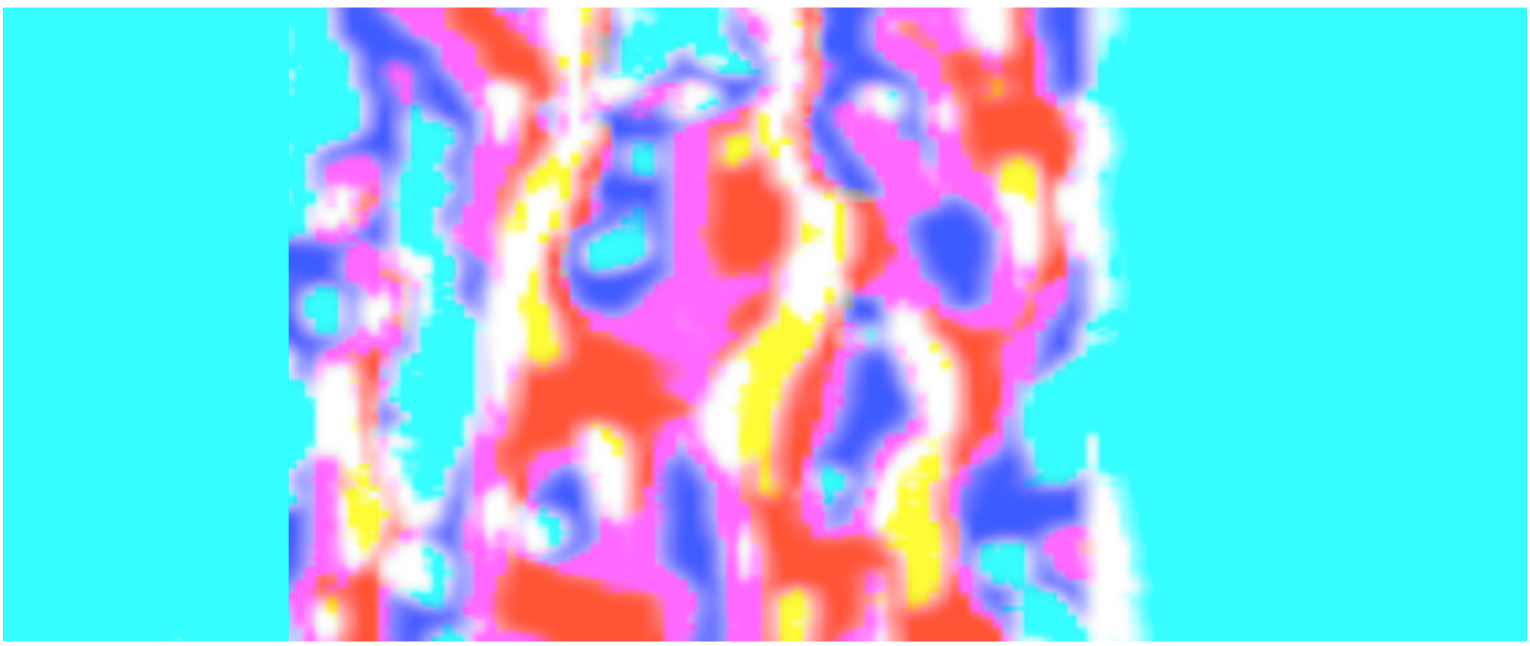
ERCOFTAC
European Research Community
On Flow, Turbulence And Combustion

9th ERCOFTAC SIG 33 Workshop

Progress in Transition Modeling and Control

Toledo, Spain

September 28 – 30, 2011



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Organisers:

Vassillios Theofilis (UPM)
Ardeshir Hanifi (FOI/KTH)

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Wedensday

Session 1		Chair: Ulrich Rist	
15:00-15:45	Alessandro	BOTTARO	Localized, Nonlinear Optimal *Alessandro Bottaro*
15:45-16:05	Frederic	ALIZARD	Lift-up Effect In An Incompressible Corner Fow *F Guiho, F. Alizard, J.-Ch. Robinet*
16:05-16:25	Oliver	SCHMIDT	On The Influence Of Wave Obliqueness And Compressibility On The Linear Stability Of Streamwise Corner Flow *Oliver T. Schmidt and Ulrich Rist*
Coffee break			
Session 2		**Chair: Luca Brandt**	
17:00-17:20	Xuerui	MAO	Optimal Control Of Transient Energy Growth *Xuerui Mao, Hugh Blackburn, Spencer Sherwin*
17:20-17:40	Viktor	KOZLOV	Subsonic Round And Plane Macro- And Micro Jets In A Transverse Acoustic Field *Viktor V. Kozlov*
17:40-18:00	Julien	HOESSLER	Stability Analysis Of Coupled Vortical Systems In The Context Of Road Car Vehicle *J. Hoessler, S. Sherwin*
18:00-18:20	Björn	SELENT	Numerical Investigation Of Jet-in-Crossflow Configurations *B.Selent, U.Rist*

Thursday

Session 3		Chair: Peter Schmid	
09:00-09:45	Bernd	NOACK	Towards A Mathematical Theory Of Turbulence Control *B. Noack, R. Niven, M. Morzynski, G. Tadmod*
09:45-10:05	Aysel	GUNGOR	The Precursor Of Kelvin-Helmholtz Instabilities In Wake-perturbed Separated Boundary Layers *A.G. Gungor, M.P. Simens, J. Jimenez*
10:05-10:25	Stefania	CHERUBINI	The Structure Of The Laminar-turbulent Edge In A Boundary Layer *S. Cherubini, P. De Palma, J.-Ch. Robinet, A. Bottaro*
10:25-10:45	Ricardo	GARCIA-MAYORAL	Kelvin-Helmholtz-like Instabilities In Turbulent Flows Over Complex Surfaces *R. Garcia-Mayoral, J. Jimenez*
Coffee break			
Session 4		**Chair: Bernd Noack**	
11:15-11:35	Angel	Velazquez	POD Based Reduced Order Models For Steady Multi-Parameter Problems *D. Alonso, B. Bache, J.M. Vega, A. Velazquez*
11:35-11:55	Jose-Manuel	VEGA	An Adaptive Reduced Order Model Based On Local POD Plus Galerkian Projection For Nonsteady Problems *M.L. Rapun, F. Terragni, J.M. Vega*
11:55-12:15	Fulvio	MARTINELLI	System Identification And Feedback Control Of The Flow Around A Circular Cylinder *F. Martinelli, P. J. Schmid*
12:15-12:35	Onofrio	SEMERARO	Transition Delay In A Boundary Layer Using Localized Sensors And Actuators *O. Semeraro, L. Brandt, S. Bagheri, J.O. Pralits, B. Belson, D. S. Henningson, C. W. Rowley*
12:35-12:55	Iman	LASHGARI	Instability Of Carreau Fluids Flowing Past A Circular Cylinder *I. Lashgari, F. Giannetti, L. Brandt and J.O. Pralits*
Lunch			
Session 5		**Chair: Alessandro Bottaro**	
15:00-15:45	Spencer	SHERWIN	Numerical Stability Studies Of Streamwise Vortices And Swirling Flows *S. Sherwin*
15:45-16:05	Kilian	OBERLEITHNER	On Global Modes In Turbulent Swirling Jet Experiments *K. Oberleithner, Ch. O. Paschereit*
16:05-16:25	Philippe	MELIGA	Optimizing Energy Production From Vortex Induced Vibrations Using An Exact Nonlinear Asymptotic Model *Ph. Meliga, J.-M. Chomaz, F. Gallaire*
Coffee break			
Session 6		**Chair: Fulvio Martinelli**	
17:00-17:20	Vladimir	PAREZANOVIC	Sensitivity Of The Global Instability Envelope To A Steady Perturbation In The Bluff Body Wake At Large Re *V. PAREZANOVIC, O. CADOT*
17:20-17:40	Matthew	JUNIPER	Combined Local And Global Stability Analysis Of Vortex Breakdown Bubbles And Confined Wakes *M. Juniper, U. Qadri, D. Mistry, O. Tammisola*
Banquet			

Friday

Session 7		Chair: Dominik Obrist	
09:00-09:45	Luca	BRANDT	Instability Of A Particle Suspension *L. Brandt, J. Klinkenberg, R. De Lange*
09:45:10:05	Miguel	FOSAS	Sound Generation In The flow Around An Aerofoil *M. Fosas, D. Sipp and P.J. Schmid*
10:05-10:25	Miguel	HERMANNS	On High Order Finite Difference Methods For Global Instability Analysis *S. Le Clainche, P. Paredes, M. Hermanns, V. Theofilis*
Coffee break			
Session 8		**Chair: Spencer Sherwin**	
11:00-11:20	Lutz	LESSHAFFT	Global Stability Of Hot Subsonic Jets *X. Garnaud, L. Lesshafft, P. J. Schmid, P. Huerre*
11:20-11:40	Dominik	OBRIST	By-pass Transition In The Swept Leading-edge Boundary Layer *D. Obrist, R. Henniger, L. Kleiser*
11:40-12:00	Pedro	PAREDES	On The PSE-3D Instability Analysis Methodology For Counter-Rotating Axially Inhomogeneous Pair Of Vortices *P. Paredes, V. Theofilis, D. Rodríguez*
Lunch			

Localized, non-linear optimals

Alessandro Bottaro
DICAT, Engineering Faculty, University of Genova

Based on work conducted with Stefania Cherubini, Pietro De Palma, and Jean-Christophe Robinet

Progress in understanding transition in linearly stable shear flows has recently proceeded along two parallel lines: one is based on the *linear* optimal perturbation theory whereas the other one focuses on the search of nonlinear, unstable, "exact" coherent states. In order to bridge the gap between these two perspectives, a variational procedure is used to identify *non-linear* optimal disturbances in a boundary layer developing over a flat plate, defined as those initial perturbations yielding the largest energy growth over a given target time. For initial energy and target time larger than a threshold value, a remarkable increase of the energy gain and strong modifications of the optimal perturbation shape with respect to the linear case are observed. Non-linear optimal perturbations are spatially localized; they are characterized by a basic structure, the *minimal seed* disturbance, formed by vortices inclined in the spanwise direction and surrounded by a region of intense streamwise disturbance velocity. The same basic structure has been found for different initial energies, target times, Reynolds numbers, and domain lengths, indicating that this is a robust feature of the considered flow. DNS has then been employed to study the mechanism of transition to turbulence when the flow is initialized using the minimal seed perturbation. Such an initial state is found to start and spread out turbulence very efficiently, its spreading rate in space and time being close to that of a turbulent spot. The transition scenario emerging from the simulations is quite different from classical ones, being based on the following steps:

(i) tilting and amplification of the initial minimal seed (Orr mechanism);
(ii) creation of Λ-shaped structures by means of momentum-transport;
(iii) non-linear redistribution of the vorticity with formation of hairpin vortices;
(iv) breakdown of the hairpins into small scale structures.

We conjecture that these could be the basic steps of a cascading process which is repeated at smaller temporal and spatial scales, up to the limiting scales defined by viscous dissipation.

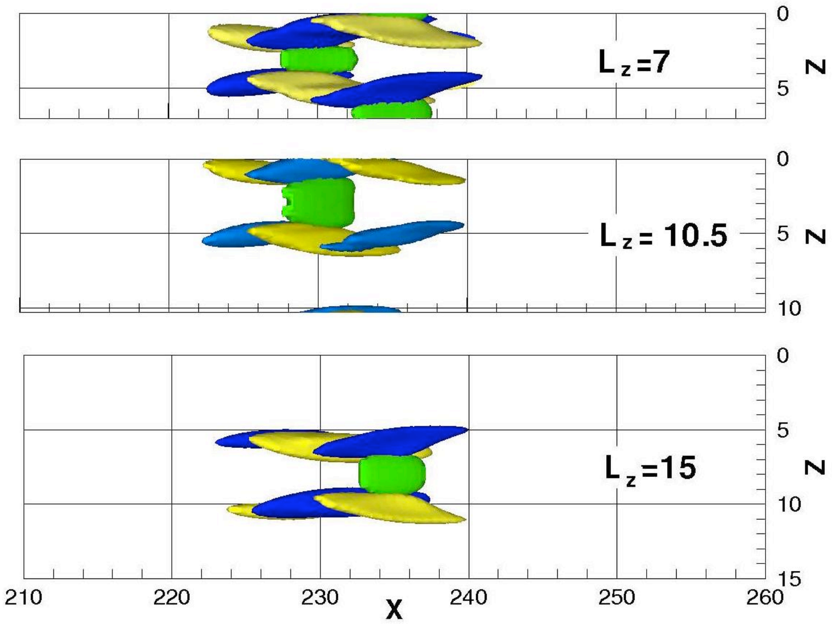

Figure 1. Pictures of the *minimal seed* as seen by looking down towards the wall, obtained for three cases characterized by the same parameters, but with a different domain size in the (periodic) spanwise direction. The structures lean against the mean shear and extract energy efficiently from the mean flow through the Orr mechanism; green surfaces indicate regions of negative streamwise velocity component, the blue and yellow ones point, respectively, to regions of negative and positive streamwise vorticity.

Lift-up effect in an incompressible corner flow

Guiho Florian *, Alizard Frédéric + and Robinet Jean-Christophe *
* DynFluid laboratory, ENSAM-Paris. + DynFluid laboratory, CNAM-Paris.

Experimental studies emphasize that the corner flow is known to be prone to instabilities with respect to a Reynolds number lower than the one corresponding to the trigger of Tollmien-Schlichting waves in a flat plate boundary layer [2]. In this context, an hypothesis based on the onset of an inflexional mechanism through a slow deviation of the base flow gives a new insight into the initial phase of the transition to turbulence [1].

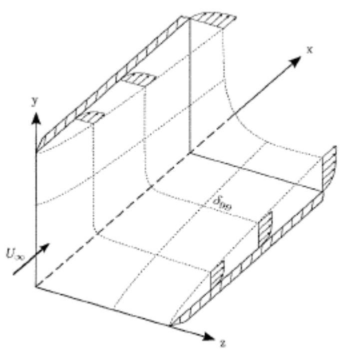

Figure 1: Schematic diagram of flow in a streamwise corner.

However, a scenario based on the optimal perturbation could be also a relevant candidate to explain discrepancies between experimental data and asymptotic stability theories. An investigation of such bypass mechanism is thus conducted by considering temporal optimal perturbation according to a streamwise corner flow formed by the intersection of two perpendicular flat plates (Fig. 1). For that purpose, an optimization procedure relying on integration in time of direct and adjoint stability equations is performed. An optimization at $Re_{\delta^\star} = 1000$ and a streamwise wave number $\alpha = 0$ is highligthed in Figure 2. The perturbation underlying a maximum energy gain takes the form of an asymmetric mode localized around the corner. A lift-up mechanism leads to the formation of low- and high-speed streaks closed to the intersection, at the optimal time. Futhermore, the maximum energy gain $G_{max} = 1910$ appears to be higher than the one corresponding to a flat plate boundary layer $G_{max} = 1504$. Therefore, it seems interesting to further explore such a mechanism in the parameters space $(Re_{\delta^\star}, \alpha)$.

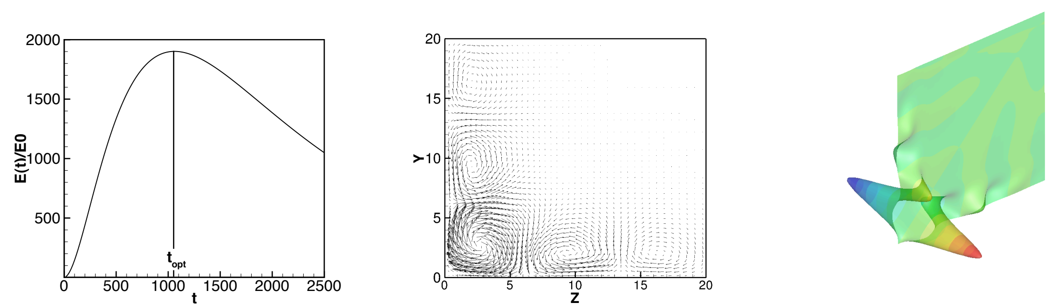

Figure 2: Left: Energy curve. $Re_{\delta^\star} = 1000$. Middle: Optimal perturbation at $t = 0$. The arrows indicate (v,w) fields. Right: Optimal perturbation at $t = t_{opt}$. Contours represent the most amplified streamwise velocity perturbation at $t = t_{opt}$.

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On the influence of wave obliqueness and compressibility on the linear stability of streamwise corner flow

Oliver T. Schmidt and Ulrich Rist

April 29, 2011

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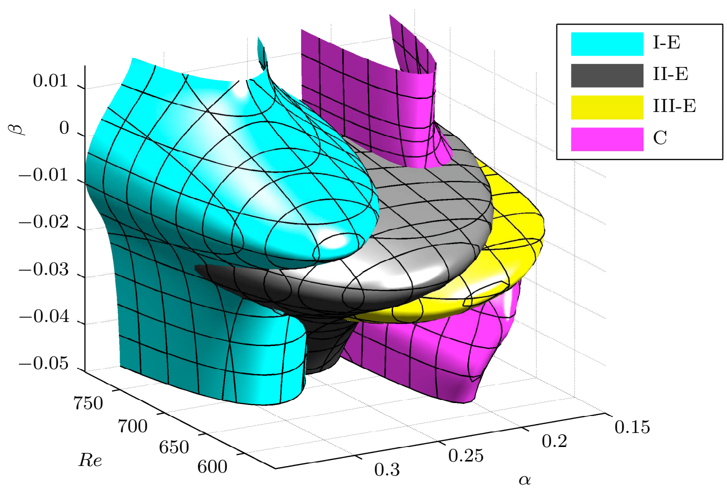
Abstract

The influence of compressibility and disturbance wave obliqueness on amplification rates on the flow in a corner formed by two perpendicular, semi-infinite flat plates is considered. The laminar base flow is calculated as a solution to the parabolized Navier-Stokes equations within a pseudo-spectral framework for the transversal planes. The linear stability eigenvalue problem is solved within the same discretization methodology using the shift and invert Arnoldi method. The application of Sommerfeld's radiation condition allows for the enforcement of a phase angle on the two-dimensional eigenfunctions on the far-field boundaries [1]. The figure shows the neutral stability surfaces of four modes in the three-dimensional parameter space spanned by Reynolds number Re, streamwise wave number α and the wave number corresponding to the phase angle enforced by the far-field boundary condition β. Incoming waves are associated with values of $\beta < 0$, outgoing waves with $\beta > 0$ and a standing wave pattern with $\beta = 0$. Latin numbers indicate fundamental (I) and higher harmonic (II-IV), even-symmetric (-E) Tollmien-Schlichting waves and C the inviscid corner mode. Here, fundamental refers to the lowest spanwise wave number dictated the the computational domain extent. New acoustic modes are identified from the spectrum of corner flow at $Ma = 1.5$ and categorized with respect to speed, symmetry and wall-boundedness.



Isometric view of neutral surfaces of different modes for $Ma = 0.01$: (cyan) I-E, (gray) II-E, (yellow) III-E, (magenta) C

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Optimal control of transient energy growth

X. Mao[*], H. M. Blackburn[*], S. J. Sherwin[†]

A base flow can be disturbed by perturbations in the form of initial perturbations, boundary perturbations or external forcing. Responses of base flow to external forcing and initial perturbations such as most unstable modes in unstable flow, optimal initial perturbations in asymptotically stable but highly non-normal flows are extensively studied but limited attention has been paid to the boundary perturbations.

The external forcing perturbation does not work well for base flow behaving as oscillators because the frequency of the response field has to follow that of the external forcing and therefore the development of the most unstable mode is artificially suppressed. The initial perturbation works well for oscillators who are insensitive to the shape of the initial perturbation, but for amplifier-type base flows, the initial perturbations can be washed out of the unstable region, and therefore after observing a transient energy growth, there is no perturbation left in the computational domain. Boundary perturbations combine the merits of both initial perturbations and external forcing. In oscillators, it perturbs the base flow but does not impose any restraint on the frequency of the response field so that the most unstable mode could be observed, while in amplifiers, it provides temporally continuous perturbation so that the convectively unstable region is continuously perturbed.

In this work, the global optimal Dirichlet-type boundary perturbations are calculated through both Lagrangian optimization and eigenvalue approaches in the context of stenotic flow. It is theoretically demonstrated that the two approaches are equivalent [1].

The Lagrangian optimization methodology to calculate optimal boundary perturbations is further extended to using boundary perturbation to suppress the transient effects induced by optimal initial perturbations. It is presented that an a fixed control cost (a function of the boundary perturbation), an unitary boundary perturbation which minimizes the transient energy growth exists and it is the only minimal point of the Lagrangian function. As the control cost increases, this optimal control boundary perturbation approaches the transient least growing mode.

The controllability of the transient effect is analyzed and the flow field developed from the optimal initial perturbation is partitioined into two parts: one can be controlled by boundary perturbations with a particular shape and magnitude and one cannot be controlled no matter what boundary perturbation to use.

This boundary control effect is examined in Direct Numerical Simulation. As expected, at small magnitudes of initial and boundary control perturbations, the linear optimized control effect is fully realized while at larger magnitudes of perturbations, the saturation owing to nonlinear effects suppresses both the energy growth of the initial perturbation and the control effect of the boundary perturbation.

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[1]Mao, X., Blackburn, H. and Sherwin, S., *Journal of Fluid Mechanics,* submitted

Subsonic round and plane macro- and micro – jets in a transverse acoustic field

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Abstract

Results of experimental studies of the mechanism of evolution of plane and round macro- and microjet flows at low Reynolds numbers in a transverse acoustic field are discussed. New data on the jet development mechanism are obtained through hot-wire measurements and smoke visualization of the jet flow with the use of stroboscopic laser illumination of the jet at frequencies of the acoustic influence on the latter.

In current research, more attention is paid to studying free macrojets because of their numerous applications in various fields of science and engineering. Nevertheless, there is considerable recent interest in studying microjets [1, 2], which is caused, in particular, by development of MEMS technologies. Microjets can be potentially used various processes, for instance, such as microcooling, jet burning, production of nanopowders, etc. Particular attention is given to the influence of the acoustic field on a microjet [3-5], which is important both for understanding the physics of the process and for practical applications of the phenomenon, for example, in aeronautical, space, chemical industry, etc.

The work presented in this paper is aimed at elucidating the mechanism of evolution of macro- and microjets at low Reynolds numbers when subjected to a transverse acoustic field and at identifying the physical phenomena involved in this mechanism. A comparison of our previous studies [6-11] of macrojets under acoustic forcing with results of the current microjet investigations provide better understanding of various features of microjet evolution in an acoustic environment.

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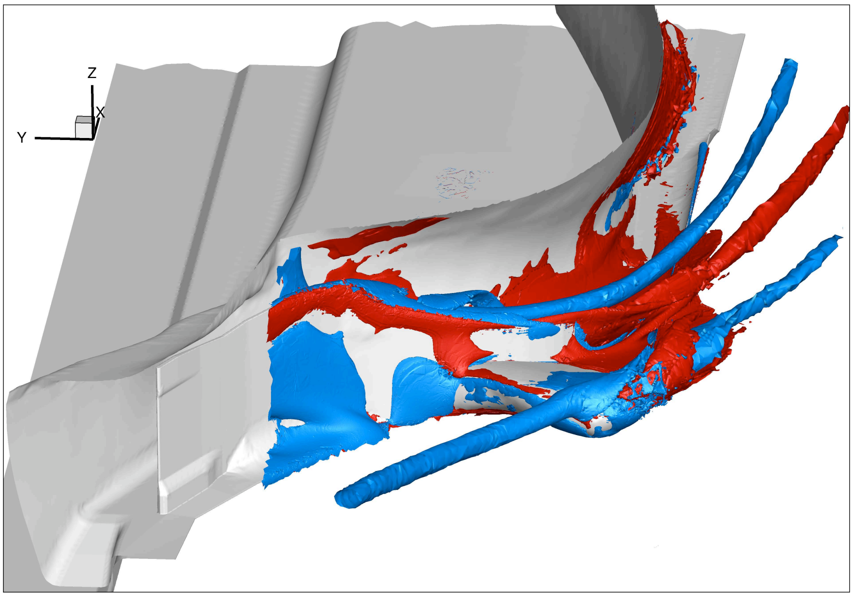
STABILITY ANALYSIS OF COUPLED VORTICAL SYSTEMS IN THE CONTEXT OF ROAD CAR VEHICLES

Julien Hoessler[1], Spencer J. Sherwin[2]
Department of Aeronautics, Imperial College, London

Summary The scope of this study is to demonstrate the use of spectral/*hp*-element based low Reynolds direct numerical simulations and direct stability methods as tools to assess the dynamics and likelyhood of breakdown of predominantly streamwise multi-vortex systems undergoing external/self-induced forcing in the context of Formula 1, where the accurate prediction of these vortices and their evolution is important to the design process.

Low Reynolds direct numerical simulations are first performed, and after careful identification of the swirling flow regimes, the regions where pressure gradients and other external effect may lead to breakdown are further investigated by means of direct stability/BiGlobal analysis initially under the assumption of axially homogeneous flow.

The axially homogeneous assumption will then be relaxed using non-parallel corrections or the parabolised stability equations. Finally, a curvilinear mapping approach will be implemented in order to enforce the PSE equations along the vortices axes, as a misalignement between the natural and enforced direction of propagation leads to artificial damping of the modes. The test case will be a system of three vortices around the sidepod of a Formula One car.



(a) 3d view of the sidepod system, counter-clockwise (blue) and clockwise vortices (red), isosurfaces of normalised helicity

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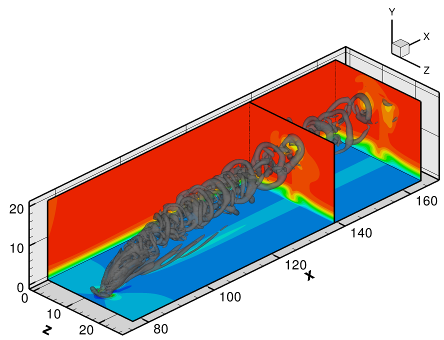
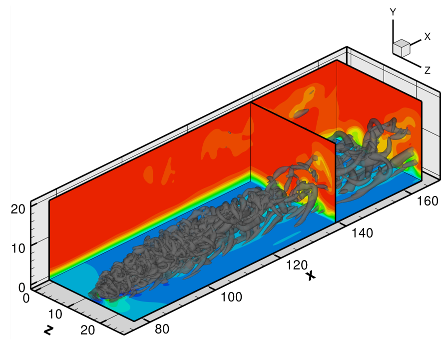
Numerical Investigation of Jet-in-Crossflow Configurations

Björn Selent, Ulrich Rist

Jet-in-Crossflow is considered a canonical flow problem with a wide range of technical applications ranging from mixing processes to thrust vector steering and flow separation control. The main parameters are the crossflow Reynolds number Re and the jet to freestream momentum ratio R. With respect to aforementioned technical applications the parameter space is increased by the inclination α and skew angle β of the jet.
The present work focuses on the variation of these angles for otherwise constant parameters. The crossflow consists of a flat plate boundary layer with $\mathrm{Re}_{\delta_0^*} = 165$ and $\mathrm{Ma} = 0.25$. A vertical jet $\{\alpha = 90°, \beta = 0°\}$ with $R = 3$ (cf. [2]) is chosen as reference and compared to two jets inclined towards and against the mean flow $\{\alpha = 30°, \beta = \pm 30°\}$. Numerical simulations using a high-order compressible Navier-Stokes solver depict clearly distinguishable flow features both in the jet's wake and the near-wall region. Especially the jet's breakup depends strongly on the skew angle. The near-wall region is influenced by Tollmien-Schlichting-like perturbations leading to a transition process downstream of the jet exit as well as streak and longitudinal vortex structures as shown in the figure. The net effect of the mean flow alterations are quantified and compared by measuring the resulting friction coefficients and show significant distinctions accordingly. In order to improve understanding of the flow evolution of the regarded configurations novel matrix-free methods as introduced in [2] are adopted to the compressible case. Steady-state baseflow solutions are obtained by means of temporal filtering [1]. The project aims to evaluate the properties of distinct eigenmodes in order to generate a flow field beneficial to later technical application.



(a) $\alpha = 90°$, $\beta = 0°$



(b) $\alpha = 30°$, $\beta = -30°$

Vortex structures and u-velocity contours of Jet-in-Crossflow computations

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Towards a mathematical theory of turbulence control

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Closed-loop turbulence control is a rapidly evolving, interdisciplinary field of research. The range of current and future engineering applications has truly epic proportions, including cars, trains, airplanes, air conditioning, medical applications, wind turbines, combustors, and energy systems.

We review successful control studies of flows around airfoils and bluff bodies at high Reynolds numbers.[1,2] These studies achieve beneficial changes of the mean flow (0 Hz) for lift enhancement or drag reduction via suppression of an instability at a natural frequency by exciting instabilities at lower or higher frequencies. This strongly nonlinear interplay between vanishing, natural, and actuation frequencies is incorporated in a generalized mean-field model and exploited for control design. It cannot be described in any linear(ized) model.

Building on these results, we pursue a model-based strategy for closed-loop manipulation of broad-band turbulence dynamics, i.e. the control of a rich kaleidoscope of such nonlinear interactions. This strategy starts with robust control-oriented low-order Galerkin models.[3] From these models, statistical balance equations are derived for the mean flow and for the fluctuation levels. In a holistic closure approach,[4] a maximum entropy principle (MaxEnt) infers the probability distribution in Galerkin state space using these balance equations as constraints. In a refined approach,[5] a finite-time thermodynamics (FTT) ansatz models all dual and triadic modal interactions yielding similar information for mean values and fluctuation levels. These closures incorporate natural and controlled dynamics, i.e. enable fully-nonlinear infinite horizon control.

The ultimate goal is a general mathematical theory for turbulence control. The talk comprises joint work with Boye Ahlborn, Michael Schlegel, the Collaborative Research Center SFB 557 'Control of complex turbulent shear flows' at TU Berlin, the DFG-CNRS Research Group FOR 508 'Noise generation of turbulent flows' and the Institut Pprime (Poitiers, France).

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THE PRECURSOR OF KELVIN–HELMHOLTZ INSTABILITIES IN WAKE–PERTURBED SEPARATED BOUNDARY LAYERS

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Computational Fluid Mechanics, School of Aeronautics, Universidad Politécnica Madrid, 28040, Madrid

The interaction of large-scale disturbance by means of wake is studied in a pressure-induced separation bubble on a flat plate. The flat plate is subject to strong adverse pressure gradient which controls the location and extent of the separated region. The wake impact modifies the separation bubble and induces roll–up vortices in the separated shear layer due to the triggering of an inviscid Kelvin-Helmholtz instability.

We performed various direct numerical simulations with different wake passing frequencies, corresponding to the Strouhal number $0.0043 < f\theta_b/\Delta U < 0.0496$ and wake profiles. The wake profile is changed by varying its maximum velocity defect and its symmetry. In all cases, there are always three roll–up vortices generated in the separated shear layer. Furthermore it is noted that the streamwise spacing between these vortices does not depend on the passing frequency or the profile of the wakes. Detailed investigations of the simulations show that the appearance of these roll–up vortices are closely associated with the initial perturbation generated as a results of the wake–passing. As the wake convects downstream in the flat plate it generates wave–trains which propagate at about half of the local convection speed of the wakes. Those wave trains are strongly amplified within the separated shear layer. Thus, the initial evolution of the flow shows an instability independent of the frequency or the shape of the forcing and responsible for the re-initiation of the vortex roll–ups in the separated shear layer.

We also evaluated the stability characteristics of the different mean flows resulting from large scale forcing at different frequencies in terms of local linear stability theory based on the Orr-Sommerfeld equation. The analysis indicate that the vortices associated with the two-dimensional Kelvin–Helmholtz instability. A good agreement between simulations and linear stability analysis is obtained with respect to the amplification of disturbances and their propagation speed.

The structure of the laminar-turbulent edge in a boundary layer

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ABSTRACT

In this work we identify the structures living on the boundary between the laminar and the turbulent states in a boundary-layer flow, extending for the first time the concept of edge of turbulence to a spatially developing flow. We use a shooting procedure to compute the trajectory in the phase-space which does not lead to turbulence nor to the laminar state (see Schneider et al. 2007). To initialize the computation, we use two different rapidly growing perturbations, a linear and a non-linear optimal one (see Cherubini et al., 2010). For both initial states, mildly varying flow structures are observed on the edge of turbulence; this indicates the existence of two embedded relative chaotic attractors. Remarkable differences have been found between these edge structures. The edge reached by the linear optimal perturbation is characterized by streamwise streaks and vortices with sinuous modulations (see Fig. 1(a)), and a low spreading rate in space/time. On the other hand, the edge structure reached by the non-linear optimal perturbation is more efficient in spreading out in space and time. It is characterized by a main hairpin vortex at the leading edge, and $\Lambda-$vortices and streaks in its body (see Fig.1(b)). The shape of the overall structure, the presence of a overhang region at its leading edge, as well as the advection velocities at its leading and trailing edges, closely recall the ones characterizing a turbulent spot. This indicates that such a chaotic attractor living on the edge of turbulence can be considered the precursor of a turbulent spot. The presence of the two slowly varying flow structures described above suggests the existence of several localized exact coherent solutions (see Eckhardt et al., 2007) embedded in the edge of turbulence for the case of the boundary-layer flow.

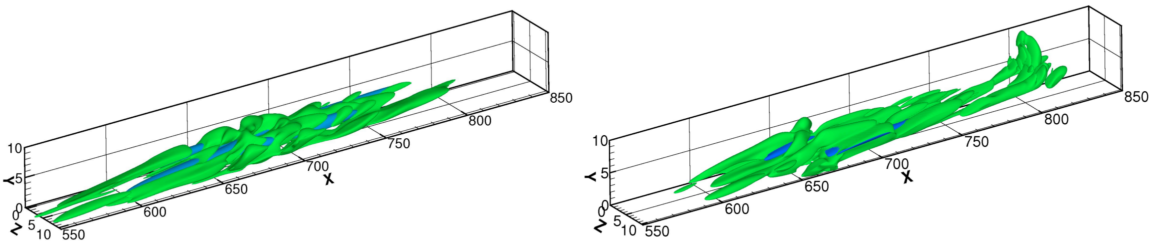

Figure 1: Snapshots of the streamwise component of the perturbation (blue) and of the Q-criterion (green) on the edge of chaos for a linear (a) and non-linear (b) initial perturbation.

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Progress in Transition Modeling and Control
ERCOFTAC-SIG33 Workshop 2011
September 28–30, 2011, Toledo, Spain

KELVIN–HELMHOLTZ-LIKE INSTABILITIES IN TURBULENT FLOWS OVER COMPLEX SURFACES

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Riblets are small surface protrusions aligned with the flow direction, which confer an anisotropic roughness to the surface [6]. We have recently reported that the transitional-roughness effect in riblets, which limits their performance, is due to a Kelvin–Helmholtz-like instability of the overlying mean flow [7]. According to our DNSs, the instability sets on as the Reynolds number based on the roughness size of the riblets increases, and coherent, elongated spanwise vortices begin to develop immediately above the riblet tips, causing the degradation of the drag-reduction effect. This is a very novel concept, since prior studies had proposed that the degradation was due to the interaction of riblets with the flow as independent units, either to the lodging of quasi-streamwise vortices in the surface grooves [2] or to the shedding of secondary streamwise vorticity at the riblet peaks [9].

We have proposed an approximate inviscid analysis for the instability, in which the presence of riblets is modelled through an average boundary condition for an overlying, spanwise-independent mean flow. This simplification lacks the accuracy of an exact analysis [4], but in turn applies to riblet surfaces in general. Our analysis succeeds in predicting the riblet size for the onset of the instability, while qualitatively reproducing the wavelengths and shapes of the spanwise structures observed in the DNSs. The analysis also connects the observations with the Kelvin–Helmholtz instability of mixing layers. The fundamental riblet length scale for the onset of the instability is a 'penetration length,' which reflects how easily the perturbation flow moves through the riblet grooves. This result is in excellent agreement with the available experimental evidence, and has enabled the identification of the key geometric parameters to delay the breakdown.

Although the appearance of elongated spanwise vortices was unexpected in the case of riblets, similar phenomena had already been observed over other rough [3], porous [1] and permeable [11] surfaces, as well as over plant [5,14] and urban [12] canopies, both in the transitional and in the fully-rough regimes. However, the theoretical analyses that support the connection of these observations with the Kelvin–Helmholtz instability are somewhat scarce [7, 11, 13]. It has been recently proposed that Kelvin–Helmholtz-like instabilities are a dominant feature common to "obstructed" shear flows [8].

It is interesting that the instability does not require an inflection point to develop, as is often claimed in the literature. The Kelvin-Helmholtz rollers are rather triggered by the apparent wall-normal-transpiration ability of the flow at the plane immediately above the obstructing elements [7,11]. Although both conditions are generally complementary, if wall-normal transpiration is not present the spanwise vortices may not develop, even if an inflection point exists within the roughness [10].

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Progress in Transition Modeling and Control
ERCOFTAC-SIG33 Workshop 2011
September 28–30, 2011, Toledo, Spain

POD BASED REDUCED ORDER MODELS FOR STEADY MULTI-PARAMETER PROBLEMS

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Multi-parameter fluid mechanics problems are ubiquitous in design and certification, in a variety of industrial sectors. Steady flows are of interest at low Reynolds number (in, e.g., micro-fluidics), and also at high Reynolds number flows number when the Reynolds averaged Navier Stokes (RANS) equations are used (in, e.g., the aerodynamics around a commercial aircraft). The number of parameters can be huge, which involves the curse of dimensionality [5] difficulty when a large part of the parameter space must be explored. The difficulty can be alleviated using low fidelity models (e.g., vortex lattice or panel methods in Aerodynamics), but also developing POD-based reduced order models (ROMs) [6,9]. A family of ROMs will be reviewed in this talk, which are based on two main ingredients:

i. A set of snapshots is CFD calculated for representative values of the parameters, and POD is applied to obtain a manifold that should approximate well the solutions that are being sought. By 'representative' we mean that the POD manifold is sufficiently good, which frequently permits that the snapshots be distributed fairly sparsely in the parameter space; the optimal selection of these is related to the so called sampling problem [3, 7].

ii. The solution is expanded in POD modes. The unknown amplitudes are calculated minimizing a residual based on the governing equations and boundary conditions.

Several additional ingredients help to further increase the computational efficiency of the ROM:

1. The residual can be calculated using only a limited number of points of the CFD mesh [1].

2. Variable geometry problems can be dealt with using a fixed virtual geometry (to calculate the POD modes), which is smoothly mapped onto the actual geometries, where the residual is minimized [4].

3. A specific treatment of shock waves (transonic aerodynamics) is possible [2,8] to obtain a formulation that is amenable to POD description.

4. At quite large Reynolds number, the residual may be defined from the Euler equations, while the snapshots are CFD calculated using viscous equations.

5. The residual can be calculated using either a genetic algorithm (GA) or a combination of a gradient-like a continuation (GL+C) methods.

The resulting ROM is tested considering both a nonisothermal microfluidics problem and the aerodynamic flow around a wing. In the latter case, the boundary layer and the wake are well described, in spite of the approximation 4. The acceleration factors are in the range 50-2,500.

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Progress in Transition Modeling and Control
ERCOFTAC-SIG33 Workshop 2011
September 28–30, 2011, Toledo, Spain

AN ADAPTIVE REDUCED ORDER MODEL BASED ON LOCAL POD PLUS GALERKIN PROJECTION FOR NONSTEADY PROBLEMS

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A local proper orthogonal decomposition (POD) plus Galerkin projection method was recently developed to accelerate time dependent numerical solvers of PDEs [6]. The method is based on the combined use of a numerical code (NC) and a Galerkin system (GS) in a sequence of interspersed time intervals, I_{NC} and I_{GS} , respectively. POD modes result from performing POD on some sets of snapshots calculated by the numerical solver in the I_{NC} intervals. The POD manifold is completely calculated in the first I_{NC} interval but only updated in the subsequent I_{NC} intervals, which can thus be quite small. The governing equations are Galerkin projected onto the most energetic POD modes and the resulting GS is time integrated in the next I_{GS} interval. Switching between the I_{NC} and the I_{GS} intervals is done using an a priori error estimate. This makes a difference with standard methods that intend to approximate the solution in attractors of the system, in which the POD manifold is precalculated from snapshots that are representative in the attractor, see [4, 9] and references there in. The present adaptive method instead is able to approximate transients, not only attractors.

For some highly unstable equations, the method still exhibits the instability due to higher order mode truncation [7], which is a major difficulty in POD+Galerkin projection methods. The instability is cured integrating a second Galerkin system, retaining a few additional modes. Comparison between the solutions provided by both Galerkin systems yields a second estimate to switch from the current I_{GS} interval to the next I_{NC} interval. Again, this makes a difference with previous treatment of the instabilities that are specific for the Navier-Stokes equations (to simulate transient, transitional, and turbulent flows) since the pioneering work by Sirovich [10] and Aubry et al. [3]. In these, stabilization is made using the so-called shift modes, which were introduced by Noack et al. [5] and Siegel et al. [8], and further used by others, see [11] and references there in.

The resulting method is both robust and computationally efficient, which will be checked considering transient chaos in the the complex Ginzburg-Landau equation [2] and the unsteady lid driven cavity problem [1] for moderate Reynolds numbers. The accelerating factors are in the range 5-10.

Several additional improvements associated with both the POD calculation and the Galerkin projection help to further increase the computational efficiency of the overall process.

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System identification and feedback control of the flow around a circular cylinder

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Recent developments in feedback flow control rely on a model-based approach, where a (generally linearized) model of the flow system is used within a state-space framework to design feedback laws. This approach led to promising results, but issues of dimensionality, controllability/observability and uncertainties have to be dealt with. Model reduction techniques can be employed to render the design of feedback laws feasible for large-scale flow problems, as the input-output mapping in typical flow control configurations is inherently low dimensional. This feature naturally suggests to explore the possibility of directly designing feedback laws within an input-output framework, without resorting to state-space representations. The present work represents an attempt in such a model-free direction.

Identification and control of the flow around a circular cylinder is considered as a model problem [1]. Localized volume forcing near the cylinder surface and close to the separation point is used as control input, and velocity measurements are available in the wake. System identification is used to approximate the input-output relation of the flow dynamics; since the impulse response of the system features significant time-scale separation, Observer Kalman identification [2] is employed to ensure rapid convergence using a limited number of measured data. On the basis of the identified response, feedback laws are designed via a variational approach. At the conference, the identification and control approaches will be briefly outlined, and the performance of the proposed control laws in suppressing the effect of upstream perturbations will be discussed.

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Transition delay in a boundary layer using localized sensors and actuators

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The main focus of our investigation is to delay laminar-turbulent transition in a boundary-layer flow, using feedback control based on reduced-order models in combination with localized sensor and actuator. We consider both TS scenario and by-pass transition, introducing localized initial conditions with realistic amplitudes; the instability mechanisms are triggered by the respective, localized, optimal disturbances[1].

The controller consists of an array of localized actuators distributed in the spanwise direction. Thus, the overall configuration resembles experimental setups[2]; Although successful, previous investigations considered perturbations of such low amplitude to be governed by linearized equations[3]; in this contribution, we examine the effects of the feedback control in the full nonlinear regime. We show that the laminar-turbulent transition can be delayed at least by $\Delta Re_x \approx 3 \times 10^5$ for both the scenarios (streaks case is shown in figure 1).

In the final contribution, the effect of the localized actuation on the disturbances and the effort of the controller will be discussed. Moreover, recent results will be proposed about a comparison between controllers based on low-order models using approximate balanced truncation[4], and full-dimensional controllers[5].

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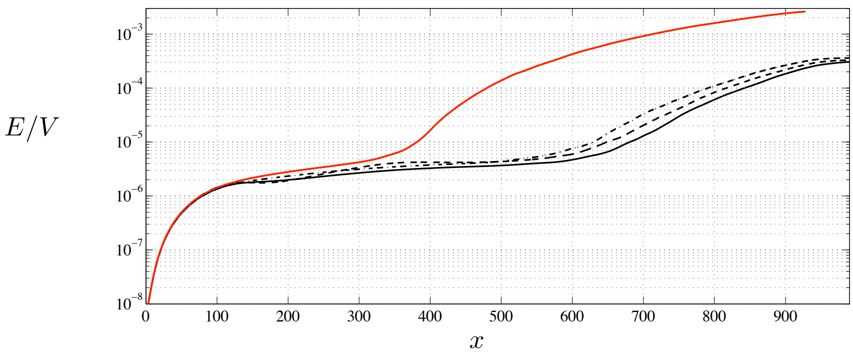

Figure 1: Energy density evolution as function of the streamwise coordinate, uncontrolled case (red) vs controlled cases (black)

Instability of Carreau fluids flowing past a circular cylinder

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The instability mechanism of the shear-thinning and shear-thickening fluids past a circular cylinder is studied using linear theory. The shear-dependent viscosity is modeled by the Carreau-law. The relation between viscosity and deformation rate is

$$\mu = \frac{\hat{\mu}_\infty}{\hat{\mu}_0} + [1 - \frac{\hat{\mu}_\infty}{\hat{\mu}_0}][1 + (\lambda\dot{\gamma})^2]^{(n-1)/2}. \tag{1}$$

$\hat{\mu}_0$ and $\hat{\mu}_\infty$ are zero shear rate viscosity and infinite shear rate viscosity and they are set to 1 and 0.001 in this work. $\dot{\gamma}$ is the second invariant of the strain rate tensor and it is determined by the dyadic product $\dot{\gamma} = (\frac{1}{2}\mathbf{G} : \mathbf{G})^{\frac{1}{2}}$, where $\mathbf{G} = \nabla\mathbf{u} + (\nabla\mathbf{u})^T$ [1]. The power law index "n" characterizes the fluid behavior: i) shear-thinning when $n < 1$, ii) Newtonian fluids when $n = 1$ and iii) shear-thickening fluids when $n > 1$. "λ" is the material time constant.

The critical Reynolds number for the first bifurcation to unsteady flow is reported in figure 1a) for both shear-thinning and shear-thickening fluids. The symbols in the figure refer to full nonlinear simulations performed with the code `Nek5000`. The latter clearly confirms the finding of the linear analysis. This work is the first complete stability analysis of the flow past a circular cylinder of a Carreau-Yasuda fluid. Here, we show how shear-thinning/shear-thickening effects destabilize/stabilize the flow dramatically. These variations are explained by modifications of the steady base flow due to the shear-dependent viscosity; the instability mechanisms are only slightly changed. The wave-maker of the instability is displayed in figure 1b). "Wave-maker" is defined as the region in the flow where variation in the structure of the problem provides the largest drift of the eigenvalues [2].

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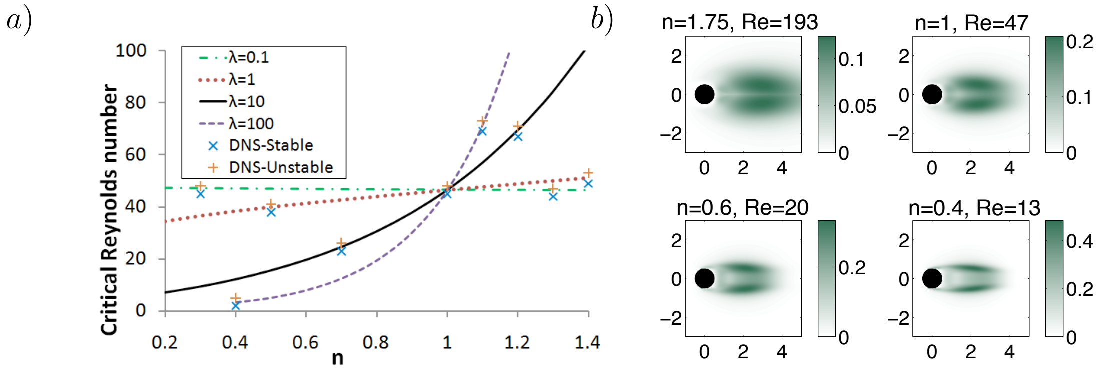

Figure 1: a) Neutral stability curve for the flow past a circular cylinder of a Carreau fluid in the Reynolds–n plane for different values of the material time constant λ. $n < 1$ indicate shear-thinning behavior whereas $n > 1$ indicate a shear-thickening fluid. b) Wave-maker, the core of the instability, along the neutral curve for $\lambda = 10$ and 4 values of the exponent n.

Numerical stability studies of streamwise vortices and swirling flows.

Spencer J. Sherwin

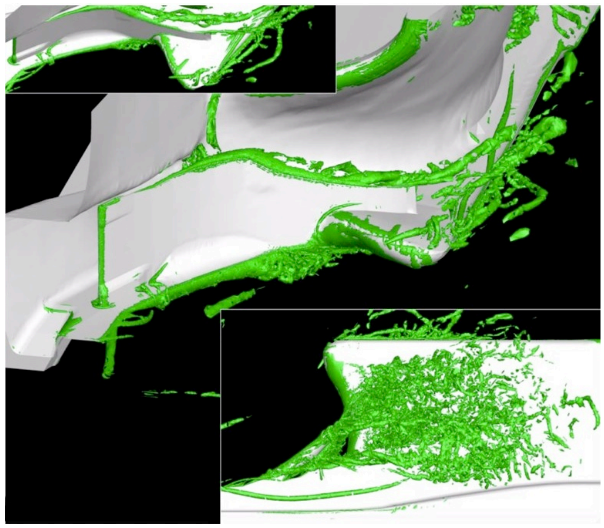

Figure 1: Vortical structures created by the side pod of a formula 1 car

Swirling flows and streamwise vortices are common place in many industrial applications. Our recent studies on swirling flows have been motivated by interactions with the Formula 1 industry where, as shown in figure 1, they are interested in the evolution and stability of multiple vortices in sheared flows typically generated by complex geometries.

We have applied complex geometry discretisation techniques, using the spectral/hp element methods, to perform direct numerical simulations and direct stability analysis on vortical flow configurations. In the first part of the presentation we will use the Formula 1 application area to motivate more fundamental studies in the understanding of discrete and continuous spectra of single and multiple Batchelor vortices.

Another example of vortical disturbances in sheared flows are streak structures in boundary layers. Recent work at Imperial has drawn a connection to the vortex wave interaction theory of Hall & Smith and the concept of self sustaining processes. In the second part of the presentation we will outline our current work on this topic.

ON GLOBAL MODES IN TURBULENT SWIRLING JET EXPERIMENTS

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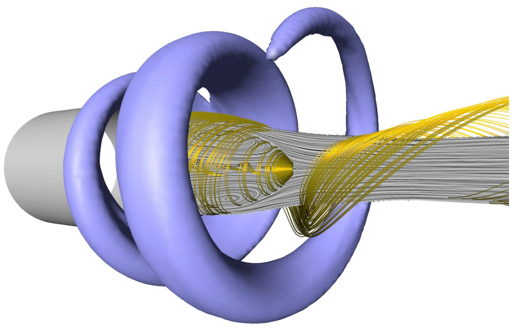
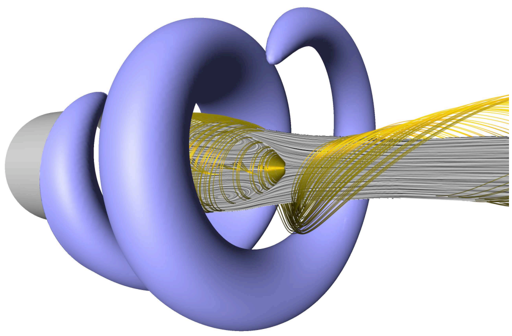
Abstract

The present study is aimed to enhance the understanding of the coherent structures that dominate turbulent swirling jets with the far goal of flow control in combustion applications. The experimental setup allows to investigate a swirling jet at Re $= 20,000$ for various swirl intensities. Experiments suggest that the flow undergoes a super-critical Hopf bifurcation to a global mode at a swirl number that is somewhat higher then the threshold of vortex breakdown. The 3D oscillatory flow associated with the global mode is constructed from uncorrelated 2D PIV snapshots, using proper orthogonal decomposition, a phase-averaging technique and an azimuthal symmetry associated with helical structures. The source of the global mode is characterized by a precessing vortex core upstream of the recirculation bubble. This internal clockwork perturbs the outer shear layer where downstream traveling eddies formate. The 3D flow field of the global mode is modeled by a convective-type linear stability analysis employing the turbulent mean flow. Stability derived modes and empirically derived modes correspond remarkably well (Fig. 1).

The amplifier dynamics of the outer shear layer enable efficient open loop control at the nozzle lip. Lock-in of the global mode is achieved when actuating the flow at mode $m = 1$ near the natural frequency. The boundaries of the lock-in region are derived experimentally, revealing typical oscillator dynamics. By sharp contrast, when forcing at a different mode number (e.g. $m = 2$), the jet acts as an amplifier and the excited waves grow exponentially in downstream direction. By utilizing the spatial amplification of these convective modes it is possible to overcome the global mode for considerably small actuation amplitudes. The effect of the forcing on the spatio-temporal stability of the natural and forced mean flow is currently investigated. It appears that the natural flow is globally unstable to solely $m = 1$ and becomes globally stable when forced at a convective mode, e.g. $m = 2$.



(a) Empirically extracted coherent structure using POD



(b) Theoretically extracted coherent structure using linear stability analysis

Figure 1: Three-dimensional shape of the globally unstable mode $m = 1$ of a strongly swirled jet. The blue iso-contour refers to constant coherent azimuthal vorticity Streamlines and LIC surface are based on the time-averaged flow, revealing the recirculation bubble and the base flow rotation (Re $= 20,000; S = 1.22$). Details can be found in [1]
.

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Optimizing energy production from vortex induced vibrations using an exact nonlinear asymptotic model

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ABSTRACT

A large body of works has been devoted to the problem of the wake flow past a fixed cylinder, and it is now well known that at a critical Reynolds number $Re_* \sim 47$, the flow undergoes a global instability responsible for the onset of the vortex-shedding phenomenon causing the cylinder to experience unsteady lift and drag forces. If mounted on elastic supports, the cylinder generally undergoes vortex-induced vibrations (VIV).[1] The present work aims at investigating VIV in the vicinity of the critical Reynolds number Re_* by combining asymptotic analyses and adjoint-based receptivity methods. The main advantage of this approach lies in the fact that the description of the flow dynamics does not resort to empirical modelling but to an exact asymptotic analysis of the Navier–Stokes equations, where the flow is forced near-resonance by the displacement of the cylinder.[2]

The asymptotic model is used in the perspective of renewable energy production. For instance, electrical energy will be produced if the oscillation of the cylinder periodically displaces a magnet inside a coil. Such an energy production device induces a structural damping term in the equation governing the motion of the cylinder, the underlying idea being that the energy dissipated by structural damping is at disposal to be harvested, as discussed by Bernitsas *et al.*.[3] We assess here the ability of a periodic control velocity applied externally at the cylinder wall to optimize the magnitude of dissipated energy. We show first that the orbit of the limit cycle reached by the system at large times can be optimized using an appropriate feedback loop designed in the framework of Lagrangian optimization. Interestingly, the control also results in a significant improvement of the system robustness with respect to small inaccuracies of the structural parameters. We also show that the system is susceptible to converge to cycles of lower energy when subjected to external disturbances, as a result of the simultaneous existence of multiple stable cycles. Consequently, we propose an additional transient control algorithm meant to force the return of the system to its optimal cycle.

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Sensitivity of the global instability envelope to a steady perturbation in the bluff body wake at large *Re*

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This experimental work is aimed at investigating the impact of a steady perturbation on the global mode of a bluff body wake. The main bluff cylinder is a “D” shaped 2D body, and a small circular control cylinder, of diameter d=1mm or d=3mm, is introduced into the near wake, at Reynolds number Re=13000. The height of the main cylinder is D=25mm, and the Reynolds number uses this, as a characteristic length.

The wake is bounded by turbulent shear layers which detach from the blunt trailing edge of the main cylinder. The shear layers roll-up at a selected downstream length and close the wake in the form of a Bénard-Von Karman global instability. Local hot wire probe measurements are used to record the frequency and the amplitude of the global mode. In our previous work, we have found that the frequency can be changed from -7% to +5%, with regard to the natural value, for the case of control cylinder of diameter d=1mm. In the case of d=3mm, the change is more effective and ranges from -14% to +18%. However, we observe that the amplitude of the global mode, measured locally, does not provide a complete picture, since the envelope might be spatially displaced. Therefore, PIV measurements of the wake are used to recover the complete envelope of the global mode, from the extracted Reynolds stress components $\overline{v'^2}$ and $\overline{u'v'}$. The Reynolds stress components give the information on the intensity and location of the maxima of the instability, and this information is correlated to the size of the recirculation region and the mean flow modifications induced by the control cylinder. In order to describe the possible effects on the wake, we have selected a fixed stream-wise position of the control cylinder, at x_c= 0.4D, and are changing its vertical position, from y_c= +0.08D to y_c= -0.82D. For certain positions of the control cylinder we observe from $\bar{u}$ that the recirculation region of the wake grows, and along with it, the instability origin, as defined by the positions of $\overline{v'^2_{max}}$ and $\overline{u'v'_{max}}$, is shifted downstream. We have observed that every time the instability is shifted downstream, its amplitude is damped. This appears to be true for both sizes of the control cylinder.

We will present detailed measurements of the locations and intensity of the global mode maxima, for each vertical position of the control cylinder. We will show and explain the relationship between the global mode frequency and the global mode envelope. These observations could be very useful for future stability analysis, based on mean flow modifications.

Combined local and global stability analysis of vortex breakdown bubbles and confined wakes

Matthew Juniper, Ubaid Qadri, Dhiren Mistry, Outi Tammisola

When analysing the stability of a steady flow that evolves reasonably slowly in one direction, it is useful to combine local and global linear stability analyses. In nearly parallel flows, local analyses can quickly give the same information as global analyses, such as the direct and adjoint linear global modes. At the very least, the local analysis gives physical insight into the results of the global analysis. In this paper, we present two examples in which this combination is useful.

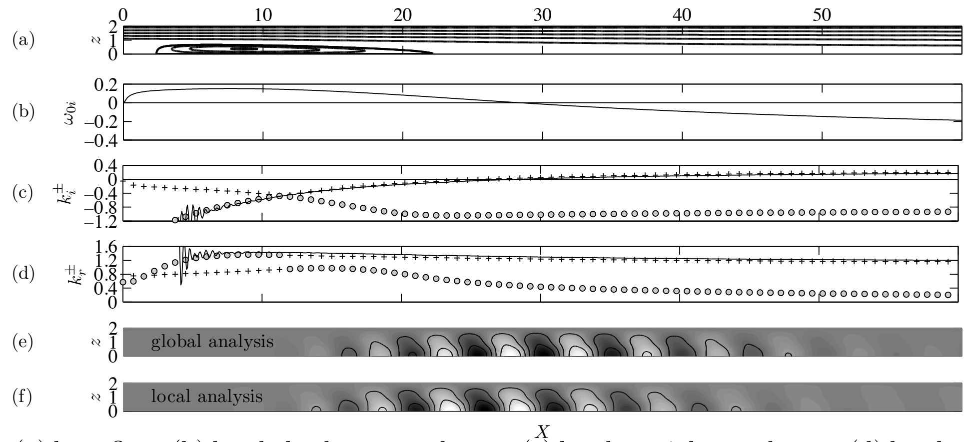

Figure 1: (a) base flow; (b) local absolute growth rate; (c) local spatial growth rate; (d) local wavenumber; (e) eigenfunction from global analysis; (d) eigenfunction from local analysis.

The first is a confined wake flow at Reynolds = 100 (Fig. 1) When the flow becomes more confined, the length of the recirculation zone changes, the boundary layers approach the shear layers, and the local absolute growth rate changes. Through the combined local and global analysis we find that these three these effects work either with or against each other to destabilize or stabilize the flow, depending on the flow parameters.

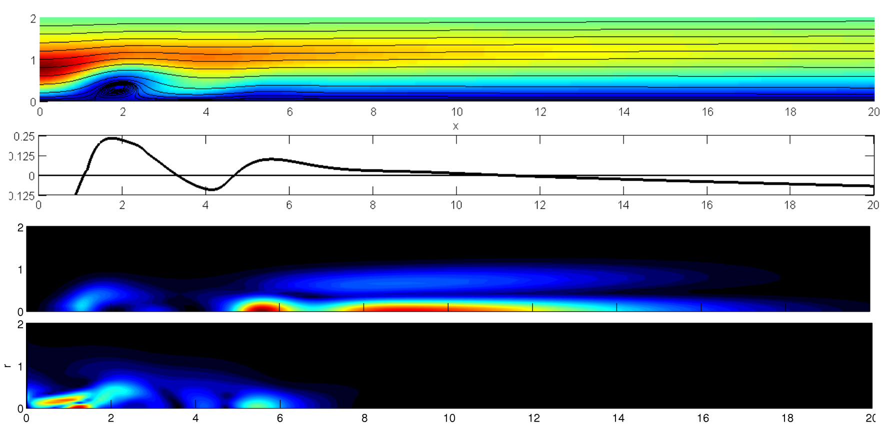

Figure 2: (a) base flow; (b) abs. growth rate; (c) wavemaker region (d) sensitivity to base flow modif.

The second is a swirling vortex breakdown bubble (Fig. 2). The local analysis shows that the flow contains two absolutely unstable regions, each with a different wavemaker position and global frequency. Through overlap of the direct and adjoint eigenfunctions, giving the wavemaker region, the global analysis reveals that the downstream bubble causes the instability. The combined local and global analysis reveals, however, that the flow remains globally unstable even when the downstream bubble is not absolutely unstable, as long as the upstream bubble remains absolutely unstable. The reasons for this are not yet clear, but it could be due to the interaction between two coupled oscillators. A global analysis alone cannot reveal this behaviour.

Instability of a particle suspension

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Modal and non-modal linear stability analysis of channel flow with a dilute particle suspension is presented where particles are assumed to be solid, spherical and heavy. The two-way coupling between particle and fluid flow is therefore modeled by the Stokes drag only. The results are presented as function of the particle relaxation time and mass fraction. First, we consider exponentially growing perturbations and extend previous findings showing the potential for a significant increase of the critical Reynolds number. The largest stabilization is observed when the ratio between the particle relaxation time and the oscillation period of the wave is of order one. By examining the energy budget we show that this stabilization is due to the increase of the dissipation caused by the Stokes drag. The observed stabilization has led to the hypothesis that dusty flows can be more stable. However, transition to turbulence is most often subcritical in canonical shear flows where non-modal growth mechanisms are responsible for the initial growth of external disturbances. The non-modal analysis of the particle-laden flow, presented here for the first time, reveals that the transient energy growth is, surprisingly, increased by the presence of particles, in proportion to the particle mass fraction. The generation of streamwise streaks via the lift-up mechanism is still the dominant disturbance-growth mechanism in the particle laden flow: the length scales of the most dangerous disturbances are unaffected while the initial disturbance growth can be delayed. These results are explained in terms of a dimensionless parameter relating the particle relaxation time to the time scale of the instability. The presence of a dilute solid phase therefore may not always work as a flow-control strategy for maintaining the flow as laminar. Despite the stabilizing effect on modal instabilities, non-modal mechanisms are still strong in internal flows seeded with heavy particles. These results indicate that the initial stages of transition in dilute suspensions of small particles are similar to the stages in a single phase flow.

Nonlinear simulations of transition triggered by finite-amplitude initial disturbances in particle-laden channel flow will be presented. Preliminary calculations confirm the significant transient growth of streamwise streaks. However, their breakdown is delayed in the presence of heavy particles so that transition is found to occur for disturbances of higher initial energy.

Sound generation in the flow around an aerofoil.

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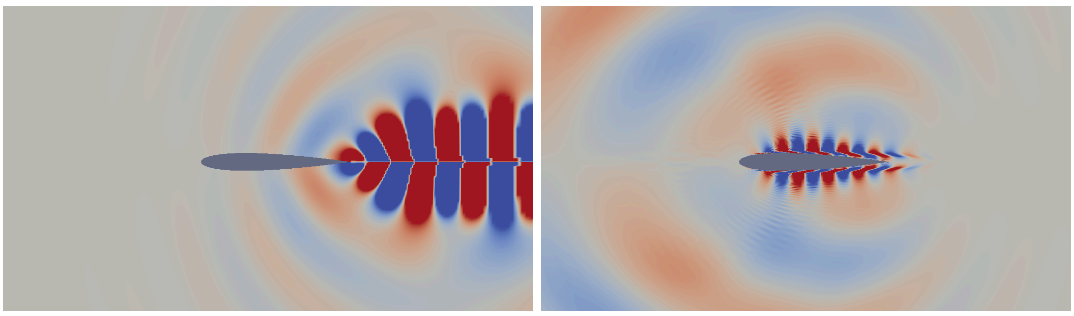
April 30, 2011

When aerofoils are subjected to uniform, high speed flows, substantial levels of sound radiation can be observed. At low Reynolds number (typically below 100.000), the noise generation mechanism is associated to the vortex shedding. At moderate Reynolds numbers (from 100.000 to approximately 2.000.000), the mechanism changes and the sound spectrum consists in a broadband component and strong, equally spaced peaks that are commonly perceived by the human ear as a whistle. This phenomenon is known in the literature as tonal noise and is present in small aircrafts, gliders, etc. The tonal noise generation mechanism commonly accepted is the presence of an aeroacoustic feedback loop where Tollmien-Schlichting waves are massively amplified close to the trailing edge[1]. Nevertheless, some aspects remain unexplained.

In this work, global stability analysis will be performed on low and moderate Reynolds number flows and first results will be discussed. Direct Numerical Simulations are carried out using a high-order compressible flow solver and the linearised direct and adjoint operators are obtained using a Matrix extraction technique recently developed[2]. This technique allows for the use of matrix-free methods that are highly desirable when using high-order spatial schemes.



Linearised direct (left) and adjoint (right) simulations of the flow around an aerofoil at $Re = 15000$ and $M = 0.6$ at zero incidence.

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On high-order finite-difference methods for global instability analysis

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The main goal of this work is to apply a new stable high order (order q) finite-difference method (FD-q), based on non-uniform grid points,[1] to instability analysis of complex flows reducing the high cost of spectral methods typically used for this class of problems, without sacrificing accuracy.

The new method has been validated on a set of different stability problems, as the classic Orr-Sommerfeld equation or the BiGlobal EVP, comparing its results at different orders against spectral collocation method based on the Chebyshev Gauss-Lobbatto (CGL) points, and results obtained by alternative FD numerical methods, such as Dispersion-Relation-Preserving finite difference (DRP), Compact finite difference (also known as Padé schemes) and Sumation by Parts operators (for further details see Paredes et al. 2011[2]). For all orders of discretization the FD-q method presents better resolution properties, reaching convergence before any alternative FD method. Computational cost in terms of memory and CPU-time is widely reduced when using FD-q thanks to the use of a parallelizable sparse matrix linear algebra package.

Results of the TriGlobal EVP of the regularized lid-driven cavity flow at $Re = 10^3$ were obtained on a desktop computer with 8Gb RAM, employing $N_x = N_y = 46$ and a FD-q10 scheme in the x and y directions, alongside $N_z = 16$ Fourier collocation points in the spanwise direction, the latter used to discretize a spanwise length $L_z = 2\pi/15$. Isosurfaces of the three-dimensional amplitude functions $\hat{q}_{3d} = (\hat{u}, \hat{v}, \hat{w}, \hat{p})^T$ of the leading eigenmode are shown in Figure 1.

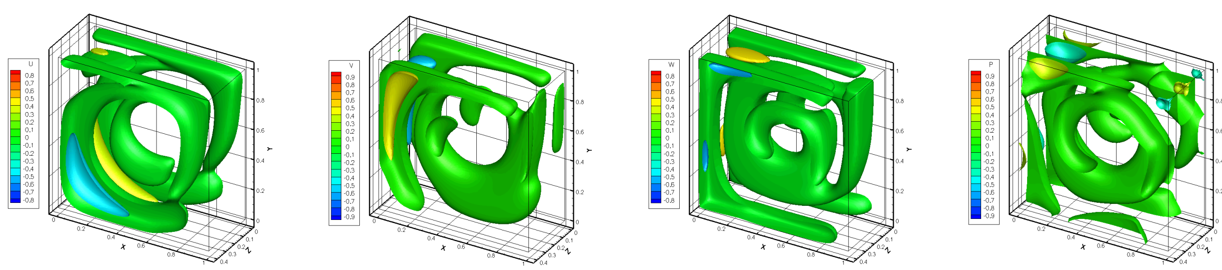

Figure 1. Amplitude functions corresponding to the leading eigenmode of the regularized lid-driven cavity flow at $Re = 10^3$ with $Lz = 2\pi/15$. Left-to-right: $\hat{u}(x, y, z), \hat{v}(x, y, z), \hat{w}(x, y, z), \hat{p}(x, y, z)$.

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Global stability of hot subsonic jets

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Global instability modes have been computed for subsonic jets issuing from a straight pipe. The compressible Navier–Stokes equations are resolved on a large domain, which includes the pipe and nozzle, as well as the acoustic far field. Isothermal and hot jets are considered. A model base flow[1] is employed that accurately reproduces experimental mean flow measurements of hot jets. The *Bandpass-Filtered Propagator* method[2,3] has been developed specifically for the present calculations. This matrix-free time-stepping method requires significantly less memory than, for instance, the shift-invert technique, and therefore holds great promise for future application to three-dimensional problems.

Isothermal jets are found to be temporally stable, whereas heating of the jet with respect to the ambient temperature has a destabilizing effect. These results are fully consistent with local instability theory[1] and with a global analysis of supersonic jets[4]. Nonetheless, significant *transient* growth of initial perturbations is observed. In a local framework, the strong convective nature of the spatial instability of isothermal jets has been well established in the literature. The stable spectrum of temporal global modes does not appropriately reflect these spatial instabilities.

We propose to characterize the instability dynamics of strongly convective systems, such as temporally stable jets, by their response to *sustained harmonic forcing*, rather than temporal global modes. A modal description of the harmonic forcing response of a jet is formally obtained from a singular value decomposition of the resolvent operator for a given frequency. The spatial structures both of the forcing and of the associated flow response are recovered, and the singular values represent the energy amplification due to the convective flow instability. Results from such computations will be presented for compressible and incompressible settings.

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By-pass transition in the swept leading-edge boundary layer

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We present results from direct numerical simulations of a spatial transition to turbulence in a swept Hiemenz flow (figure 1) which is an established model for the leading-edge boundary layer of swept wings. Our numerical investigations use a Reynolds number of $\mathrm{Re} = 300$ which is in the range of experimentally observed transition in leading-edge boundary layers, but lies well below the stability limit predicted by linear theory of $\mathrm{Re}_{\mathrm{crit,lin}} = 581$.

A detailed analysis will show that the transition process can be classified as a by-pass transition because it contains several features which are well known from by-pass transition in two-dimensional boundary layers. These are, for instance, a non-modal generation of streaks through streamwise vortices and a varicose secondary instability of these streaks which leads to the breakdown to turbulence.

We will present a spatial modal analysis of the transition process which will help us to put the results in the context of the established theory for two-dimensional boundary layers. We will point out analogies to two-dimensional theory, e.g. fundamental vs. sub-harmonic secondary modes. Further, we will discuss those effects which cannot be found in classical two-dimensional theory and which are directly related to the three-dimensional character of the base flow. In particular, we will investigate the phenomenon that the secondary instability of the streaks does not only depend on the amplitude of the primary disturbance but also on the downstream location.

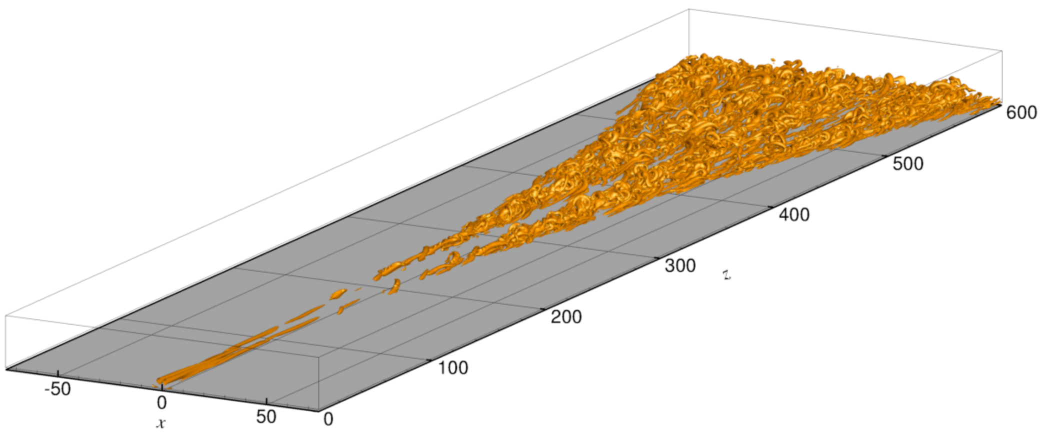

Figure 1: By-pass transition in a swept Hiemenz flow at $\mathrm{Re} = 300$ (isosurface of the λ_2 vortex criterion with $\lambda_2 = -0.001$).

On the PSE-3D instability analysis methodology for counter-rotating axially inhomogeneous pair of vortices

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The present contribution discusses the development and application of a PSE-3D instability analysis algorithm. This methodology permits arbitrary development of the vorticity distribution on the plane normal to the vortrex axis, alongside mild dependence of the base flow along the axial direction. The approach we follow for the numerical solution of the PSE-3D problem is challenging, as it involves the inversion of a large matrix resulting from the discretization of a system of two-dimensional, partial derivative equations, with leading dimension $O(10^4 - 10^5)$. The challenge is met by usage of stable high-order finite-difference numerical schemes for spatial discretization[1] and a parallelizable sparse matrix linear algebra package.

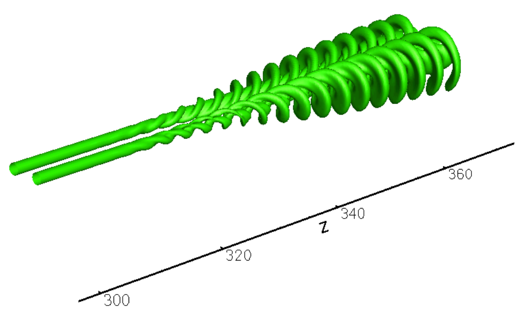

Figure 1. Iso-surface of axial velocity flow field ($\bar{u} = U + \varepsilon u$) with $\varepsilon = 10^{-4}/|u_0|$ in the range $x \in [300, 370]$

Figure (1) shows the iso-surface of axial velocity flow field ($\bar{u} = U + \varepsilon u$) with $\varepsilon = 10^{-4}/|u_0|$ for the initial most unstable perturbation with the selected parameters, U being axially-developing Batchelor vortices. The inhomogeneous nature of the underlying flow is evident in the non-axisymmetric shape of the amplitude functions of the perturbations. First results have been presented in[2] and a complete parametric study will be available at the time of the Conference.

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