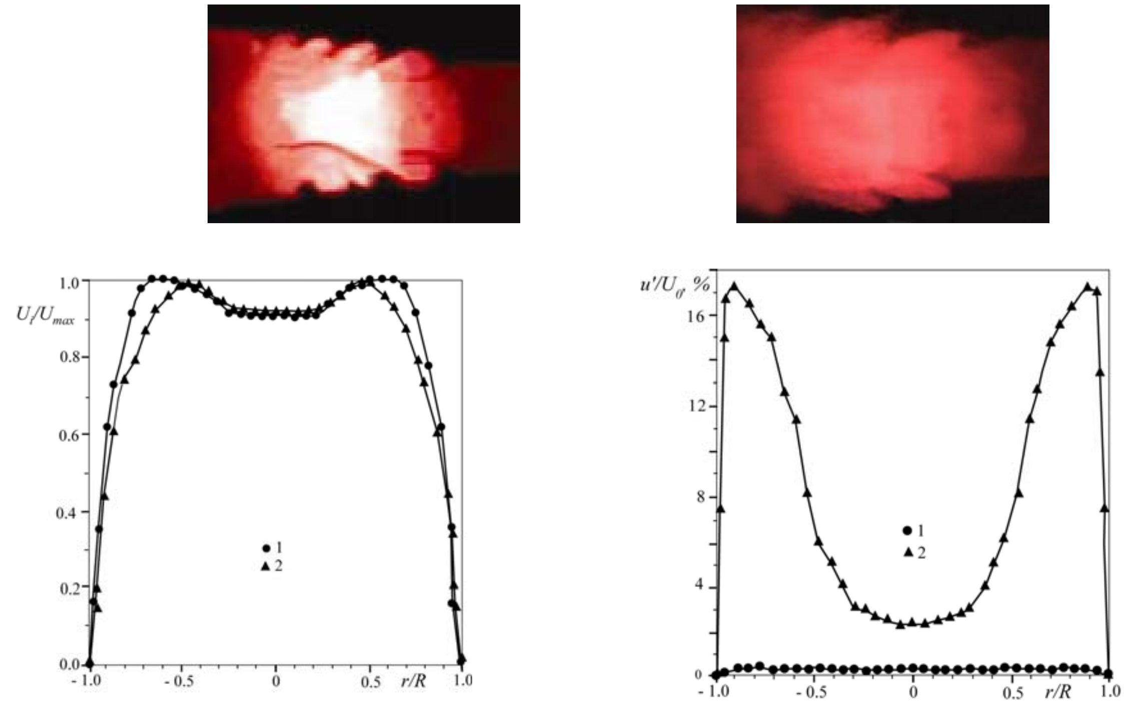

Figure 1: *Smoke visualization of the ring vortices in the classical laminar (left) and turbulent (right) round jets. Mean (left) and fluctuation (right) velocity profiles in a cross-section near the nozzle of laminar (1) and turbulent (2) round jets, flow velocity at the jet axis* U_0 *is equal to 5 m/s (*$Re = U_0 \times d / \nu = 6667$*).*

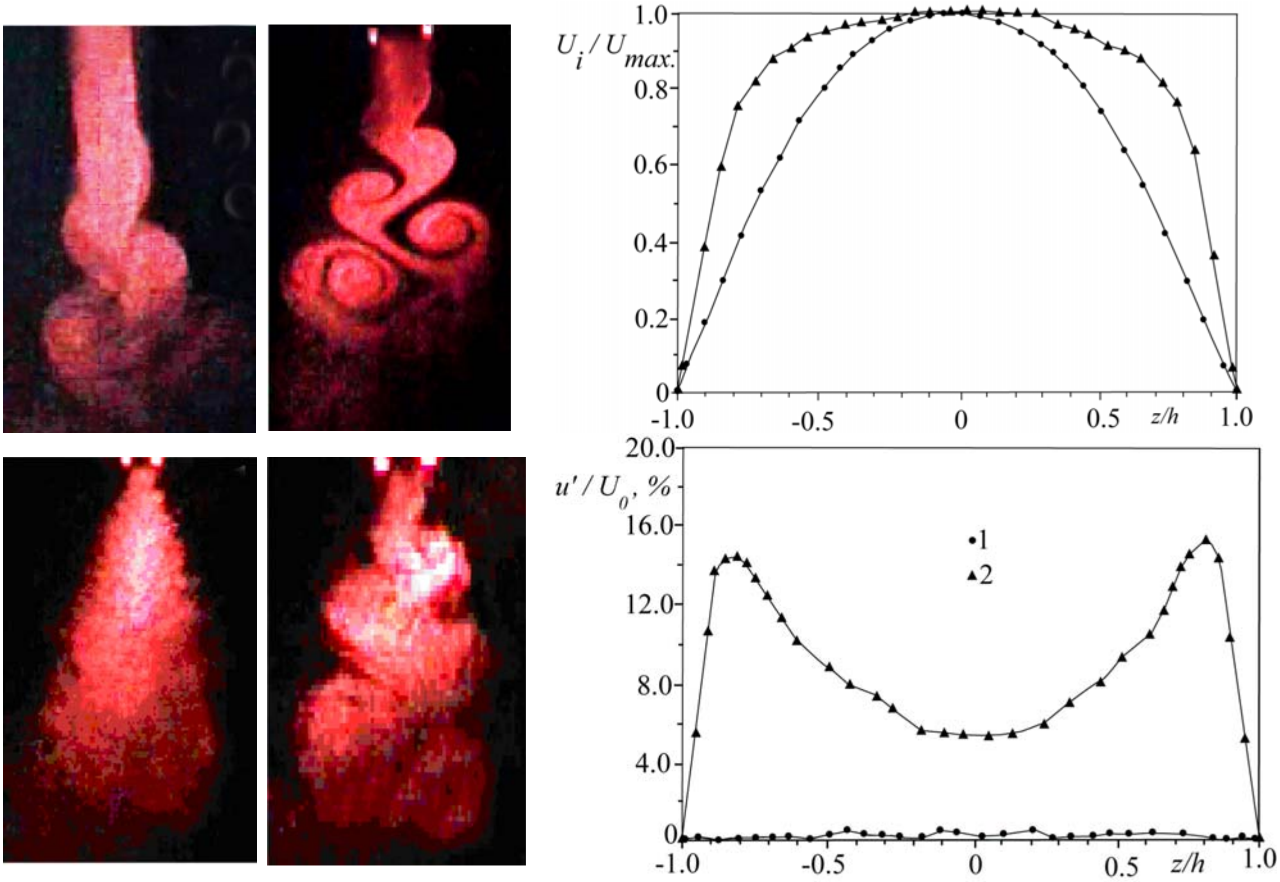

Figure 2: *Smoke visualization of the laminar (top) and turbulent (bottom) plane jets (left images are without acoustics and the right ones are with acoustics). Mean (top) and fluctuation (bottom) velocity profiles in a cross-section near the nozzle of laminar (1) and turbulent (2) plane jets, flow velocity at the jet axis* U_0 *is equal to 5 m/s (*$Re = U_0 \times 2h / \nu = 4833$*).*

Edge states and puff-like turbulent regimes

Y. Duguet, P. Schlatter
Linné Flow Centre, KTH Mechanics, SE-10044 Stockholm, Sweden

One of the most striking experimental features of transition in shear flows at moderate Reynolds number is the appearance of 'puffs', i.e. statistically stable turbulent structures co-existing with more laminar spatial regions of the flow. These structures have been well documented in cylindrical pipe flow and can exist there when $1700 < Re < 2300$ (Ref.1). Numerical simulation also suggests their existence in plane channel flow, at least for $60 < Re_\tau < 80$ (Ref.2, see Figure). On a more theoretical side, a new picture is emerging, according to which transition to turbulence in these geometries can be described in terms of dynamical systems. This requires the knowledge of unstable finite-amplitude solutions (mainly travelling waves or more generally edge states) and their interconnections (Ref.3). However, this seducing idea has been so far applied only to small computational domains with simplest dynamics. In this talk we will explain how smoothly the whole dynamical system approach can be extended to larger computational domains. In the case of pipe flow in a domain of length $L \sim 32D$, constraining edge trajectories to symmetric subspaces has lead to the recent discovery of a travelling wave solution for a large value of Re corresponding more to an expending 'slug' regime. The solution is localised both in the axial and radial direction, and displays a clear critical layer in the vicinity of the walls. The same strategy is now used to detect such localised exact solutions in channel flow. The computational domain has to be large enough for localised turbulence to sustain itself. Re-scaling the numerical amplitude of a given puff-like initial condition (until the dynamics is restricted to the laminar-turbulent boundary) allows the flow to approach exact and unstable coherent states.

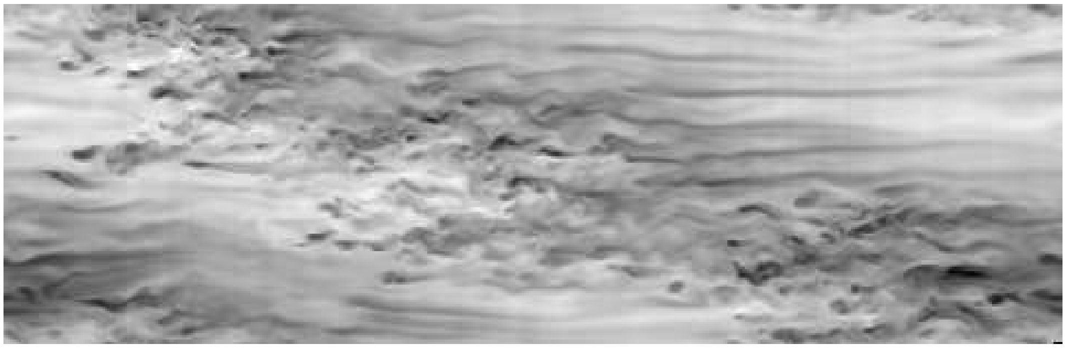

Figure 1: Direct numerical simulation of a puff in channel flow, $Re_\tau = 64$. Near-wall slice of the axial velocity state in plane Poiseuille flow, in a box of dimension $70h \times 2h \times 22.5h$. The mean flow is from left to right and the structure travels at a speed of approximatively $0.8U_c$.

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Optimal perturbations in zero pressure gradient turbulent boundary layers

Gregory Pujals [1,2], Carlo Cossu [1] and Sebastien Depardon [2]

[1] LadHyX, CNRS-École Polytechnique, F-91128 Palaiseau, France

[2] PSA Peugeot Citroën, Centre Technique de Velizy, 2 Route de Gisy, 78943 Vélizy-Villacoublay Cedex, France

Abstract:

The optimal energy growth of perturbations sustained by a zero pressure gradient turbulent boundary is computed using the eddy viscosity associated with the turbulent mean flow, following the same approach used by del Álamo & Jiménez (1) for the turbulent channel flow case. The turbulent mean flow is approximated using the asymptotic expression proposed by Monkewitz et al. (2).

It is found that even if all the considered turbulent mean profiles are linearly stable, they support transient energy growths. The most amplified perturbations are streamwise uniform and correspond to streamwise streaks originated by streamwise vortices. For sufficiently large Reynolds numbers two distinct peaks of the optimal growth exist respectively scaling in inner and outer units. The optimal structures associated with the peak scaling in inner units correspond well to the most probable streaks and vortices observed in the buffer layer (see Fig. 1 (a)) and their moderate energy growth is independent of the Reynolds number.

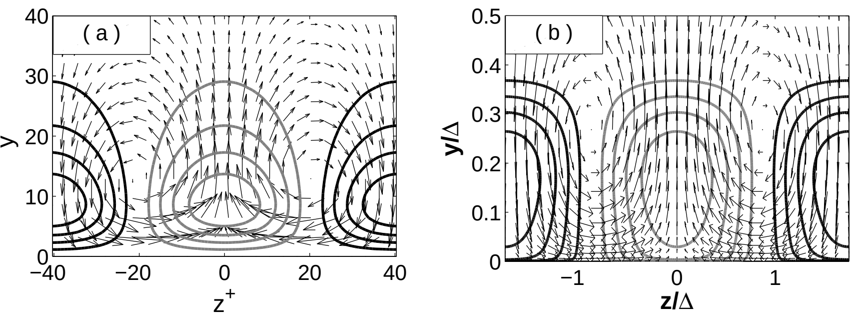

Figure 1: Cross-stream view of the v-w component of the optimal initial vortices (arrows) and of the u component of the corresponding maximally amplified streak (contour-lines) for $Re_{\delta_*} = 17300$ and $\alpha = 0$. (a) the secondary peak optimal is plotted in wall units while (b) the primary peak optimal is plotted in external units. Black contours represent positive u while grey contours represent negative u.

The energy growth associated with the peak scaling in outer units is larger than that of the inner peak and scales linearly with an effective turbulent Reynolds number formed with the maximum eddy viscosity and a modified Rotta-Clauser length based on the momentum thickness. The corresponding optimal perturbations consist in very large scale structures with a spanwise wavelength of the order of $8\,\delta$. These optimal vortices are centered near the edge of the boundary layer while the associated optimal streaks spread the whole boundary layer (see Fig. 1 (b)) and seem to scale in outer variables in the outer region and in wall units in the inner region of the boundary layer, there being proportional to the mean flow velocity. These outer streaks protrude far into the near wall region, having still 50% of their maximum amplitude at $y^+ = 20$ (see Fig. 2).

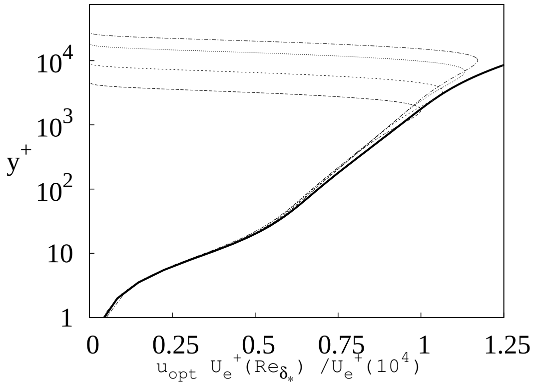

Figure 2: Normalized u component of the optimally amplified streaks corresponding to the main peak plotted in wall units and normalized. The solid line represents the mean flow profile corresponding to $Re_{\delta_*} = 10^4$ and normalized with an arbitrary constant to match the normalization of the optimal streaks.

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The DNS of the Reynolds experiment ”On the circumstances which determine whether the motion shall be direct or sinuous”

P. Orlandi

Dip. Mecc. e Aer., Università “La Sapienza”, Rome, Italy

The experiments performed by O. Reynolds at the end of the 19th century can be considered one of the turning point of the research in fluid mechanics. A non dimensional number was defined and it was stated that at a certain value the flow was passing from a laminar status (” the elements of fluid follow one another along lines”) to a turbulent status (” they eddy about in sinuous path the most indirect possible”). After that paper the research on transition and turbulence begun. Reynolds suggested two ways to understand the phenomenon: one theoretical and the other practical. At that time, without the computers, the integration of the Navier-Stokes equations was impossible. So he had to choose the experimental approach to study the growth of the instability. If we imagine to neglect the progress in fluid dynamics from 1883, and that, we may have access to supercomputers, today the most efficient approach to understand the transition from laminar to turbulent flows relies on the discretization of the Navier-Stokes equations.

Reynolds in investigating the instability of profiles without inflectional points, repeated several times that ”the critical velocity was very sensitive to disturbance in the water before entering the tubes”. The sensitivity to the disturbances, after Reynolds, was carefully investigated, and recently, experimentally, has been proved that the transition Reynolds number increases with the decrease of the amplitude of the disturbance (Fitzgerald 2004 Physics Today,57,2004). From these results and by numerical simulations it turns out that, without disturbances, the parabolic Poiseuille velocity profile, is stable as predicted by the Rayleigh criterion.

In this paper we are interested to verify the importance of initial rather than inlet conditions. So time developing instead of space evolving flows are considered, which require a reduce amount of computational power. Usually the DNS of transition is performed by adding disturbances, from the linear stability theory, to a mean velocity profile. In a laboratory, instead, at a certain distance from the entrance, there is a mean velocity profile with superimposed flow structures, solution of the Navier-Stokes equations. A first set of simulations has been performed, starting from fully turbulent conditions, and by reducing the Reynolds number until there is a number when the flow leaves the ”sinuous” state and reaches an ordered state. Statistics profiles, together with visualizations, give insights on the role of the structures. To understand the importance of the structures on the transition, combinations of mean velocity profiles and of fluctuating velocity field, have been assumed as initial conditions.

DNS of jet in crossflow on a flat plate boundary layer

Björn Selent

Future wing design aims towards high lift configurations (HLC) for which means of flow control (passive or active) have to be developed. One aspect of current research effort involves the prevention of flow separation on the airfoil. In order to achieve reattachment a strong jet is blown into the turbulent boundary layer with the aim to create a longitudinal steady vortex. Thus, fluid layers with higher momentum are transferred towards the near wall region and larger pressure gradients can be overcome. These effects have already been shown for incompressible flows both in experiments and numerical simulations.

The presented work aims to perform a direct numerical simulation of the flow in the vicinity of a jet actuator inside a turbulent boundary layer on a flat plate. Therefore a computational method that solves the complete compressible Navier-Stokes equations is used and extented. The method is based on the conservative formulation of the governing equations and uses compact finite differences for the approximation of derivatives in streamwise and normal direction and a spectral method for spanwise derivatives. Further extensions include grid transformations to resolve the geometry of the slits and compact filters to suppress numerical instabilities. The jet is introduced into the flow by means of suitable wall boundary conditions. Thus it is possible to simulate flows with sufficient jet to freestream velocity ratios which are necessary to create the desired vortex. The computational results are verified by existing experimental data and the method is used for the simulation of the jet/boundary layer flow interaction. The resulting effects, namely the exchange of momentum in the boundary layer are to be simulated correctly in order to both verify and develop new models for numerical simulations involving coarser models such as LES and or (U)RANS. Furthermore the expected positive effects of the blowing mechanisms are to be simulated and clarified. This includes simulations of detached turbulent flows and of the reattaching of a seperation bubble due to the vortices generated by the actuator.

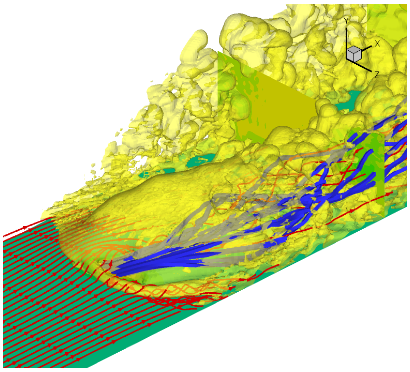

Figure 1: Jet in crossflow

Global Stability of a Jet in Crossflow

Shervin Bagheri[*], Philipp Schlatter[*], Peter J. Schmid[†]
and Dan S. Henningson[*]

Recent advances in computational methods have enabled global stability analyses of flows with nearly arbitrary complexity and have furnished the possibility to assess fully two- and three-dimensional base flows as to their stability and response behavior to general three-dimensional perturbations. Specifically, the combination of new efficient methods for computing steady-state solutions and for treating very large eigenvalue problems based on only minimal modifications of existing numerical simulation codes has provided the necessary tools for an encompassing study of the disturbance behavior in complex flows.

The jet in crossflow is a flow which is ubiquitous in a great variety of industrial applications. It is mainly characterized by a counter-rotating vortex pair in far-field, loop-shaped vortices along the shear layer, horseshoe vortices which form in the form in the flat-wall boundary layer near the jet exit and vertically-oriented shedding vortices in the wake of the jet. A linear stability analysis shows that the jet in cross-flow is characterized by self-sustained global oscillations for a jet-to-cross-flow velocity ratio of three. A fully three-dimensional unstable steady-state solution and its associated global eigenmodes are computed by direct numerical simulations and iterative eigenvalue routines. The steady flow, obtained by means of selective frequency damping, consists mainly of a (steady) counter-rotating vortex pair (CVP) in the far field and horseshoe-shaped vortices close to the wall. High-frequency unstable global eigenmodes associated with shear layer instabilities on the CVP and low-frequency modes associated with shedding vortices in the wake of the jet are identified. Different spanwise symmetries of the global modes are discussed.

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[*] Linné Flow Centre, KTH Mechanics, Stockholm, Sweden

[†] LadHyX, CNRS-Ecole Polytechnique, Palaiseau, France.

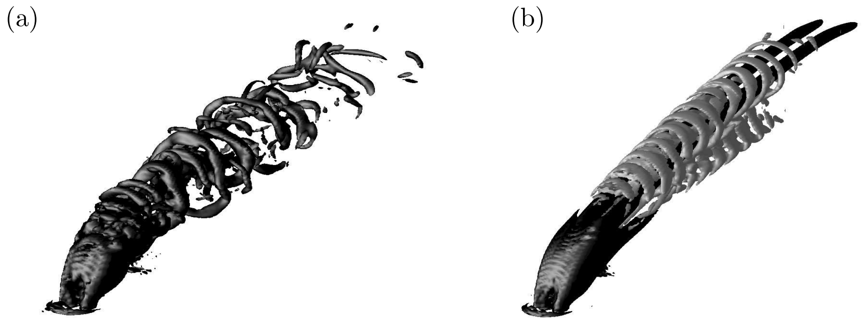

Figure 1: Isocontours representing the λ_2 vortex-identification criterion. a) Snapshot of the flow for $R = 3$. b) The steady state in black isocontours and the most unstable global mode in gray. The crossflow is from lower left to upper right.

Low-dimensional model for control of the Blasius boundary-layer by balanced truncation.

E. Åkervik, S. Bagheri, L. Brandt and D.S. Henningson

April 30, 2008

Abstract

Low-dimensional models of the transitional Blasius boundary-layer flow are considered for the design of feedback control. The starting point of modern optimal and robust control design, such as $\mathcal{H}_2$ or $\mathcal{H}_\infty$, is an input-output formulation referred to as the standard state-space formulation. We consider three inputs and two outputs. The inputs represent external disturbances, measurement noise and the actuator. We model the external disturbances as an upstream localized volume forcing and enforce wall actuation through a lifting procedure. The first output, or the sensor, approximates the action of extracting wall shear stress in a streamwise domain around the sensor location, whereas the second output measures the kinetic energy (i.e. the objective function to be minimized) far downstream on the flat plate. The control problem is to supply the actuator with an optimal and/or robust signal based on the measurements taken from the first output, such that the effect of external disturbances and measurement noise on the disturbance energy is minimized at the location of the second output. A low-dimensional model for control design is constructed by Galerkin projection of the full Navier–Stokes onto a set of balanced modes. This bi-orthogonal basis is obtained by the recently introduced technique for approximating balanced truncation for very large systems using the method of snapshots, taking into account all the inputs and outputs except the measurement noise. Figure 1 shows the leading direct and adjoint balanced truncation mode. The reduced-order model preserves flow states that are both controllable and observable and thus captures input-output characteristics of the flow, making it a natural projection basis for flow control. The error of the flow approximation obtained from balanced truncation is computed in terms of transfer function norms. The reduced-order model is then used to design a feedback control strategy such that the perturbation energy is minimized.

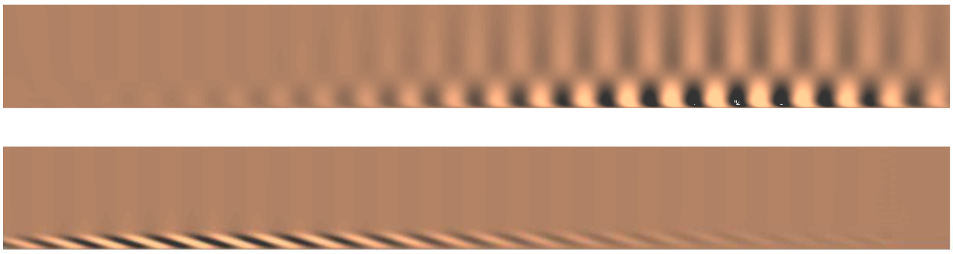

Figure 1: Streamwise component of the first direct and adjoint balanced truncation modes. Upper frame shows the direct mode that has a shape similar to the leading global eigenmode and the lower frame shows the adjoint mode that has a similar shape as the adjoint global mode, but both are spanning a larger streamwise domain than the eigenmodes.

Robust reduced order models of a wake controlled by synthetic jets

Jessie WELLER, Edoardo LOMBARDI, Angelo IOLLO

Institut de Mathématiques de Bordeaux

In the context of optimization and flow control, direct numerical simulation of the Navier-Stokes equations is too expensive. It is therefore interesting to build reduced order models that can describe the dynamics of a relative complex flow at a negligible cost.

A 2-D laminar flow past a square cylinder is considered. This setup presents a reasonable compromise between physical complexity and computational cost. For control purposes, actuators, that can alternate blowing and suction, are placed on the upper and lower sides of the cylinder. The control law can be precomputed, or obtained by feedback. In the second case the control is proportional to measurements of the velocity taken in the cylinder wake.

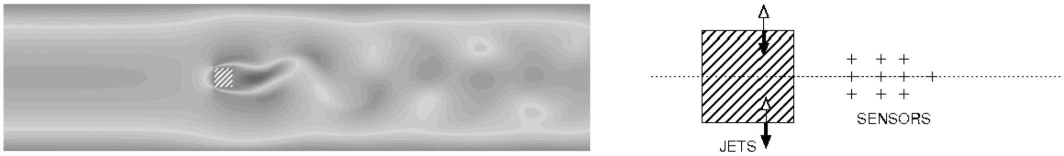

Figure 1: Definition of the geometry (with a solution for $Re = 150$) and control setup

POD consists in using results of existing simulations to build a low dimensional functional space that is optimal in terms of solution representation. A reduced order model can be obtained by Galerkin projection of the Navier-Stokes equations onto this subspace. A vast literature concerning this way of modeling wake flows exists[1] [2] , and some results show the possible interest of using POD in applications such as flow control [3]. However, several problems related to the idea of modeling a flow by a small number of variables are open, such as the robustness of the models to parameter variation, and numerical stability.

The simple Galerkin projection of the Navier-Stokes equations onto a POD basis isn't sufficient to obtain an accurate model, some adjustments to the coefficients of the reduced order system need to be made [4]. We propose a simple, and computationally inexpensive method to do this based on a Tikhonov regularization of an inverse problem. Several tests are performed at $Re = 60$ and $Re = 150$ to numerically show the effectiveness of this approach. We then introduce a procedure to make the model robust enough to react correctly to a change of the control law. We finally look at an application of this method : the design of a control law for reducing vortex shedding in the flow past the cylinder.

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Jessie WELLER, Université Bordeaux I - 351 Cours de la Libération - 33405 Talence - FRANCE
`jweller@math.u-bordeaux1.fr`

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Qualitative and Quantitative Characterization of a Jet and Vortex Actuator

Ulrich Rist, Institut für Aerodynamik und Gasdynamik Universität Stuttgart; Germany
Hasan Günes, Sertac Cadirci, Istanbul Technical University, Turkey

The Jet and Vortex Actuator (JaVA) according to Lachowicz *et al.*, 1999 appears to be a very flexible and interesting zero-net-mass-flux flow control device for boundary layer control because it appears to produce qualitatively different flow regimes depending on its actuation parameters, e.g. frequency and amplitude, or subtle changes in geometry. This latter effect, which is illustrated in Figure 1 was only discovered recently. Since little is known about the underlying fluid dynamics and because of a complete lack of *unsteady* data, we have designed and built an according device for experiments in water. Using fluorescent dye and a high speed camera the *unsteady* flow field has been recorded for visualization and quantitative evaluation by means of the “optical flux” concept from image processing. PIV, Fourier analysis, Kriging estimation and smoothing of the acquired velocity fields have been used as well.

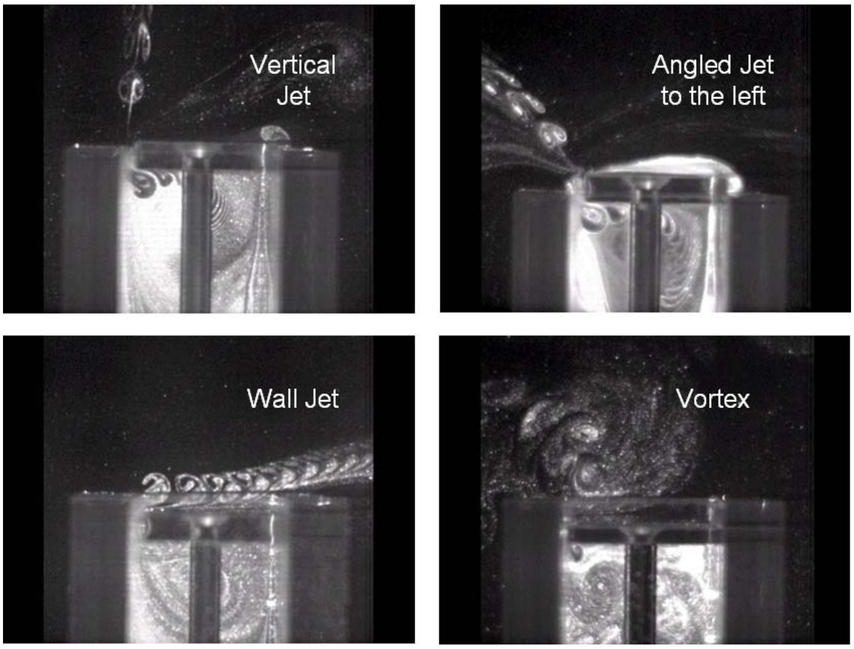

Figure 1: Examples for different actuator flows for an actuation frequency of $f = 1\ Hz$ and different mean actuator-plate positions

All qualitative features described by Lachowicz *et al.* have been reproduced (see Figure 1) but our results are much more detailed and consist of instantaneous velocity fields for quantitative analysis. Thus, the velocity magnitudes show the achievable zones of influence for the different flow regimes much clearer and allow a better comparison of different setups, as well as a better basis for their improvement. At present, three-dimensional (side-) effects are investigated as well and the actuator will be tested in a boundary layer cross-flow in a new measurement campaign during this summer. Comparisons with results of numerical simulations in another project are also possible.

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Control of a round jet by modification of the initial conditions at nozzle exit

G.R. Grek, G.V. Kozlov, A.M. Sorokin and Yu.A. Litvinenko

Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Division of the Russian Academy of Sciences,
Institutskaya st. 4/1, Novosibirsk, 630090 Russia

Abstract:

Experimental data on control of a round jet varying the initial conditions, that is, the distributions of mean and fluctuation velocity components close to the nozzle exit, are presented. Both laminar and turbulent regimes of the jet are considered involving results of smoke visualization of the flow patterns performed at one and the same Reynolds number.

Variation of the initial conditions near the exit of the round jet nozzle may have a pronounced effect upon the jet structure and its evolution characteristics. In particular, transformation of the mean velocity distribution at the nozzle from the classical one with a flat section in the jet core to a parabolic profile, results in an extended laminar flow region and suppression of the ring vortices (see figure 1). In the case of parabolic mean flow distribution, the laminar jet is observed up to 200 mm downstream of the nozzle at the exit diameter of 20 mm. Also, such variation of the initial conditions reduces the intensity of velocity fluctuations from about $u'/U_0 = 1$ % in the shear layer and 0.4 % in the jet core to 0.3 % in the entire cross section of the jet, where U_0 is the mean velocity at the jet axis. An effect of acoustic forcing on the ring vortices developing in the laminar jet has been revealed. It is shown, that their scale depends on the frequency of acoustic oscillations (see figure 2) which is in agreement with our previous observations [1].

Then, using surface roughness spaced close the nozzle exit, the turbulent jet with a parabolic mean velocity profile has been modeled. Comparing the laminar and turbulent jets, both at $Re = U_0 \times d / \nu = 6667$, it is shown that the laminar one is converged downstream while the turbulent jet spreads at an angle of about fifteen degrees (see figure 3). Velocity fluctuations in the turbulent jet are more than fifteen times higher than those in the laminar flow regime.

As a whole, the results we obtained for the first time show a possibility to control the flow structure in a round jet through modification of the initial conditions at the nozzle, i.e. the transformation of the mean velocity distribution from the classical one to its parabolic profile.

This work was supported by the Russian Foundation for Basic Research (grant no. 08-01-00027), the Ministry of Education and Science of the Russian Federation (project RNP 2.1.2.3370) and by the grants of President of the Russian Federation (NSh-454.2008.1 and MK – 420.2008.1).

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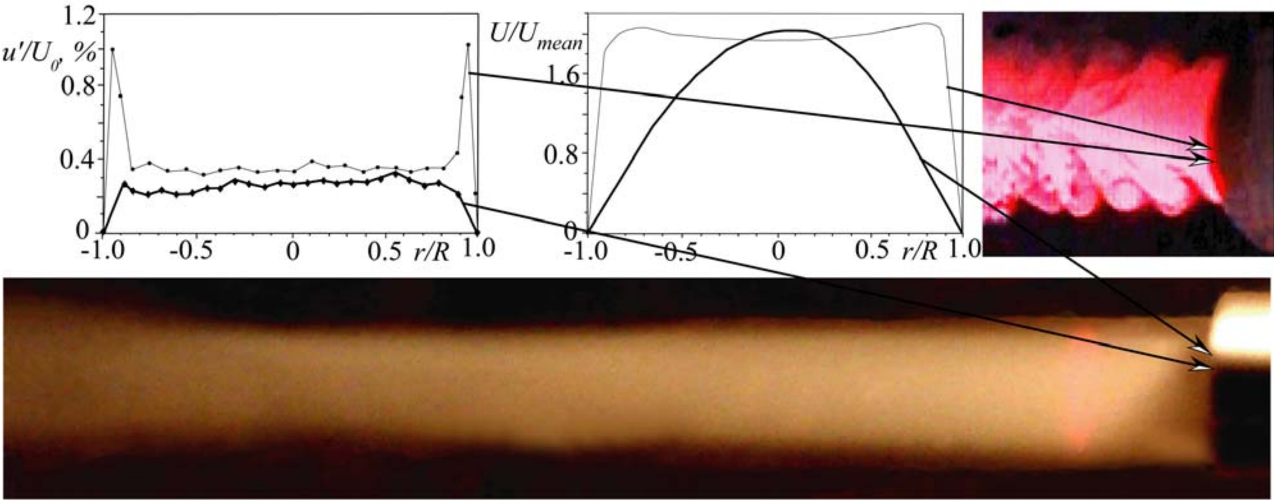

Figure 1: *Mean and fluctuation velocity profiles in a cross-section near the nozzle of classical laminar round jet (thin lines) and the same in case of the initial conditions changed (thick lines). Smoke visualization of the classical jet (top) and the parabolic one (bottom), flow velocity at the jet axis* U_0 *is equal to 5 m/s (Re =*$U_0 \times d / \nu = 6667$*).*

Figure 2: *Smoke visualization of the classical jet under the effect of acoustic excitation at 110 Hz (left) and 250 Hz (right), flow velocity at the jet axis* U_0 *is equal to 5 m/s (Re =*$U_0 \times d / \nu = 6667$*).*

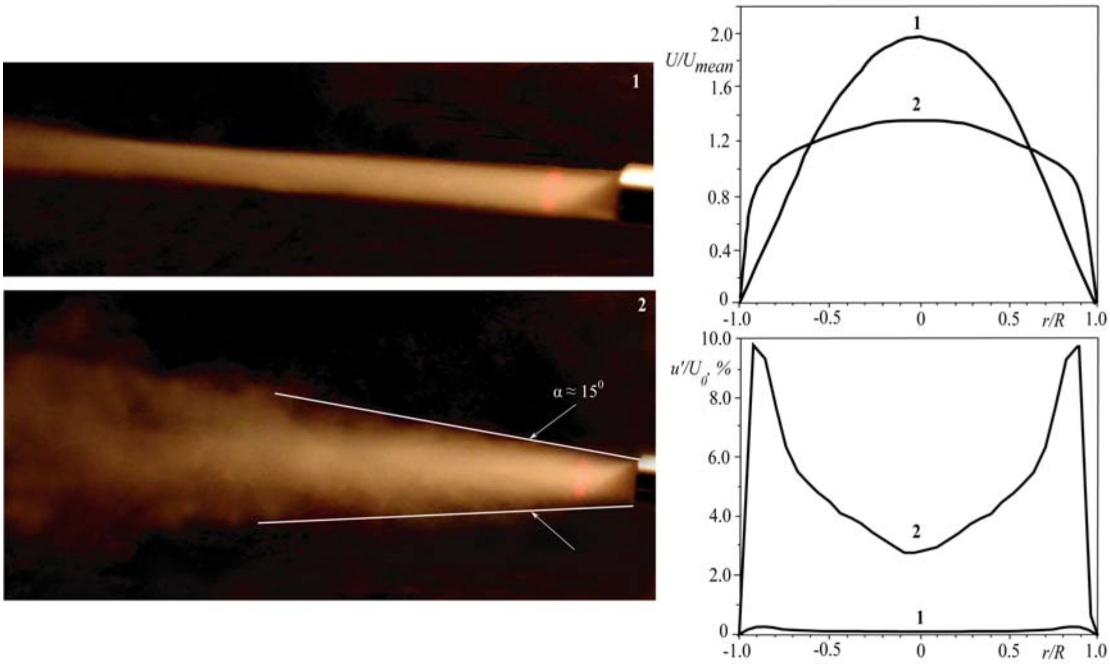

Figure 3: *Smoke visualization of the laminar* **(1)** *and turbulent* **(2)** *jets; mean (top-right) and fluctuation (bottom-right) velocity profiles for the laminar* **(1)** *and turbulent* **(2)** *jets near the nozzle exit, flow velocity at the jet axis* U_0 *is equal to 5 m/s (Re =*$U_0 \times d / \nu = 6667$*).*

EnVE: A consistent hybrid ensemble/variational estimation strategy for multiscale uncertain systems.

By Thomas Bewley, Joe Cessna, and Chris Colburn
Flow Control Lab, Dept of MAE, UC San Diego, USA

Chaotic systems are characterized by long-term unpredictability. Existing methods designed to estimate and forecast such systems, such as Extended Kalman filtering (a “sequential” or “incremental” matrix-based approach) and 4Dvar (a “variational” or “batch” vector-based approach), are essentially based on the assumption that Gaussian uncertainty in the initial state, state disturbances, and measurement noise leads to uncertainty of the state estimate at later times that is well described by a Gaussian model. This assumption is not valid in chaotic systems with appreciable uncertainties. A new method is thus proposed that combines the speed and LQG optimality of a sequential-based method, the non-Gaussian uncertainty propagation of an ensemble-based method, and the favorable smoothing properties of a variational-based method. This new approach, referred to as Ensemble Variational Estimation (EnVE), is an extension of algorithms currently being used by the weather forecasting community. EnVE is a hybrid method leveraging sequential preconditioning of the batch optimization steps, simultaneous backwards-in-time marches of the system and its adjoint (eliminating the checkpointing normally required by 4Dvar), a receding-horizon optimization framework, and adaptation of the optimization horizon based on the estimate uncertainty at each iteration. If the system is linear, EnVE is consistent with the well-known Kalman filter, with all of its well-established optimality properties. The strength of EnVE is its remarkable effectiveness in highly uncertain nonlinear systems, in which EnVE consistently uses and *revisits* the information contained in recent observations with batch (that is, variational) optimization steps, while consistently propagating the uncertainty of the resulting estimate forward in time.

Feedback stabilization of the wake behind a steady and a rotating cylinder

JAN PRALITS[1], THOMAS BEWLEY[2] AND PAOLO LUCHINI[1]
[1]Dipartimento di Ingegneria Meccanica , Università di Salerno, 84084 Fisciano (SA), Italia
[2]Flow Control Lab, Dept. of MAE, UC San Diego, USA
jpralits@unisa.it, bewley@ucsd.edu, luchini@unisa.it

Modern control algorithms, based on the Riccati equation, are usually difficult to apply to real applications such as the flow past a cylinder because of the large number of degrees of freedom originating from the discretized Navier-Stokes equations. Here we want to show a recent method, that at least in some cases, can make mathematically rigorous optimal control a reality.

If a minimal-energy stabilising feedback rule $\mathbf{u} = K\mathbf{x}$ is applied to the system $\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u}$, the eigenvalues of the closed-loop system $A + BK$ are given by the union of the stable eigenvalues of A and the reflection of the unstable eigenvalues of A into the left-half plane. Since we know where the closed-loop eigenvalues of the system are, the requisite feedback gain matrix K in this problem may be computed by the process of *pole assignment*. Applying this process to the equation governing the dynamics of the unstable modes of the system in modal form and then transforming appropriately, this leads to a simple expression for K. Here we consider the following optimization problem: for the state $\mathbf{x}$ and the control $\mathbf{u}$ related via the *state equation* $\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u}$ on $0 < t < T$ with $\mathbf{x} = \mathbf{x}_0$ at $t = 0$, where $\mathbf{x}_0$ is initially unspecified, find the control $\mathbf{u}$ that minimizes the *cost function* $J = \frac{1}{2}\int_0^T \left[\mathbf{x}^H Q\mathbf{x} + \mathbf{u}^H R\mathbf{u}\right] dt$.

In the first part of this analysis we will show that, when a modal representation of the original linear system is used, the feedback gain matrix K is a function solely of the left eigenvectors and the unstable eigenvalues.

In the second part we will show numerical results applying the minimal-energy feedback control to suppress the vortex shedding behind a circular cylinder, where the mean to control is rotation about its symmetry axis. This new technique has already been applied to a more simple flow model, see Lauga & Bewley[2], and the feedback gain matrix K has been shown for a few cases regarding the flow past a cylinder by ourselves[1]. Results will first of all be shown for the flow past a fixed cylinder at a given Reynolds number such that the vortex shedding exists in the absence of the control. Further, results will be shown for the flow past a rotating cylinder for rotation rates at which the so called second shedding mode exists.

An example of the feedback matrix K is given below for the case of the flow past a steady cylinder at $Re = 60$. In Figure 1 the u and v components of K are given in separate plots. It is interesting to note that even though the globally unstable mode, which is known to extend from the trailing edge of the cylinder far downstream, the feedback K is localized in the vicinity of the cylinder.

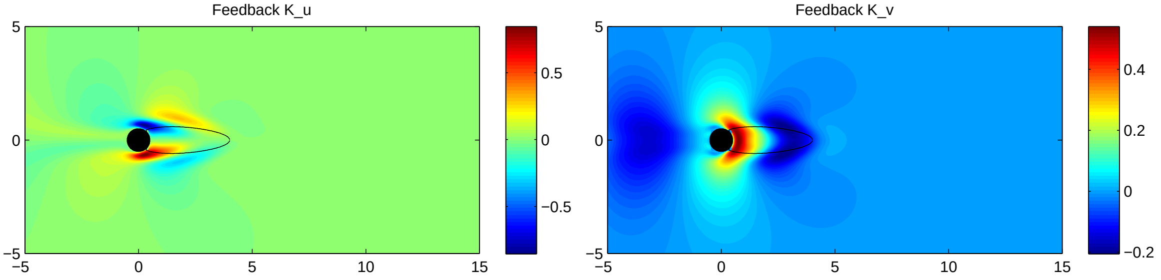

Figure 1. (left) The u component of K, (right) the v component of K.

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Identification and Quantification of the Interaction between Shear Layers and Vortices

Kudret Baysal, Ulrich Rist, Institut für Aerodynamik und Gasdynamik, Universität Stuttgart

For real-life flow control applications it is desirable to have a better understanding of fundamental fluid dynamics' mechanisms and to possess methods for their automatic detection, quantification and monitoring. Traditionally, people use the concept of vortices to describe and generalize a multitude of fluid motions. For a viscous flow, however, shear layers are equally important. This leads to the question of their interactions, i.e. the formation of new vortices either by shear-layer roll-up or by the interaction and merging of already existing vortices, and the formation of new shear layers by vortices. Such problems have been already studied in the past, however, at a time where numerical methods for an automatic detection and quantification have not yet been available.

In the present work we first identify shear layers and vortices in a given flow field using numerical implementations of analytical criteria. During their lifetime, criteria, like position, size, vorticity, enstrophy, circulation, etc. of each structure are recorded and tracked, such that a compact graphical representation of the identified dynamics can be shown. We then look for the birth of new vortices, e.g. out of shear layers or by the merging of two interacting vortices. Once these have been found "by hand" we evaluate and compare the extracted data for these events. Our intent is to find criteria for an automatic identification of events in general configurations using these methods.

The current state of the work will be explained starting with an isolated vortex in a viscous flow, where we have observed that the vortex is surrounded by shear. Via the interaction of two co-rotating vortices (Josserand & Rossi, 2007) we then turn to the analysis of a two-dimensional laminar shear layer that has been generated by the merging of two parallel streams with different velocity (see figure). Note the emergence of the first vortex out of pure shear, the almost complete absence of shear inside the vortices and the formation of new shear between neighbouring vortices. Our last example will be the formation of three-dimensional vortices in a transitional flat-plate boundary layer.

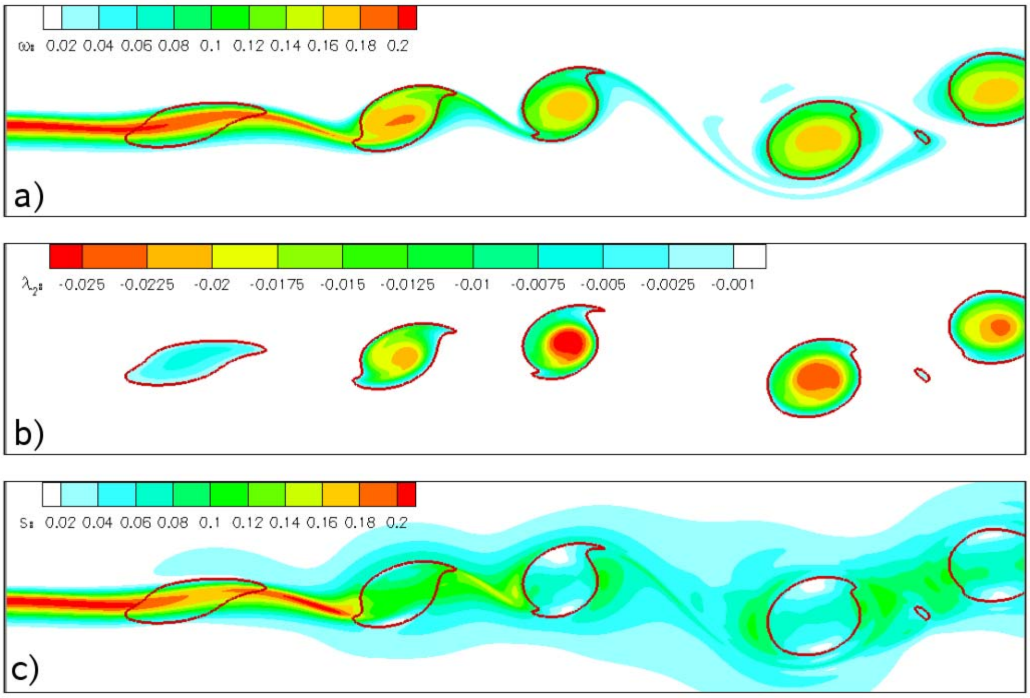

Figure 1: Visualization and analysis of a plane mixing layer. Identified vortices are repeated in each subfigure for comparison. a) Color contours of vorticity; b) Color contours of λ_2<0; c) Color contours of shear

Optimal growth in the turbulent pipe

Ashley P. Willis & Carlo Cossu

LadHyX, Ecole Polytechnique
CNRS

The viscosity in turbulent pipe flow may be parameterised by a radially-dependent eddy viscosity. This in turn determines a turbulent mean profile. Optimal growth of purturbations to this mean profile is considered, where the viscosity is approximated by the analytic expression given by Reynolds & Tiederman (1967) (after Cess 1958), with updated fitting parameters compatible with the observations of Zagarola & Smits (1998). The turbulent profile remains linearly stable for all Reynolds numbers considered (up to $O(10^6)$ based on constant mean flux, wall *Re* up to $O(10^4)$). A peak in growth for the azimuthal wavenumber $m=1$ for the z-independent mode remains, as for the laminar profile. A secondary peak appears for high m which scales with the inner wall units at large *Re*, similar to the analogue results for channel flow (Alamo & Jimenez 2006).

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Name	First name	Affiliation	E-mail
ALIZARD	Frédéric	SINUMEF Laboratory	frederic.alizard@paris.ensam.fr
ÅKERVIK	Espen	KTH	espena@mech.kth.se
BAYSAL	Kudret	University of Stuttgart	baysal@iag.uni-stuttgart.de
BEWLEY	Thomas	UC San Diego	bewley@ucsd.edu
BOTTARO	Alessandro	University of Genova	bottaro@dicat.unige.it
BRANDT	Luca	KTH	luca@mech.kth.se
CAMARRI	Simone	University of Pisa	s.camarri@ing.unipi.it
CHERUBINI	Stefania	Politecnico di Bari	s.cherubini@gmail.com
CHOMAZ	Jean-March	LadHyX	Jean-Marc.Chomaz@ladhyx.polytechnique.fr
DONELLI	Raffaele	CIRA	r.donelli@cira.it
DUGUET	Yohann	KTH	duguet@mech.kth.se
EKHARDT	Bruno	University of Marburg	bruno.eckhardt@physik.uni-marburg.de
GIANNETTI	Flavio	University of Salerno	fgiannetti@unisa.it
GREK	Genrikh	ITAM	grek@ itam.nsc.ru
HANIFI	Ardeshir	FOI/KTH	ardeshir.hanifi@foi.se
HEIN	Stefan	DLR	stefan.hein@dlr.de
HENNINGSON	Dan	KTH	henning@mech.kth.se
IOLLO	Angelo	Université Bordeaux 1	angelo.iollo@math.u-bordeaux1.fr
JUNIPER	Matthew	Cambridge University	mpj1001@cam.ac.uk
KATASONOV	Mikhail	ITAM	mikhail@itam.nsc.ru
KOZLOV	Grigory	ITAM	kozlov@itam.nsc.ru
KOZLOV	Viktor	ITAM	kozlov@itam.nsc.ru
LOMBARDI	Edoardo	Université Bordeaux 1	edoardo.lombardi@math.u-bordeaux1.fr
LUCHINI	Paolo	University of Salerno	luchini@unisa.it
NAGATA	Masato	Kyoto University	nagata@kuaero.kyoto-u.ac.jp
ORLANDI	Paolo	Universit`a “La Sapienza”	orlandi@kolmogorov.ing.uniroma1.it
PRALITS	Jan	University of Salerno	jpralits@unisa.it
PUJALS	Gregory	LadHyX	gregory@ladhyx.polytechnique.fr
RIST	Ulrich	University of Stuttgart	rist@iag.uni-stuttgart.de
RODRíGUEZ	Daniel	UPM ETSIA	dani.torroja.dmt.upm.es
ROWLEY	Clancy	Princeton University	cwrowley@princeton.edu
SCHLATTER	Philipp	KTH	pschlatt@mech.kth.se
SELENT	Björn	University of Stuttgart	selent@iag.uni-stuttgart.de
WEDIN	Håkan	University of Genova	wedin@diam.unige.it
WELLER	Jessie	Université Bordeaux I	jessie.weller@math.u-bordeaux1.fr
WILLIS	Ashley	LadHyX	willis@ladhyx.polytechnique.fr