ERCOFTAC
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On Flow, Turbulence And Combustion

13th ERCOFTAC SIG 33 Workshop

Progress in Flow Instability, Transition and Control

Paraty, Barazil, March 6-8, 2018

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Organisers:

André Cavalieri (ITA)
Ardeshir Hanifi & Dan Henningson (KTH)

Tuseday, March 6	Venue:	CASA DA CULTURE DE PARATY, R. DONA GERALDA, 157 – CENTRO HISTÓRICO	
9:45	Dan Henningson	WELOCOME	Chair: D. Henningson
10:00	Outi Tammisola	SENSITIVITY ANALYSIS OF COMPLEX FLOWS - ELASTIC, YET UNYIELDING GOAL	
10:45	Leandro Souza	STABILITY ANALYSIS OF VISCOELASTIC OLDROYD-B AND GIESEKUS FLUIDS IN A POISEUILLE FLOW	
11:00	Ricardo Dias dos Santos	GENERATION OF STEADY-STATE FLOWS WITH MINIMAL GAIN MARCHING SCHEMES	
11:15	Gustavo Patino	BUILDING A LOW DIMENSIONAL GALERKIN MODEL USING SENSITIVITY ANALYSIS	
11:30	coffee		
11:45	Jean-Christophe Loiseau	MODAL STABILITY ANALYSIS OF AN OVER-EXPANDED NOZZLE FLOW	Chair: A. Hanifi
12:00	Shahid Mughal	EVOLUTION OF TOLLMIEN-SCHLICHTING DISTURBANCES OVER NATURALLY DISTRIBUTED ROUGH SURFACES	
12:15	Henrique Raposo	UNCERTAINTY QUANTIFICATION OF ACOUSTIC RECEPTIVITY WITH AN ADJOINT LINEAR NAVIER-STOKES APPROACH	
12:30	Koen Groot	LINEAR AND NON-LINEAR DYNAMICS OF A MICRO-RAMP WAKE	
12:45	Lunch		
14:30	Vassilis Theofilis	GLOBAL LINEAR STABILITY THEORY IN AEROSPACE APPLICATIONS	Chair: L. Lesshafft
15:15	Marlon Sproesser Mathias	GLOBAL STABILITY ANALYSIS OF ROSSITER MODES IN A COMPRESSIBLE OPEN CAVITY	
15:30	Thibaut Appel	BIGLOBAL STABILITY ANALYSIS OF A BOUNDARY LAYER IN PRESENCE OF A SURFACE INDENTATION	
15:45	Daniel Rodriguez	SELF-EXCITED PRIMARY AND SECONDARY INSTABILITY OF LAMINAR SEPARATION BUBBLES	
16:00	Coffee		
16:30	Daiane Iglesia Dolci	MODAL LINEAR STABILITY ANALYSIS APPLIED IN VORTEX-INDUCED VIBRATIONS AT LOW REYNOLDS NUMBER	Chair: H. Fasel
16:45	Mattias Brynjell-Rahkola	LINEAR INSTABILITY OF TWO HELICAL VORTICES	
17:00	Elektra Kleusberg	REDUCED ORDER MODELING OF A WIND TURBINE WAKE UNDER YAWED INFLOW CONDITIONS	
17:15	Carlo Cossu	NONLINEAR SECOND-ORDER SENSITIVITY AND INFLUENCE OF OPTIMALLY FORCED STREAKS ON THE KELVIN-HELMHOLTZ INSTABILITY	
17:30		DISCUSSION	
18:00		END OF THE DAY	
20:00	Dinner	RESTUARANTE DONA ONDINA, R. DO COMÉRCIO, 32	
Wedensday, March 7			
		SOCIAL ACTIVITY	
Thursday, March 8	Venue:	CASA DA CULTURE DE PARATY, R. DONA GERALDA, 157 – CENTRO HISTÓRICO	
9:45	Julio Soria	DNS OF A SELF-SIMILAR ADVERSE PRESSURE GRADIENT TURBULENT BOUNDARY LAYER	Chair: V. Theofilis
10:30	André Cavalieri	LARGE-SCALE, STREAKY STRUCTURES IN TURBULENT JETS	
10:45	Peter Jordan	THE LOCAL MODES UNDERPINNING OSCILLATOR BEHAVIOUR IN JETS	
11:00	Lutz Lesshafft	SUCCESS AND OPEN QUESTIONS IN THE MODELLING OF JET TURBULENCE THROUGH STATISTICAL STATE DYNAMICS	
11:15	Coffee		
11:30	Léopold Shaabani-Ardali	MIXING ENHANCEMENT THROUGH OPTIMALLY CONTROLLED JET BIFURCATION	Chair: P. Luchini
11:45	Eduardo Martini	THE ROLE OF ACOUSTICS MODES IN JET AND WAKE STABILITY	
12:00	Jeffrey Crouch	CHARACTERIZING SURFACE-STEP EFFECTS ON TRANSITION	
12:15	Maksim Ustinov	AMPLITUDE METHOD OF LAMINAR-TURBULENT TRANSITION PREDICTION ON THE SWEPT WING	
12:30	Lunch		
14:15	Marcello Mederios	IS IT POSSIBLE TO COMBINE GOOD AERODYNAMICS AND LOW ACOUSTIC NOISE IN THE SLAT?	Chair: P. Jordan
15:00	Filipe Amaral	THE NEW USP-EESC CLOSED-SECTION WIND-TUNNEL	
15:15	Fernando Himeno	THE EFFECT OF A BULB SEAL ON THE SOUND EMITTED BY THE SLAT ANALYZED BY PROPER ORTHOGONAL DECOMPOSITION	
15:30	Leandra Abreu	REDUCED ORDER MODELS TO ANALYSE WAVEPACKETS IN TURBULENT FLOW OVER AN AIRFOIL	
15:45	Coffee		
16:15	Flávio Silvestre	LINEAR-QUADRATIC, OUTPUT-FEEDBACK FLOW CONTROL BASED ON REDUCED ORDER MODELS	Chair: A. Cavalieri
16:30	Thomas Bewley	IMPLEMENTATION OF BOOSTCONV TO ACCELERATE THE OPPOSITELY-SHIFTED SUBSPACE ITERATION (OSSI) METHOD FOR APPROXIMATE OPTIMAL CONTROL WITHOUT MODEL REDUCTION	
16:45	Paolo Luchini	OPTIMAL GUIDANCE OF BUOYANCY-CONTROLLED BALLOONS IN TURBULENT FLOWS USING A NON-QUADRATIC OBJECTIVE AND DISCONTINUOUS ACTUATION	
17:00	Hermann Fasel	ROLE OF KLEBANOFF MODES IN ACTIVE CONTROL OF LAMINAR SEPARATION BUBBLES	
17:15	Henry Tol	EXPERIMENTAL STUDY ON ESTIMATION AND CONTROL OF NATURAL TS-WAVES	
17:30		DISCUSSION	
18:00		END OF THE DAY	

ADJOINT-BASED SENSITIVITY ANALYSIS OF A TURBULENT SWIRLING FLOW

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[2] *Dept. of Engineering, Univ. of Cambridge.*

The large-scale coherent motions in a realistic swirl fuel-injector geometry are analysed by direct numerical simulations (DNS), proper orthogonal decomposition (POD), and linear global modes. The aim is to identify the origin of instability in this turbulent flow in a complex internal geometry . The flow field in the nonlinear simulation is highly turbulent, but with a distinguishable coherent structure: the precessing vortex core (a spiralling mode). Linear global modes are computed around the mean flow from DNS, applying the turbulent viscosity extracted from POD modes. A slightly stable discrete eigenmode is found, well separated from the continuous spectrum, in very good agreement with the POD mode shape and frequency. The structural sensitivity of this global mode reveals that the mode originates inside the nozzle. We also go further and use sensitivity analysis to reveal the (linear) feedback between flow and acoustics in another injector[2]. These studies show how she sensitivity analysis can identify which parts of the flow in a complex geometry need to be altered in order to change its hydrodynamic stability characteristics.

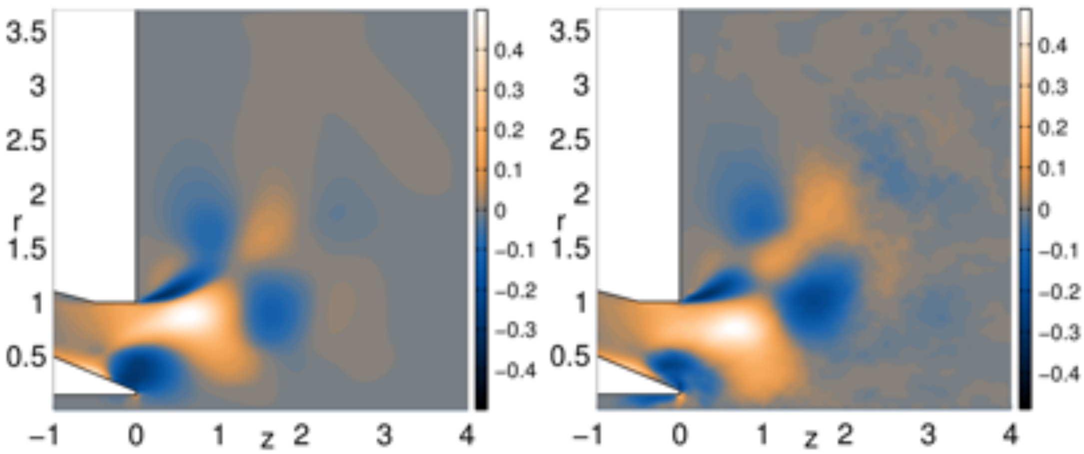

FIGURE 1. *Left: Leading linear global mode of the mean flow (axial vel.), Right: Leading POD mode (axial vel.)*

References

[1] O. Tammisola, and M. P. Juniper Coherent structures in a swirl injector at Re=4800 by nonlinear simulations and linear global modes *J. Fluid Mech.*, 792, 620-657, 2016.

[2] L. Magri, Y. C. See, O. Tammisola, M. Ihme and M. P. Juniper. Multiple scale thermoacoustic stability analysis of a coaxial jet combustor. *Proc. of the Combustion Institute*, 36(3):3863–3871, 2017.

STABILITY ANALYSIS OF VISCOELASTIC OLDROYD-B AND GIESEKUS FLUIDS IN A POISEUILLE FLOW

Analice C. Brandi[1], Laison J. S. Furlan[1], Arianne A. Silva[2], Matheus T. Araujo[2], Leandro F. Souza[2]
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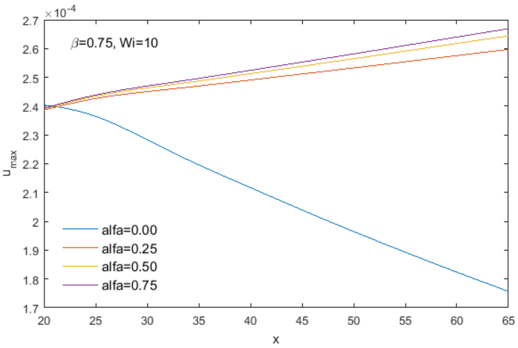
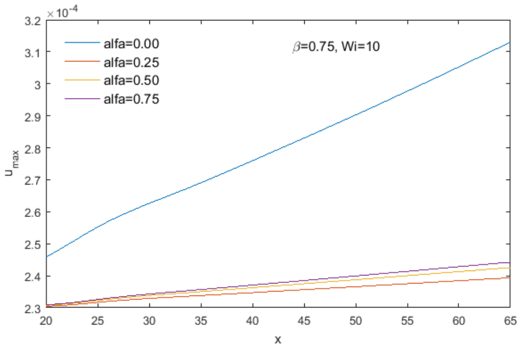
The hydrodynamics of viscoelastic fluids are strongly affected by the balance between inertia and elastic forces in the flow, the effect of elasticity on the stability of inertial flows has not been completely established. Hydrodynamic instability has emerged as an active field of study in non-Newtonian fluid mechanics. The rising interest in this phenomenon originates mainly from its technological importance in polymer industry. The Poiseuille and Couette flows are generally used as benchmark tests for the new constitutive equations. Therefore, the stability of non-Newtonian fluid flow between parallel plates is a problem of practical interest. In this paper, the development of unsteady disturbances in a Poiseuille viscoelastic fluid flow is studied through DNS – Direct Numerical Simulation. The mathematical models adopted here for the non-Newtonian fluids stress tensors are the Oldroyd-B [1] and the Giesekus [2] models. In the DNS formulation the Navier-Stokes equations along with the Oldroyd-B and the Giesekus constitutive equations are solved using high-order numerical methods.

Results are presented for the Oldroyd-B fluid (alfa=0) and compared with the Giesekus fluid (alfa > 0). Alfa is the dimensionless mobility factor and controls the extensional viscosity and the ratio of second normal stress difference to the first one. In order to evaluate the evolution of the unsteady disturbances, different numerical simulations were performed by varying the non-dimensional parameters for the viscoelastic fluid. Considering the viscoelastic Poiseuille flow, using the Oldroyd-B and the Giesekus models, the effect of the alfa parameter in the numerical simulations were analyzed and can be seen in the Figure 1. Figure 1 (a) shows that increasing alfa de flow becomes more unstable, while for the Oldroyd-B model, the flow is stable for this disturbance. In Figure 1 (b) it can be seen that the flows become more stable with increasing alfa, and that the Oldroyd-B model is much more unstable than the Giesekus model for these parameters.



(a)



(b)

FIGURE 1. *Maximum streamwise velocity disturbance development in the streamwise direction for different* α *values. Fixed constant* $\beta = 0.75$ *and* $Wi = 10$. *a)* $Re = 5000$ *and b)* $Re = 7000$.

References

[1] E. Brasseur, M. Fyrillas, G. Georgioou, and M. Crochet. The time-dependent extrudate-swell problem of an Oldroyd-B fluid with slip along the wall. *J. Rheol.*, 42:549566, 1994.

[2] H. Giesekus. A simple constitutive equation for polymer fluids based on the concept of deformation-dependent tensorial mobility. *J. Non-Newtonian Fluid Mech.*, 11:69109, 1982.

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GENERATION OF STEADY-STATE FLOWS WITH MINIMAL GAIN MARCHING SCHEMES

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Some problems in computational fluid mechanics are shown that stationary crossflow modes can be sudden amplifying and possibly making breakdown. The interaction between an existing stationary crossflow instability and a two-dimensional step is an example. Computational and experimental results agree in the existence an additional local travelling instability in the recirculation region for forward-facing step for a specific critical height of the step. What is not known, however, is the manner in which crossflow vortices will interact with a shear layer, such as that coming of a step or gap [1].

Both forward-facing and backward-facing steps, for small step sizes, there is no discernible effect on the location of transition to turbulence, however, once a certain step size was reached, the transition front moved quickly to the location of the step itself. The critical step height was found to be relatively insensitive to the angle of attack, however, a strong dependence on the Reynolds number of the freestream was observed [2].

In order to get a better understanding about this instabilities, good base flows are necessary as reference solutions for linear instability analysis. Selected Frequency Damping (SFD) is a methodology developed, motivated trough the difficulty of obtaining steady-state flows with standard marching schemes or steady governing equations. This approach does not require a good initial condition and works well for self-excited flows, on the other hand, it seems unable to damp stationary disturbances. Furthermore, flows with a broad unstable frequency spectrum might require the use of multiple filters, which delays convergence significantly. Both scenarios appear in convectively, absolutely or globally unstable flows.

An alternative approach was proposed by [3]. It modifies the coefficients of a marching scheme in such a way that makes the absolute value of its linear gain smaller than one within the required unstable frequency spectra, allowing the respective disturbance amplitudes to decay given enough time. Diagonally Implicit Runge-Kutta (DIRK) methods can be strong S-stable [4], and this is a good characteristic for MGM schemes. Figure 1 shows that is a significant reduction of the gain on the unstable region and also maintain the strong S-stable stability, this indicate that DIRK-MGM presents be more efficient for problems with strong instability.

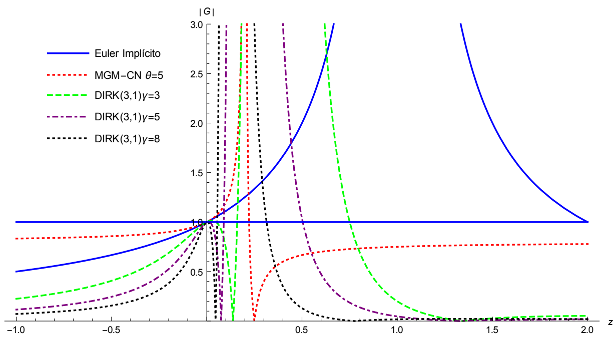

FIGURE 1. ***Gain comparison between MGM multi-step and MGM-DIRK developed in this work.***

The study of [3] only included low Mach number compressible flow with multi-step methods. An extension to multi-stage MGM schemes will be developed in this paper, and as test case a steady-state flow for the forward-facing step will be generated.

References

[1] Tufts, M.W., Reed, H.L., Crawford, B.K., Duncan, Ducan Jr., G.T. and Saric, W.S., 2016. Computational investigation of step excrescence sensitivity in a swept-wing boundary layer. In *JOURNAL OF A IRCRAFT*. Dallas, TX, EUA.

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BUILDING A LOW DIMENSIONAL GALERKIN MODEL USING SENSITIVITY ANALYSIS

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This work focuses on the representation of the two-dimensional flow around a cylinder in the Reynolds range $100 \leq \mathrm{Re} \leq 300$ through a reduced model. The reduced model will be constructed by the projection of the incompressible flow equations into an appropriate orthonormal basis, built from the most energetic Fourier modes plus a disturbance of the mean flow pointing in the direction of the greatest eigenvalue growth rate. The Fourier modes are obtained through snapshots of the temporal simulation, and the optimal disturbance is calculated using sensitivity analysis ([1] and [2]). The temporal dynamics, the hydrodynamic forces as well as the stability properties are calculated in the reduced space and compared with the results of the physical space showing a significant similarity. The addition of the mean flow disturbed by the sensitivity to base flow modifications [1] aids to build a base flow that has a nonzero growth rate, allowing to describe the saturation path of the system in an appropriate way.

References

[1] O.Marquet, D. Sipp and L.Jacquin *Sensitivity analysis and passive control of cylinder flow.* Journal of Fluid Mechanics,615:221252,2008

[2] F. Giannett and P.Luchini *Structural sensitivity of the first instability of the cylinder wake* Journal of Fluid Mechanics, 581:167197,2007

MODAL STABILITY ANALYSIS OF AN OVER-EXPANDED NOZZLE FLOW

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A fully three-dimensional global stability analysis is carried out on an over-expanded rocket engine nozzle configuration to investigate the role of the internal shock induced separation on the mechanism of generation of side loads during start-up and shutdown transients. An axi-symmetric steady base flow is obtained and well compares with the experiments performed at Pprime Institute in Poitiers in terms of separation and shock locations and pressure distributions. The stability analysis shows the existence of a globally unstable mode, whose features are in reasonable good agreement with the experimental characterization of the unsteady nozzle flow behavior. At the conference, hybrid RANS/LES simulations will be presented

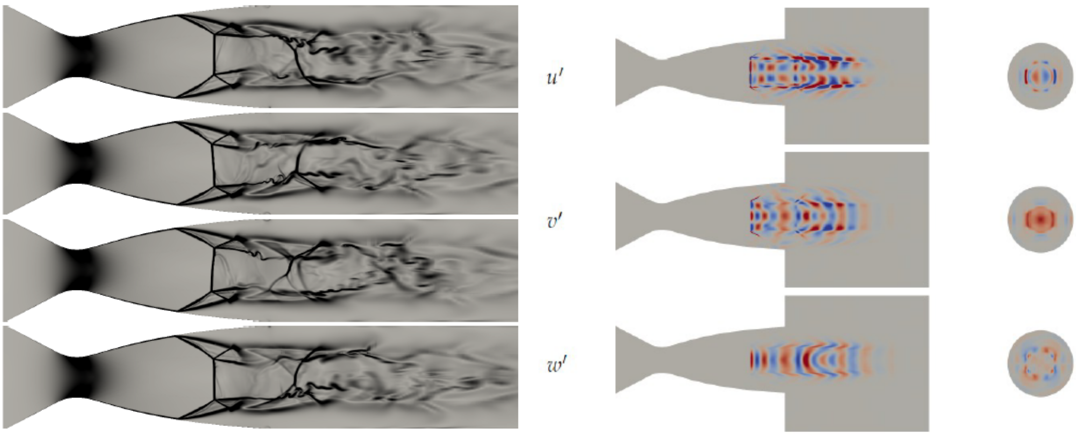

FIGURE 1. *(Left column): Instantaneous Flow: Schlieren-like representation. Eigenfunctions associated to the globally unstable mode at $St \simeq 1.6$. Longitudinal (central column) and transversal (right column) slices of the reconstructed streamwise (top), normal (center) and transversal (bottom) eigenfunction perturbation velocities.*

for an over-expanded TIC nozzle flow ($NPR = 9$). These results will be compared with the experiments carried out at the Pprime Institute. Contours of the gradient of density in a Schlieren-like visualization are reported on a longitudinal slice and shown in Fig. 1-Left. The base flow is then obtained by using an implicit continuation method for which the Navier-Stokes equations are discretized by an implicit scheme and solved by a pseudo-unsteady approach with high CFL number. This method provides a base flow converged well when the computation remains close to the threshold of onset of instabilities. Global stability analysis is performed on the base flow. A Krylov subspace of dimension 100 is selected to examine the eivenvalue spectrum. A globally unstable mode (positive growth rate) is found for $St \simeq 1.6$. The eigenfunction associated to the global unstable mode is represented in Fig. 1-(Central and Right). The global unstable eigenmode is very localized on the shear layer starting from the triple point and in the core part of the nozzle downstream of the first Mach disk. The normal and transversal velocity perturbations are rotated of 90 degrees, showing the potential characteristics of a $m = 1$ azimuthal mode like reported by the experimental Fourier transformations in the azimuthal direction.

EVOLUTION OF TOLLMIEN-SCHLICHTING DISTURBANCES OVER NATURALLY DISTRIBUTED ROUGH SURFACES

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Department of Mathematics, Imperial College London, SW7 2AZ, United Kingdom

The work concerns investigating boundary-layer instabilities of the Tollmien-Schlichting (TS) type which are known to be either induced or modified by small surface geometrical imperfections in the form of surface roughness and waviness. These are of course facets of the *real-world*, surfaces are naturally rough, materials will have some form of waviness and due to moving parts (*i.e.* engine nacelle or wing planforms), surfaces may well be vibrating at frequencies and length scales in resonance with the TS disturbance scales. Use of rivets, fasteners or impact damage during lifetime operation will lead to small localised three-dimensional surface indentations or protuberances, from the ideal manufactured surface, which are known to trigger local tripping of the laminar flow to an expanding wedge-shaped turbulent flow downstream of the damage site.

The specific topic to be discussed is that of pre-existing 2D Tollmien-Schlichting disturbances having their behaviour altered as they convect over a rough surface, relative to a nominally smooth surface. Specifically the presentation will discuss attempts at modelling the effects of natural distributed 2D and 3D surface roughness on TS disturbances, including stochastic effects. The mere issue of computing base flows comprising surface roughness effects is quite demanding. A methodology which allows these features to be assessed will be described. The instability analysis tools used range from linear PSE, Linear Navier-Stokes (LNS)[1] and the more recent marching-in-planes PSE3D equations[2]. With the latter, we use the properly 3D stability analysis capability to model spanwise-non-modal instability behaviour over fully 3D roughness fields. The steady base flows are computed using a high-fidelity DNS solver (Nektar++)[3].

Typical results (Figure 1, left) shows instability N-factors computed with linear PSE for a range of roughness rms amplitude values with identical roughness spectra for the $F = \omega 10^6/R_\delta = 50$. The TS disturbance wavelength $\lambda_{TS} \approx \lambda/5$ and one interest is in exploring how roughness grain size impacts upon the TS disturbance evolution. As the rms amplitude increases we find N-factors increase rapidly beyond values exceeding 8, which is generally a criterion for imminent tripping of the flow to turbulence (*i.e.* the e^N criterion). A key finding was that within the roughness troughs, localised pockets of reversed low velocity flow does arise (Figure 1, right), but the PSE equations were still able to compute results which agreed with the more physically correct LNS solver. Only in the very-large and deeper roughness grain size situations were differences found between the two radically different models, with the LNS solver essentially predicting upstream reflected effects of the propagating TS disturbance.

In the meeting we will attempt to draw conclusions of our findings, outline in detail our surface roughness modelling work and present more details of the numerical techniques employed and conclusions on the efficacy of using PSE and LNS to model such flows. In particular further and more detailed analysis of our PSE3D analysis will be covered.

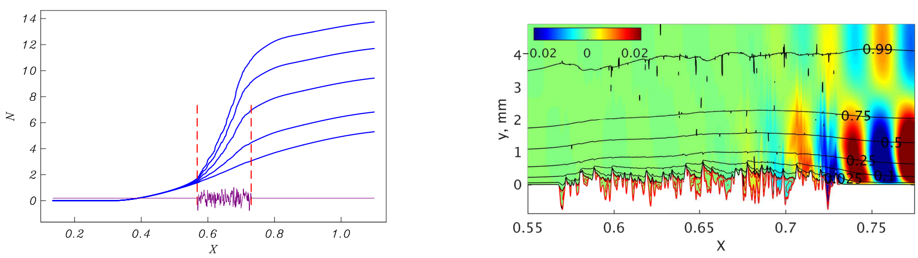

FIGURE 1. *(a) N-factor variation with roughness rms amplitude for $F = \omega 10^6/R_\delta = 50$ disturbance. (b) Linearised Navier-Stokes solution of TS-disturbance evolution over the rough surface, colour shading is the TS u-disturbance. The red contours represent pockets of negative values of the steady base flow U.*

References

[1] S. Mughal and R. Ashworth. *Uncertainity quantification based receptivity modelling of crossflow instabilities induced by distributed surface roughness in swept wing boundary layers. AIAA Paper*-2013-3106, 2013.

[2] S. Mughal and R. Ashworth. *Modeling three-dimensional effects on cross flow instability from leading edge dimples. IUTAM-ABCM Symposium on Laminar Turbulent Transition.* Vol. 14, 2015, pp. 201-210.

[3] C. Cantwell, D. Moxey *et al. Nektar++: An open-source spectral/hp element framework. Computer Physics Communications.* Vol. 192, 2015, pp. 205-219.

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UNCERTAINTY QUANTIFICATION OF ACOUSTIC RECEPTIVITY WITH AN ADJOINT LINEAR NAVIER-STOKES APPROACH

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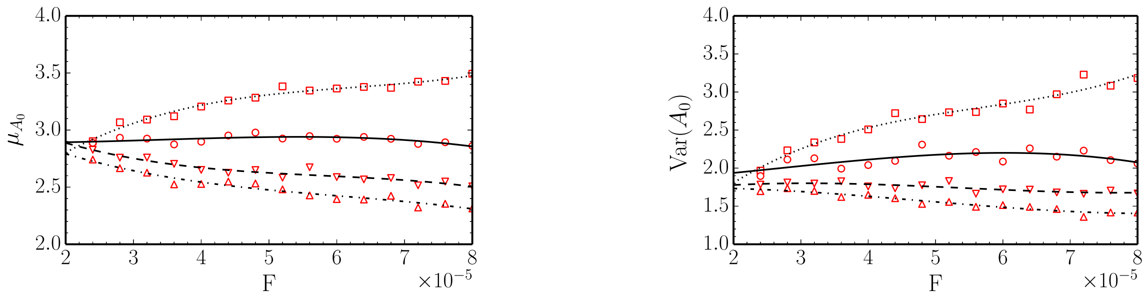
[2] *Department of Mathematics, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom*

Receptivity is the first stage of a complex process leading to boundary layer transition to turbulent flow. At this stage external perturbations penetrate the boundary layer and generate disturbances. The state of the art transition prediction model in industry - the e^N method - assumes the presence of such disturbances in the boundary layer but disregards their initial amplitude as well as any non-linearities. A more realistic amplitude-based model of transition must account for non-linear growth, the later stage of transition in a small perturbation environment. This can only be done if the amplitudes of the instabilities are known, i.e. if receptivity is modelled.

In this work the acoustic receptivity to Tollmien-Schlichting (T-S) waves in the presence of surface roughness is investigated for an unswept flat plate configuration using the time-harmonic incompressible linearised Navier-Stokes equations (LNS) and their adjoint (ALNS) [1]. The "exactness" of the governing equations allows us to model finite-Reynolds number and non-parallel effects. Furthermore, the time-harmonic form of the LNS equations allows for an important reduction in computational cost when compared to the more popular time-stepping technique. The base flow and the acoustic signature within the boundary layer are calculated using the boundary layer equations. By exploring the parabolic nature of these two flow fields, one can further reduce the total cost of predicting receptivity amplitudes. Lastly, the adjoint capability is meant to provide a highly efficient means to investigate the vast parameter space.

Most receptivity models in the literature are limited by their narrow applicability to specific test cases and/or conditions. The model proposed in this work is meant to overcome this hindrance, by providing an inexpensive and general framework to which other forcing mechanisms can be added. An accurate characterization of the external disturbance environment is another major obstacle preventing the generalized use of receptivity models and therefore of amplitude-based transition prediction criterion. In this work we focus on modelling randomized surface roughness which, together with freestream acoustic disturbances, is known to play a prominent role in natural transition on an unswept flat plate [2]. In figure 1 we present an example of how the mean receptivity amplitude of T-S waves (μ_{A_0}) and its variance ($Var(A_0)$) vary with the non-dimensional frequency (F) of the acoustic wave. Each curve corresponds to a roughness field with a power spectral density following a power law of exponent k. The stochastic nature of surface roughness yields an uncertainty in the T-S wave initial amplitude that is comparable to its mean value, thus being expected to affect transition location. This effect will be explored by coupling the receptivity model with non-linear PSE computations.



(a) Mean receptivity amplitude

(b) Receptivity amplitude variance

FIGURE 1. *Receptivity to different acoustic wave frequencies and power spectral densities of the random distributed surface roughness. Squares - $k = 0.75$, Circles - $k = 0.9$, Downward facing triangles - $k = 1.0$, Upward facing triangles - $k = 1.05$*

References

[1] D. C. Hill. Adjoint systems and their role in the receptivity problem for boundary layers. *Journal of Fluid Mechanics*, 292 (1995): 183-204.

[2] W. S. Saric, H. L. Reed, and E. J. Kerschen. Boundary-layer receptivity to freestream disturbances. *Annual review of fluid mechanics*, 34.1 (2002): 291-319.

LINEAR AND NON-LINEAR DYNAMICS OF A MICRO-RAMP WAKE

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Micro-ramps have been widely deployed as passive flow control devices for promoting transition and for avoiding separation, see Lin [1]. Ye *et al.* [2] assessed the instantaneous and mean flow fields of the micro-ramp wake in detail through tomographic particle image velocimetry (tomo-PIV). The wake's spanwise propagation was identified to be driven by secondary vortices in the mean flow field.

The present study complements previous experimental work by direct numerical simulations (DNS, see [3]), which allow us to computationally identify the non-linear development of the perturbations and the time-averaged flow field. Comparisons with the PIV measurement show excellent agreement of instantaneous flow features, see Figure 1. In addition, we calculated the laminar base flow and analyse the linear perturbation dynamics. Secondary (induced) vortices are observed in the laminar base flow, but they are much weaker than the secondary vortices observed in the mean flow. We find that the non-linear perturbations are responsible for the generation of a positive mean velocity streak close to the wall, which is important for preventing flow separation.

Stability analysis is performed on spanwise planes of the base flow to identify the most dominant modes, see Groot *et al.* [4]. In particular, the most unstable eigenmode is found to have an important role in the development of the secondary vortices. To further analyse differences between the computational and experimental data, the stability analysis is performed on both datasets in the streamwise range close to the micro-ramp, where the base flow closely approximates the mean flow. By applying a filter on the computational base flow that mimics the processing inherent to PIV, matching growth rates are obtained.

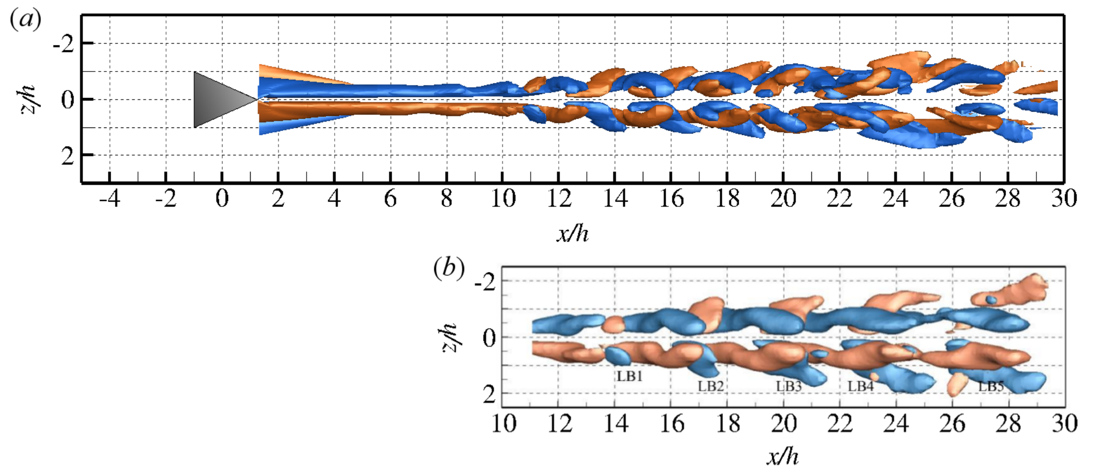

FIGURE 1. *Isocontours of streamwise vorticity based on (a) the instantaneous DNS data and (b) a POD reconstruction of the PIV data presented by Ye et al. [2].*

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GLOBAL LINEAR STABILITY THEORY IN AEROSPACE APPLICATIONS

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Laminar-turbulent flow transition prediction remains one of the main scientific and technological frontiers in fluid mechanics research. Linear (and nonlinear) stability theory forms the cornerstone of flow transition prediction and is rooted in the work on boundary layer stability and transition performed in the first half of last century by W. Tollmien, H. Schlichting, H. Görtler and others, under the auspices of Ludwig Prandtl. Today, achieving natural laminar flow on commercial aircraft is synonymous with controlling Tollmien-Schlichting instability waves, as well as crossflow and Görtler vortices, all of which develop in boundary layers on aircraft wings, fins and engine nacelles. In supersonic and hypersonic flow, choice of materials and design of optimal thermal protection systems relies on knowledge of the state, laminar or turbulent, of the flow in the different phases of the vehicle mission. In the latter part of last century, classic linear stability theory has been substantially expanded in scope by developments in two key areas: global linear stability theory, which extends the classic analysis to flows with multiple inhomogeneous spatial directions (as opposed to the single such direction in the boundary layer), and transient growth theory, which has unravelled the potential of fluid flows to sustain strong non-modal growth of small-amplitude perturbations that can lead flow to transition while by-passing eigenmode growth. In the talk it will be argued that, seemingly unrelated technological issues, such as increased authority over aerodynamic control surfaces or adequate heat-shield protection, can be resolved through better understanding of the physical mechanisms of instability of the underlying spatially inhomogeneous flows.

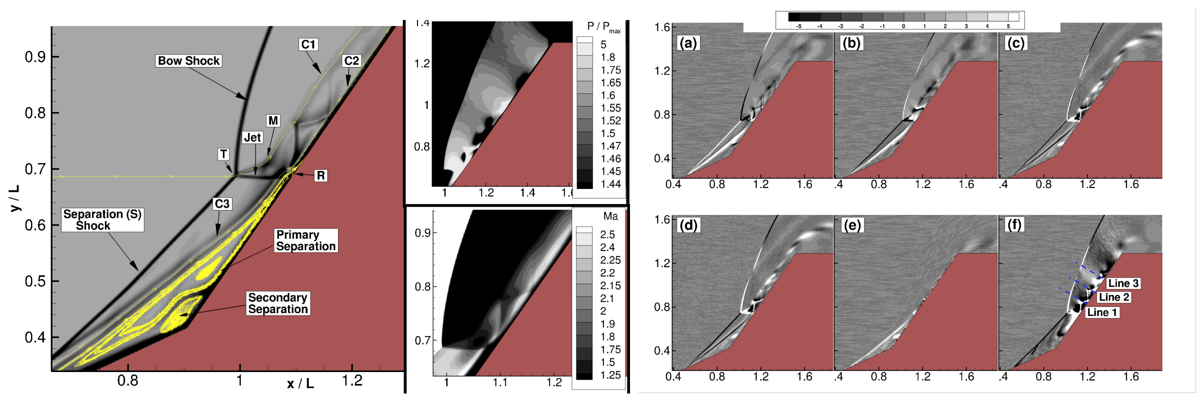

FIGURE 1. *Base flow (left) and amplitude functions $\hat{u}, \hat{T}_{tr}, \hat{T}_{vib}, \hat{T}_{rot}, \hat{p}$, of the corresponding leading global mode (right) in Ma=16 flow over a double cone (Tumuklu, Theofilis, Levin, Pérez; in preparation)*

The presentation will commence by highlighting results of global modal and non-modal instability analysis in flows of aerospace interest. Numerical solution of two-dimensional global eigenvalue problems will be introduced in the context of instability in the boundary layer at the leading edge of swept wings, where eigenmodes additional to those postulated by Görtler over half a century ago have been discovered and modeled. Instability and transition in separated flows will be discussed in some detail, following the discovery, also by global modal analysis, of a previously unknown class of self-excited stationary three-dimensional flow instability mechanism that can lead separated flow to transition through a scenario different to the well-known Kelvin-Helmholtz instability. Separation bubbles in the adverse pressure gradient flat plate boundary layer, in flow over stalled airfoils and wings, as well as in a cascade of low-pressure turbine blades will be monitored in this context, and the connection of global transient growth to laminar-turbulent transition on airfoils, wings, and turbine blades will be highlighted. Flow instability in a lateral-wall bounded three-dimensional cavity (modeling three-dimensional imperfections of a flat surface or flow in an aircraft bay) will be presented and results of numerical solution of the three-dimensional eigenvalue problem will be contrasted with those obtained in over-simplified analyses. Modal and non-modal instability analysis results in the hypersonic boundary layer on an elliptic cone will be presented and compared with those obtained in recent flight testing. The presentation will close with presentation of on-going work on instability of shock-induced laminar separation bubbles in hypersonic flows over a double cone, where it will be shown that unsteadiness of the entire shock system that develops on a vehicle are intimately connected with linear amplification of the recently identified global flow instabilities, shown in figure 1.

GLOBAL STABILITY ANALYSIS OF ROSSITER MODES IN A COMPRESSIBLE OPEN CAVITY

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A global instability analysis routine is used to compute the modes of a compressible flow in an open cavity. Two parameters are checked for their influence: the incoming boundary layer thickness, ranging from one to two orders of magnitude smaller than the cavity depth; and the free flow Mach number, in the subsonic range. The cavity aspect ratio (length by depth) is set to 2 and the Reynolds number, relative to the cavity depth, is close to 1000.

[1] brings a diagram that describes where two-dimensional modes are expected to become unstable before three-dimensional ones. This parameter range is into the two-dimensional region.

In a two-dimensional analysis, where the span-wise direction is considered constant, most instability modes remain roughly stationary as the Mach number is increased. One notable exception are the Rossiter modes [2], which usually become more unstable. An increased instability of these modes is also seen as the boundary layer becomes thinner.

Three physical phenomena are checked for their role in this effect. The first is a resonance between Rossiter modes and standing wave modes [3]. At this parametric space, this resonance only plays a minor role.

The second phenomenon is the spatial instability of the mixing layer, at the cavity opening. Thinner boundary layers create thinner mixing layers, which are considerably more unstable. The spatial growth in this region was found to be a major part of the Rossiter modes selection. This growth is known to be attenuated by higher Mach numbers.

Finally, the amount of energy transfered from the disturbances in the mixing layer to the acoustic feedback mechanism is measured. In most situations, the acoustic source in the cavity's trailing edge behaves as a dipole, having its emissivity increased with the cube of Mach number. In some regions, a monopole becomes the main source, causing this rate to become quadratic. This matches [4], but for a wider span of Mach numbers.

Figure 1 shows the evolution of the mode's eigenvalues as Mach changes with an incoming boundary layer thickness of one hundredth of the cavity depth. The real part relates to the stability, higher values are more unstable. The imaginary part relates to the mode frequency. The right hand side shows isocontours of wall-normal velocity at an arbitrary phase for Rossiter modes 1 to 4 at Mach 0.5.

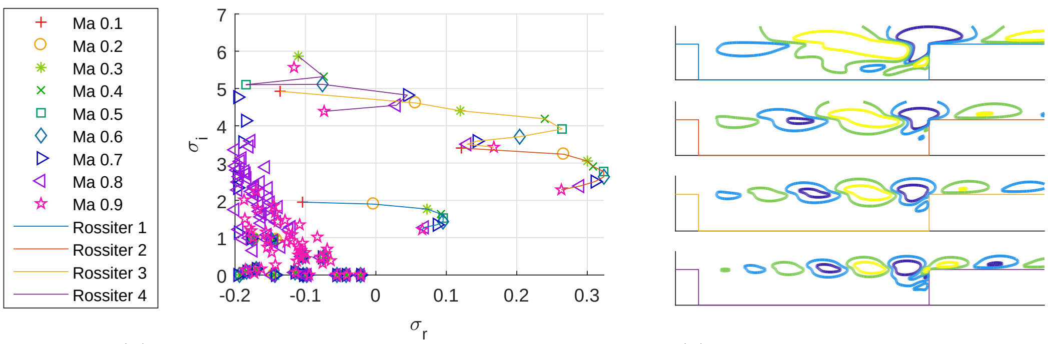

FIGURE 1. *(a)Evolution of Rossiter modes with Mach number. (b)Isocontours of Rossiter modes 1 to 4.*

Later, fully non-linear simulations are performed to check the influence of non-linearities over these modes. Lower Mach number cases, which are marginally unstable, remain very close to the linear prediction.

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BIGLOBAL STABILITY ANALYSIS OF A BOUNDARY LAYER IN PRESENCE OF A SURFACE INDENTATION

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In the aeronautical context, one of the challenges in modelling the laminar-turbulent transition of a boundary layer is assessing the impact of surface imperfections. Examples include damage due to scratches, dents or erosion as well as residuals of grease and insects. Small scale irregularities located on the leading edge or further downstream on the wing, are now known to create receptivity sites for disturbance generation. These geometrical features generally lead to fully three-dimensional modifications to the base flow, which then impacts upon disturbance convection and evolution.
Different strategies have been employed in an effort to understand the full road-map to turbulence within a boundary layer. Standard methodologies of analysis, from local Orr-Sommerfeld theory and non-local linear and nonlinear Parabolised Stability Equations (PSE) are mature and have been extensively used. In recent work [1], a very good agreement was found between the more accurate Linearised Navier-Stokes (LNS) modelling and the lower-order PSE modelling in the context of flow destabilisation due to laminar separation bubbles (LSB). While convective instabilities may be treated adequately and at a reasonable computational cost with these methods, global stability analysis holds potential for yielding more complex, localised 2D/3D instability modes [2] which are distinct from those determined with PSE-type analyses.

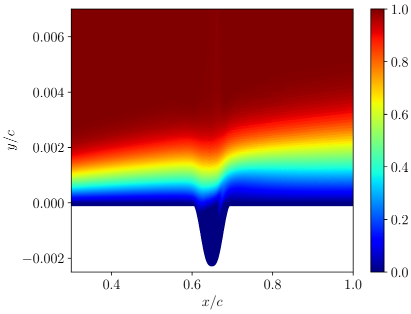

FIGURE 1. *Streamwise velocity component u of the base flow where $h/\delta \equiv 60\%$*

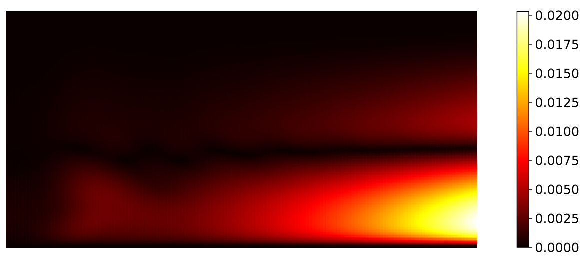

FIGURE 2. *One corresponding BiGlobal eigenmode, $|\hat{u}|$ magnified in the wake of the indentation*

The main objective of the present study is to investigate in detail the possible existence of 2D (BiGlobal) and 3D (TriGlobal) unstable temporal eigenmodes with 2D/3D laminar separation bubbles. An efficient parallel eigenvalue solver has been developed and fully validated on a parallel and non-parallel Blasius boundary layer flow. We report on findings for base flows examined by Xu *et al.* [3]. The base flows feature LSB confined in the area of the surface indentation as depicted in Figure 1. The LSB are found to have a significant impact on the advected Tollmien-Schlicting (TS) disturbances, in that the TS-destabilisation was linked to the inflectional instability of the separated shear layer. Results to be presented can be considered as an extension of the work conducted in [3] from the viewpoint of global (Bi/TriGlobal) stability analysis. Three different indentation heights, and thus separation bubble intensities are examined. A preliminary result of our analysis is shown in Figure 2, highlighting the structures of the eigenfunctions downstream of the indentation. A key component in the analysis is quantifying the effect of inflow and outflow boundary conditions as well as discerning between the global eigenvalue modes and those uncovered in the LNS analysis of Xu *et al.* [3].

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SELF-EXCITED PRIMARY AND SECONDARY INSTABILITY OF LAMINAR SEPARATION BUBBLES

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Laminar separation bubbles (LSB) have the potential to amplify external disturbances in a explosive manner: the orders-of-magnitude amplitude growth resulting from convective instability mechanisms typically leads to strong non-linear phenomena and transition to turbulence, even at low excitation levels. On the other hand, the absence of external excitation neglects the amplifier behavior of the bubbles, and only self-excited global instabilities have the potential of initiating the transition process. Recently it was demonstrated that a 3D global instability eigenmode becomes active for LSBs that are significantly weaker (with a reversed-flow magnitude $u_{rev} \approx 7 - 8\%$) than required for the onset of self-sustained two-dimensional oscillations ($u_{rev} \approx 16 - 20\%$) [1].

The present contribution addresses the subsequent non-linear evolution of the three-dimensional flow, including the characterization of the supercritical pitchfork bifurcation associated to the primary instability, and secondary instability analyses by means of three-dimensional eigenmodes and on the WKB approximation based on cross-stream planes [2]. Direct numerical simulations are used to cross-check the linear stability results and to investigate the non-linear regimes. The results demonstrate the existence of a self-excited secondary instability, that can explain the origin of the unsteadiness and laminar-turbulent transition recovered by numerical simulations of unforced LSBs with time-averaged peak reversed flows below 15% (e.g. [3]). This instability gives rise to vortical structures which resemble qualitative and quantitative the vortex loops studied experimentally by [4]. It is also shown that linear stability calculations considering spanwise-averaged flows necessarily fail to predict the existence of a global oscillator for most realistic applications.

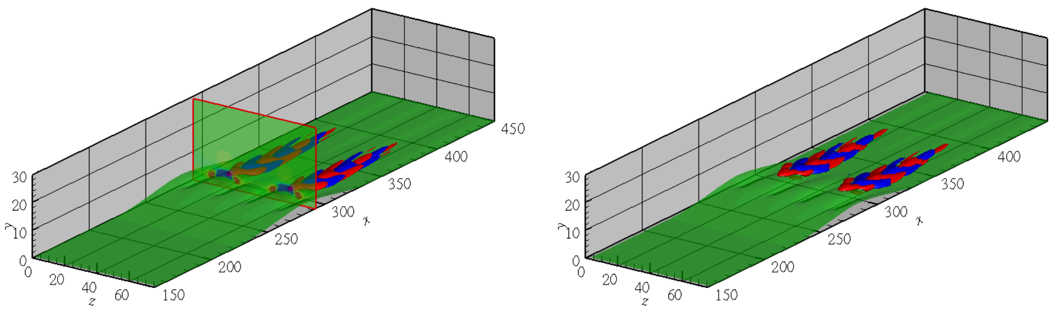

FIGURE 1. *Self-excited secondary instability of the three-dimensional laminar separation bubble resulting from the centrifugal instability. Green: $u = 0$ surface of the steady, three-dimensional LSB. Blue/red: contours of $\pm 0.1\hat{u}_max$, the eigenmode's streamwise velocity component. Left: Global oscillator obtained by WKB method on cross-planes; the plane located shows the approximate location of the wavemaker. Right: Leading three-dimensional eigenmode.*

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MODAL LINEAR STABILITY ANALYSIS APPLIED IN VORTEX-INDUCED VIBRATIONS AT LOW REYNOLDS NUMBER

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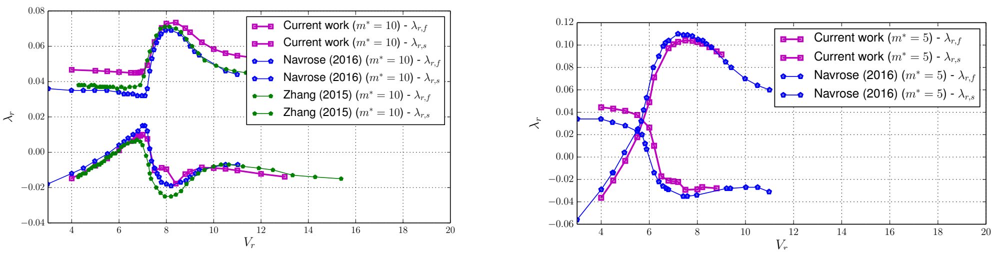
ABSTRACT

Two-dimensional problems with vortex-induced vibrations (VIV) are investigated via modal linear stability analysis (LSA). Studies on this topic have been carried out in the last years ([1], [2], [3], [4], [5]). Recently, Yao and Jaiman (2017) [4] introduced a study of the mechanism of VIV using a reduced model based in eigen-frequencies for flow around bluff bodies. From the results for Reynolds number $Re = 60$ and mass ratio $m^* = 10$, they verified different patterns of frequency lock-in phenomenon: "resonance-induced lock-in", "flutter-induced lock-in", "flutter-resonance-induced lock-in" and galloping. They showed that these instabilities depend of the geometry. For example, resonance regime is dominant in the frequency lock-in during VIV of a square cylinder, while forward triangle undergoes only the "flutter-induced lock-in" regime. Navrose and Mittal (2016) [2] also studied the lock-in via linear stability analysis around a circular cylinder at $Re = 60$ and defined decoupled and coupled modes. Decoupled modes appear for relatively large m^*, while coupled modes can appear for relatively low m^*. Navrose and Mittal (2016) verified that for coupled modes the behaviour of eigenvalues can change if compared with decoupled modes. Besides that, using the energy ratio calculation the unstable modes that can lead to lock-in were investigated, showing that the these eigenvalues (λ) depend on the combinations of Re and m^*. Therefore, knowing that the instabilities depend on m^* and that the resulting configuration can change for relatively low m^* (as it is noticed in Figure 1, where for a circular cylinder the growth rate λ_r exhibits different behaviours for $m^* = 10$ and $m^* = 5$), this work proposes to investigate wheter the pattern of instability introduced by Yao and Jaiman (2017) [4] can change for $m^* \leq 10$ on a steady flow past an oscillating square and forward triangle cylinders. In these cases, stability analysis is performed by varying the reduced velocity (V_r) with fixed m^* and Re. Spectral/hp element is used for spatial discretization and the Arnoldi method is employed to compute the eigenvalues.



(a) (b)

FIGURE 1. *Linear stability analysis of the steady flow past an oscillating circular cylinder at $Re = 60$. (a) Decoupled modes at $m^* = 10$ (b); Coupled modes at $m^* = 5$. $\lambda_{r,s}$ represents the growth rate associated to structure mode and $\lambda_{r,f}$ represents the growth rate associated to the fluid mode.*

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LINEAR INSTABILITY OF TWO HELICAL VORTICES

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The linear instability of helical vortices is an important topic that finds a wide range of applications including horizontal axis wind turbines and helicopters. The instabilities of such a vortex system can generally be categorized as either displacement instabilities, where the vortex core is shifted, or as core instabilities, where the internal structure of the vortex core is altered [1]. In order to numerically investigate these different instabilities in detail, an accurate representation of the baseflow is needed. Many possible techniques exist to this end, but most tend to prioritize accuracy either inside or outside of the vortex core, which therefore makes them unsuitable for a stability analysis considering the entire flow field.

In the present work, a simple method is presented that yields an accurate representation of the flow inside and outside of the vortex core. The method is implemented in the incompressible Navier–Stokes solver `Nek5000` [2], which uses primitive variables and Cartesian coordinates. Given a local axisymmetric vorticity profile, the method involves projecting this profile onto every grid point in the domain and solving a Poisson-problem to get the vector potential of the velocity. After specifying a frame of reference in which the vortex is approximately steady, the velocity field is integrated in time whereby the vortex cores adapt to the surrounding strain field.

The outlined methodology is herein used to reproduce a recent experiment by Quaranta *et al.* [3], where the stability of two helical vortices is considered. A three-dimensional stability analysis is performed of the corresponding baseflow, which yields an eigenvalue spectrum that features both long- and short-wave instabilities (Figure 1a). The growth rates of the long-wave instabilities are in close agreement with the theoretical ones, which are obtained by adapting the growth rates of the three-dimensional pairing instability of an array of straight parallel vortices to the helical geometry [3, 4].

During the talk, the above mentioned method with which the baseflow is generated will be discussed in detail, alongside the results on the long-wave instabilities. Some findings on the short-wave (elliptic) instability plotted in Figure 1b, will also be presented.

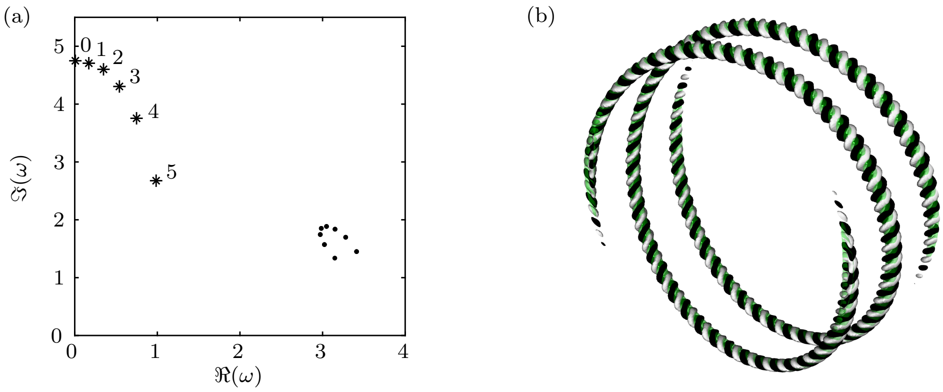

Figure 1: (a) Computed eigenvalues corresponding to long-wave (✳) and short-wave (•) instabilities. The azimuthal wavenumber for the long-wave instability modes are indicated with numbers. (b) Example of an eigenvector corresponding to the short-wave (elliptic) instability. Streamwise component is visualized with white and black contours indicating positive and negative velocities, respectively. The baseflow is shown in green using the λ_2-criterion.

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REDUCED ORDER MODELING OF A WIND TURBINE UNDER YAWED INFLOW CONDITIONS

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Wind turbines are currently often clustered closely together in wind farms which leads to strong wake interaction and reduces the power output of downstream turbines. Lately, yaw misalignment of the first row of wind turbines in wind farms is being explored as a means to optimize the total power output of a wind farm, instead of optimizing the operation of each individual turbine. Yawing wind turbines curbs their power and additionally introduces a deflection into the previously axisymmetric wake. Understanding the mechanisms of wake breakdown is of crucial importance as the wakes of upstream turbines can increase the fatigue loading of a wind turbine significantly, thus shortening its expected lifetime. The wake behind a wind turbine perpendicular to the incoming flow has been extensively analyzed with respect to the stability and the dominant modes leading to wake breakdown. Ivanell *et al.* [1] used Fourier analysis to determine the growth rates of the most unstable modes in a symmetric domain while Sarmast *et al.* used proper orthogonal decomposition (POD) and dynamic mode decomposition (DMD) to distinguish the unstable modes in a full domain. However, for a yawed wind turbine the wake breakdown has yet to be fully understood. The added spanwise forcing imposed on the wake by the yaw causes the wake to develop asymmetrically and leads to a kidney-shaped wake cross-section. In the presented work the wind turbine is modeled after experiments conducted at the Norwegian University of Science and Technology [3]. The wind turbine is yawed by $\gamma = 0°$ and $\gamma = 30°$ and perturbed both using low-turbulence inflow and perturbations introduced at the tip of each rotor blade. To reduce computational cost, the rotor blades are modeled using the actuator line method [4], which computes the blade forces using two-dimensional airfoil theory and tabulated airfoil data, and then includes the blades as body forces in the incompressible Navier–Stokes equations. Using POD the wake of the two studied cases is decomposed into coherent structures which are ranked by their energy content. Figure 1 shows the most energetic POD modes $1-2$ for both the yawed and unyawed case. In the yawed case, the POD modes are located where the streamwise velocity gradient is the highest in the asymmetric wake, coinciding with the observation that the wake destabilizes first at this position. At the conference a comprehensive study of the most energetic modes, their energy and frequency content will be presented.

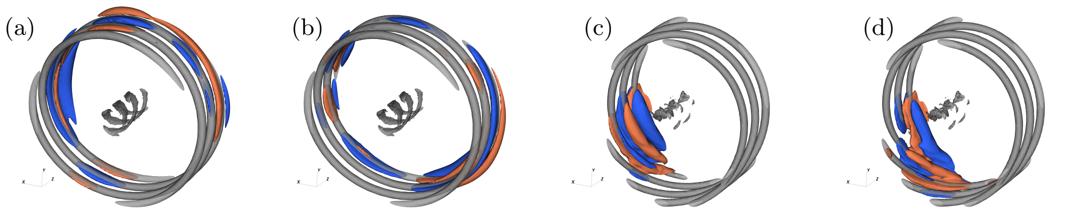

FIGURE 1. *Grey isosurface: Visualization of the zeroth mode (mean flow) using the λ_2-criterion. Blue/orange: isosurfaces of the POD modes $1-2$. (a-b) Yaw angle $\gamma = 0°$ and (c-d) $\gamma = 30°$. (a,c) Mode 1 and (b,d) mode 2. Approximately one period is shown from $6.5 \leq z \leq 7.1$. The z-coordinate is the streamwise direction and the rotor center is located at $(x_c, y_c, z_c) = (0, 0, 5)$.*

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NONLINEAR SECOND-ORDER SENSITIVITY AND INFLUENCE OF OPTIMALLY FORCED STREAKS ON THE KELVIN-HELMHOLTZ INSTABILITY

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We consider the control of nominally two-dimensional (2D) shear flows invariant in the spanwise direction, by three-dimensional (3D) spanwise-periodic perturbations associated with streamwise streaks. For this type of control the first-order sensitivity of the eigenvalues to the control amplitude is zero and the leading order variation of the eigenvalues depends quadratically on the streaks' amplitude A_s as $\mu_{3D} - \mu_{2D} \sim A_s^2 \mu_2$. In many previous studies aimed at understanding the stabilizing mechanism of 3D perturbations and/or explicitly computing the second-order sensitivity μ_2 [3, 2, 4, 1] only the effect of the first spanwise harmonic (the 'linear streaks') of the basic flow distortion was included in the analysis. As the linear streaks are of amplitude A_s, these analyses considered only a first-order perturbation of the linear stability operator $\mathcal{L}_{3D} \sim \mathcal{L}_{2D} + A_s \widetilde{\mathcal{L}}$. When the streaks are forced starting with streamwise vortices, however, the Reynolds stresses induce a spanwise uniform (0th spanwise harmonic) deformation of the basic flow. The inclusion of this $O(A_s^2)$ deformation in the analysis (i.e. $\mathcal{L}_{3D} \sim \mathcal{L}_{2D} + A_s \widetilde{\mathcal{L}} + A_s^2 \overline{\mathcal{L}}$) leads to a 'composite' and consistent second-order sensitivity $\mu_2 = \widetilde{\mu}_2 + \overline{\mu}_2$ (where the additional term $\overline{\mu}_2$ was neglected in previous analyses). In this study we address this issue using as a testbed for the analysis the 3D control of the Kelvin-Helmholtz instability developing in the (2D) parallel mixing layer with hyperbolic-tangent profile. We compare the results obtained using as basic flow the 3D profile $U_{3D}(y,z)$ issued from the nonlinear Navier-Stokes equations without any assumption to (a) those, associated to $\widetilde{\mu}_2$, obtained using a first-harmonic approximation on the basic flow $U_{SA} = U_{2D}(y) + A_s u_1(y)\cos\beta z$, (b) those, associated to $\overline{\mu}_2$, obtained including only the spanwise uniform part of the basic flow distortion $\overline{U}(y) = U_{2D}(y) + \overline{\Delta U}(y)$ and (c) those obtained including only the spanwise varying part of the basic flow distortion $\widetilde{U}(y,z) = U_{2D}(y) + \widetilde{\Delta U}(y,z)$ The main findings, illustrated in Figure 1, can be summarized as follows: (1) the sensitivities based on U_{SA} (magenta) and on $\widetilde{U}$ (red) are very similar, (2) the sensitivities based on U_{SA} and $\widetilde{U}$ have almost always a sign opposite to those based on U_{3D} (black), while the opposite is true for those (blue) based on $\overline{U}$, (3) the composite second order sensitivities $\mu_2 = \widetilde{\mu}_2 + \overline{\mu}_2$ based on the inclusion of the first and zero-th harmonics in the linear operator (green) are in good agreement with those based on U_{3D} (black) for small to moderate values of A_s.

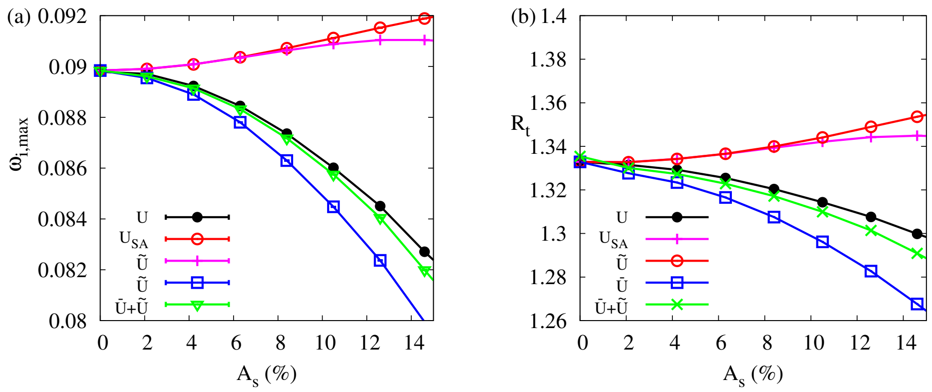

FIGURE 1. *Influence of increasing amplitudes of optimal streaks on (a) the maximum temporal growth rate $\omega_{i,max}(A_s)$ and (b) on critical velocity ratio R_t for the onset of absolute instability. The streaks are streamwise uniform and spanwise periodic with spanwise wavenumber $\beta = 3$ and Re= 1000.*

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DNS OF A SELF-SIMILAR ADVERSE PRESSURE GRADIENT TURBULENT BOUNDARY LAYER

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The efficient design and performance of many engineering systems relies on fluid flows remaining attached to aerodynamic surfaces in regions of adverse pressure gradient (APG). Separation of the boundary layer can potentially result in catastrophic consequences or at best sub-optimal performance. Adverse pressure gradients typically arise due to the presence of convex curved surfaces, such as those on wind turbine blades, turbo-machinery and aircraft wings. These configurations are difficult to systematically study, since the pressure gradient applied to the turbulent boundary layer (TBL) is constantly changing in the streamwise direction [1]. There has been a long history of theoretical, experimental and numerical research into TBLs. However, the vast majority of this research has been centred on the zero pressure gradient (ZPG) case, while many aspects of turbulent structure and appropriate scaling of APG TBL remain largely unresolved. The study of APG turbulent boundary layers (TBL) in an appropriate canonical form is, therefore, of utmost importance to understand the influence of the local pressure gradient. The most appropriate canonical APG TBL to study is arguably one that is self-similar.

A self-similar TBL is defined as one in which each of the terms in the governing equations have the same proportionality with streamwise position [2, 3, 4, 5]. This also indirectly means that the non-dimensional pressure gradient, β, is constant over the domain of interest, where $\beta = 0$ for ZPG, $\beta < 0$ for a favourable pressure gradient (FPG), $\beta > 0$ for an APG, and immediately prior to separation $\beta \to \infty$. This talk will present research that we have been conducting towards setting up such a self-similar APG-TBL at the verge of separation using direct numerical simulations and the structure of this APG-TBL with particular emphasis on intense Reynolds stress structures (uv-structures). Figure 1, the intense Reynolds stress structures (uv-structures) are detached from the wall and that is true for the fine-scale vortex clusters represented by isosurfaces of the second invariant of the velocity gradient tensor (not shown). Most of events are generated in the outer region of APG-TBL where the interaction of the local shear and the Reynolds stress (uv-structures) is of great interest, in comparison with those in zero pressure gradient TBL (ZPG-TBL) and homogeneous shear turbulence (HST), which will be discussed in this talk.

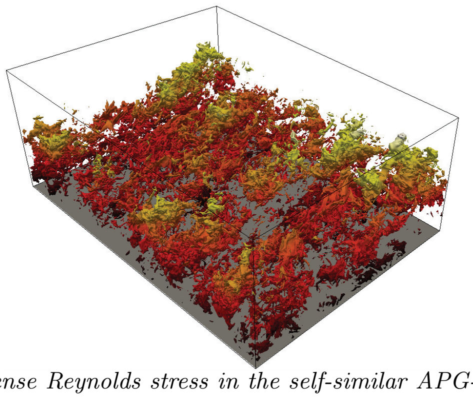

FIGURE 1. *The isosurfaces of intense Reynolds stress in the self-similar APG-TBL. Only the domain of interest* $[L_{\rm DoI}, 0.27L_y, L_z] = [6.4, 3.43, 8.8]\delta_1(x_{\rm DoI})$ *is shown.* $x_{\rm DoI}$ *denotes the beginning of the domain of interest (DoI), where* $Re_{\delta1}(x_{\rm DoI}) \approx 25,000$ *for the strong APG-TBL, and* $L_{\rm DoI} \times L_y \times L_z$ *represents the dimensions of DoI. The isosurfaces are* $-uv/U_e^2 = 0.016$ *and the colourmap of isosurfaces is the distance from the wall (white represents roughly* $3\delta_1$*). The flow is from left to top-right.*

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LARGE-SCALE, STREAKY STRUCTURES IN TURBULENT JETS

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We present results of the experiments performed at the 'Bruit et Vent' anechoic facility, in Poitiers, for a turbulent $M = 0.4$ and diameter-based Reynolds number $Re = 4.2 \cdot 10^5$ jet. These experiments were previously used to study the acoustic efficiency of wavepackets [1] and, for that, stereoscopic TR-PIV measurements were obtained for this jet for a jet cross-section at $x/D = 2$; the mixing layer at this location has a momentum-thickness Reynolds number $Re_\theta = 2.8 \cdot 10^4$. This database is now revisited, using a different approach for the analysis: with the axial velocity fluctuations in the cross-section for several times,, we choose a radial position r and study the velocity field at that specific radius, with pseudo-streamwise and spanwise coordinates (x, z). The spanwise coordinate is obtained by rescaling azimuth as $z = r\phi$, and the x coordinate is obtained using a Taylor hypothesis ($x = tU(r)$), where $U(r)$ is the mean velocity at the chosen radial position. Figure 1(a) shows the velocity field in this plane for $r/D = 0.55$. As can be seen, elongated streaky structures in the streamwise direction , reminiscent of large-scale motions in wall-bounded turbulent flows [2, 3] can be visually identified. The wavenumber spectrum normalised by the momentum thickness (θ) for the fluctuations in Figure 1(a) can be seen in Figure 1(b), for $r/D = 0.55$. The spectrum shows a clear signature of streaky structures in the z coordinate for low axial wavenumbers, peaking at $(k_x, k_z) \approx (0.12, 1.3)$, showing streaky structures with aspect ratio of about 10. Significant energy is found for $k_x \to 0$. The energy peaks around $k_z\theta = 1.33$, which is similar to results from [3], who found $k_z\theta \approx 1$ for a turbulent boundary layer at $Re_\theta = 7705$. The present results show that large-scale motions similar to those observed in wall-bounded turbulence are also observed in a turbulent jet, suggesting that free-shear flows also support such high-energy motions.

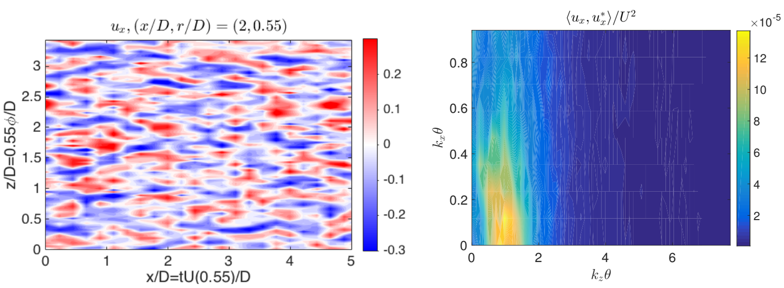

FIGURE 1. *Axial velocity fluctuations over a (x, z) plane (left) and energy spectrum in the (k_x, k_z) domain at $r/D = 0.55$ (right) for a $M = 0.4$ jet. Spectrum normalised by the momentum thickness θ*

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THE LOCAL MODES UNDERPINNING OSCILLATOR BEHAVIOUR IN JETS

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We consider a variety of jet flows in which oscillator behaviour is observed: subsonic turbulent jets interacting with a sharp edge; impinging subsonic and under-expanded supersonic jets; free under-expanded supersonic jets that 'screech'. Experiments are performed in which the observed tonal dynamics are characterised with respect to changes in the key parameters (Mach number, nozzle pressure ratio, jet-plate or jet-edge distance). The oscillator behaviour is then studied in the framework of the families of jet modes recently studied by Towne *et al.* [1] and Schmidt *et al.* [2], which include those originally discovered by Michalke [3] and later considered by Tam & Hu [4].

We find that many of the observed phenomena are underpinned by the said families of discrete jet modes. Figure 1 shows an example from Jordan *et al.* [5], who considered the interaction of high-Reynolds-number subsonic jets with a sharp edge, representative of interactions that may occur on aircraft equipped with new-generation Ultra-High-By-Pass-Ratio engines. Strong tones are observed in nearfield pressure measurements, and these exhibit an interesting $St - M$ distribution of power-spectral-density peaks, shown in the right-hand plot ($St = fD/U$ is the Strouhal number, f being frequency, D the jet nozzle diameter and U the exit velocity; $M = U/c$ is the Mach number, with c the ambient speed of sound). This distribution can be reproduced with good accuracy by considering resonance between downstream-travelling Kelvin-Helmholtz modes and the upstream-travelling jet modes of Towne *et al.* [1], all of which are modelled using a cylindrical vortex-sheet (left-hand plot). We will show that these modes also explain many features of impinging and screeching jets.

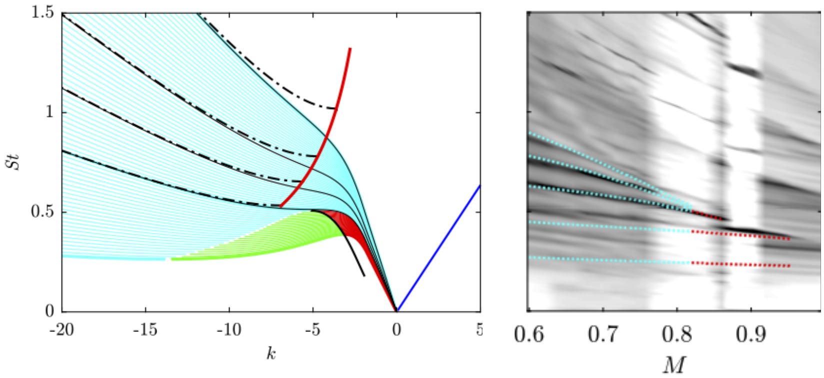

FIGURE 1. **Jet-edge interaction tones**. **Left:** *Cylindrical vortex-sheet dispersion relations in range,* $0.6 \leq M \leq 0.97$*, showing downstream-travelling (blue, green) and upstream-travelling (red, cyan) branches. Black dashed lines: dispersion relations (top to bottom:* $M = 0.6$, 0.7, 0.75 *&* 0.82*) for porous-walled duct, which model upstream-travelling vortex-sheet modes at frequencies above the solitary thick red line, where they have zero reflection coefficient in the jet exit plane. Modes of the red upstream-travelling branches become evanescent at the saddle point identified by the thick black line. Resonance cut-off observed in data can be understood in terms of these features.* **Right:** *Comparison of data (grayscale, showing power-spectral density of measured hydrodynamic pressure) with resonance predictions (cyan and red dotted lines) based on coupling between downstream-travelling Kelvin-Helmholtz modes (blue in left plot) and upstream-travelling jet modes (cyan and red in left plot).*

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SUCCESS AND OPEN QUESTIONS IN THE MODELLING OF JET TURBULENCE THROUGH STATISTICAL STATE DYNAMICS

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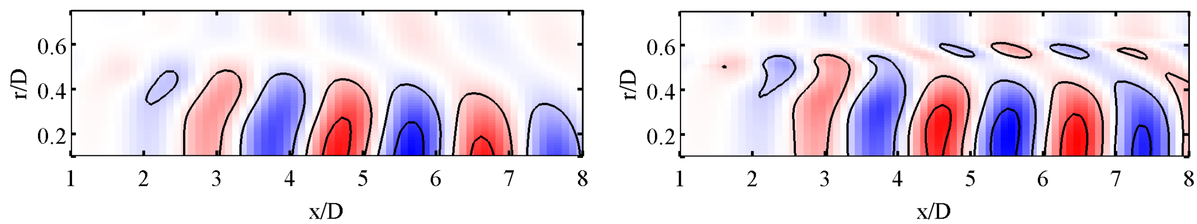
The prevalence of coherent structures in jet turbulence at high Reynolds number, and more specifically their resemblance to linear instability wavepackets developing in the time-averaged mean flow, has long been observed and discussed. However, still in the recent review by Jordan & Colonius [1], a clear theoretical argument for this resemblance seemed elusive. Over the course of the last two years, the conceptual link between these two has been clarified to a large degree, in particular due to the research activities at Caltech and CTR [2] and in the French-Brazilian CoolJazz project [3].

It has thus been established that singular modes of the mean flow resolvent operator correspond, in a justifiable way, to eigenmodes of the cross-spectral density (CSD) tensor of a turbulent jet. Similar inferences have been made in recent years for related shear flows, like boundary layers [4] and backward-facing steps [5, 6], but all these applications are rooted in the theory of statistical state dynamics, developed by Brian Farrell and his co-workers in the context of atmospheric flow and climate modelling.

Farrell [7] draws the conclusion that "turbulence in shear flow can be essentially understood as determined by quasi-linear interaction occurring directly between a spatial or temporal mean flow and perturbations. This result provides a profound simplification of the dynamics of turbulence (...) and shows that the role of nonlinearity in the dynamics of turbulence is highly restricted."

We will present evidence for this quasi-linear character of large-scale jet turbulence, by comparing experimentally measured CSD eigenmodes, for a jet at $Re = 460\,000$, to the dominant singular modes of the linear resolvent (see figure 1). Loose ends of the current theoretical model will be discussed, with a focus on the necessity of closure strategies for the remaining nonlinearity.



(a) experiment: leading CSD eigenmode
(b) linear analysis: leading singular mode

FIGURE 1. *Comparison of a coherent turbulent structure in the experiment with the leading singular mode of the mean flow resolvent operator, both at $St = 0.4$.*

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MIXING ENHANCEMENT THROUGH OPTIMALLY CONTROLLED JET BIFURCATION

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Increasing jet mixing properties is interesting in many industrial applications, ranging from fuel injection into combustion chambers to the cooling of electronic circuits. In this study, we rely on the dynamics of the large-scale structures of a jet – the vortex rings – to increase mixing. Even though these structures arise naturally, by prescribing an axisymmetric forcing at ω at the inlet, one is able to control the frequency of these vortices and thus, their spacing. Therefore, if an additional helical forcing at $\omega/2$ is added, the consecutive vortices are alternatively shed on one side and on the other side. Then, with mutual induction, the vortex rings bifurcate, entraining the jet (Fig. 1). By increasing the spreading of the jet, this enhances dramatically its mixing. Lee and Reynolds [1] and Parekh *et al.* [2] first investigated this phenomenon and developed this bifurcation scenario. A comprehensive review of early work on the subject can be found in Reynolds *et al.* [3].

However, besides parametric optimization (Tyliszczak *et al.* [4]), no study has ever intended to optimize globally the jet bifurcation. Here, following the scenario mentioned earlier, we aim to find the optimal helical forcing that shifts the most the first vortices off the axis to further trigger the bifurcation. The displacement of these first vortices can be assumed small enough to remain linear, greatly reducing the optimization cost. The base flow for the optimization is a time-periodic axisymmetric array of vortices at $Re = 2000$ obtained through axisymmetric forcing of the jet [5]. After developing an appropriate displacement norm for the vortices, we set up an optimization framework for periodic flows, for which traditional methods (resolvent…) are not applicable. We then plug our optimal forcing into $3D$-simulations and compared the results to traditional forcing (Fig. 2): the optimal forcing triggers earlier upstream a larger and more defined (i.e. symmetrical) bifurcation, leading to a more pronounced jet flaring and better mixing. By carrying this study for different axisymmetric Strouhal numbers (ranging from 0.35 to 0.80), we found that optimizing the forcing largely increases the Strouhal band at which bifurcating jets can be observed (usually $[0.40, 0.60]$), as we have been able to trigger bifurcation at all Strouhal studied.

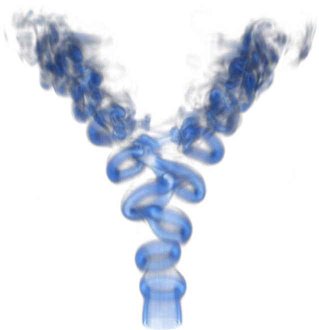
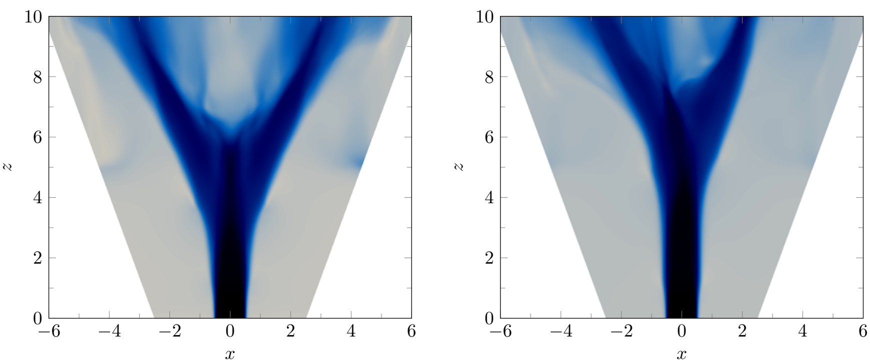


FIGURE 1. *Instanataneous $3D$-view of the vorticity magnitude of the optimal bifurcating jet (1% helical forcing) for $Re = 2000$ and $St = 0.50$.*



(a) Cut with optimal forcing.

(b) Cut with “traditional” forcing.

FIGURE 2. *Cut of the mean axial velocity along the bifurcation plane for bifurcating jets at $Re = 2000$ and $St = 0.50$. The helical forcing amplitude is 1%.*

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THE ROLE OF ACOUSTICS MODES IN JET AND WAKE STABILITY

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Throughout the research of jet stability acoustic modes have been frequently cited. In 1984, Michalke identified what he called "irregular modes" [1], whose properties were later identified with incompressible evanescent waves. Tam [2] & Hu identified three families of instability waves, two of which had acoustic characteristics to them and were only found in specific frequency ranges, particularly in subsonic regimes. In supersonic regimes these waves appear to be reflected by the jet shear layer. Tam & Hu also found similar results in supersonic channel flows [3]. Acoustic modes were also proposed as a feedback mechanism for the generation of tonal noise in impinging jets [4]. More recently, Towne et al [5] found trapped waves within the core of subsonic compressible jets and Jordan [6] proposed that trapped waves are responsible for the appearance of loud tonal noises when a sharp plate is placed in the near pressure field.

In this article we study the mechanisms by which acoustic modes are formed within the core of jets, both in the compressible and incompressible regimes, by mean of an analytical model based on a double vortex sheet (DVS). We demonstrate the existence of modes that behave like acoustic waves in ducts (*duct modes*) in specific regions of the parameter space, as illustrated in figure 1. Analysis of the model explains why the acoustic modes are only found for specific frequencies, showing how they are distorted outside those frequencies. We show that these distorted acoustic modes interact with the K-H modes forming a saddle point, thus establishing a connection between the acoustic modes and the absolute,or global, stability of jets, clarifying the physical mechanism by which incompressible jets are destabilized when heated. We expand the analogy to the stabilization of incompressible wakes due to heating.

Finally, the transition between idealized vortex sheets and finite thickness shear layers is analyzed, and the origins of 'column' and 'shear layer' modes is clarified. We show that the former are related to acoustic duct modes and the latter to a finite thickness vortex sheet effect. The impulse response of a jet leads to a wave packet, highlighting regions where the 'column' and 'shear layer mode' are dominant. By changing the frame of reference we construct wave packets for the whole family of double shear layer flows, including: wakes, with and without back flow, and jets, with and without flight effects.

The difference in symmetry of the unstable mode in a jet (symmetric) and a wake (asymmetric) is explicitly recovered, and a sensitivity analysis elucidates the reasons why a thicker shear layer leads to an absolute instability of an ideal isothermal wake but not for a jet.

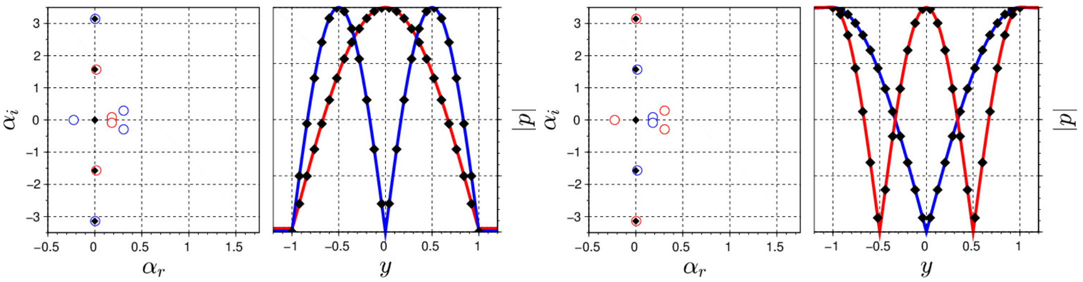

FIGURE 1. *Comparison between wave numbers and modes between the DVS and an acoustic duct for a jet (left) and a wake (right). Blue and red indicate symmetric and a asymmetric DVS modes, diamonds indicate the duct modes. Pressure eigenfunction correspond to the wave numbers close to $i\pi/2$ and $i\pi$. Results for $\omega = 0.1$, and $M = 10^{-2}$.*

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CHARACTERIZING SURFACE-STEP EFFECTS ON TRANSITION

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Surface nonuniformities can significantly alter the boundary-layer transition location through modifications to the underlying instabilities causing transition. These modifications can be linked to changes in the instability excitation or to alterations of the instability growth characteristics. In Tollmien-Schlichting (TS) dominated transition, spanwise uniform steps have been shown to act as local growth modifiers. If the growth modifications associated with the critical modes causing transition can be quantified, this can be correlated to the movement of transition. One way to isolate these effects is to experimentally determine the transition movement and the associated TS-wave frequencies for a given surface step. Linear stability analysis can then be used to back out the associated growth modification required for the identified modes to cause the transition movement. This approach was successfully used in an earlier study to determine the change in critical N-factor as a function of step height, as shown in Figure 1 for a backward-facing step [1]. These results were for a single step in the neighborhood of the branch-I neutral point for the instabilities.

In this paper, we consider results from new studies aimed at generalizing the earlier work in two important directions. First, the sensitivity to streamwise position is investigated to determine if the results can be generalized to regions far away from the neutral point location. Second, the superposition of two steps is investigated as a generalization of the results to spanwise protuberances or spanwise gaps.

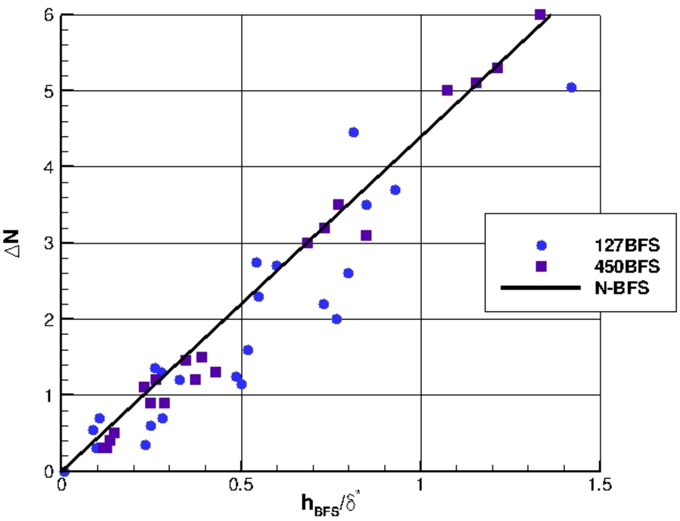

FIGURE 1. *Reduction in TS-wave critical N-factor due to a backward-facing step (after [1]). Results for steps at two different streamwise positions (x=127mm and x=450mm) near the critical-mode neutral point (x ≈300mm).*

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AMPLITUDE METHOD OF LAMINAR-TURBULENT TRANSITION PREDICTION ON THE SWEPT WING

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Transition location in the boundary layer on the swept wing is rather sensitive to surface roughness and level of free-stream turbulence [1,2]. Conventional e^N method based on computation of linear amplification coefficients of instability modes can not describe dependence of transition Reynolds number from these factors. Alternative amplitude method of cross-flow dominated transition prediction based on computation of amplitudes of steady and traveling cross-flow instability modes is developed here. Initial amplitudes of disturbances in the boundary layer are found by means of decomposition of free-stream turbulence and surface roughness into a set of periodical waves and consideration of generation of Eigen modes in the boundary layer by these elementary waves via non-localized receptivity mechanism [3]. Subsequent evolution of steady and non-steady modes with continuous spectra and random phases is computed by simplified non-linear PSE-method. Transition location is determined as a place where the sum of amplitudes of steady and non-steady modes reaches a threshold value 0.34. This transition criterion was recently introduced from analysis of experimental data for wide range of surface roughness and turbulence level in [4].

The amplitude method developed reproduces satisfactorily the dependence of transition location on the Reynolds number, the surface roughness, and free-stream turbulence level observed in experiments [1,2] (see Figure 1,a). Moreover, it gives the evolution of almost all measurable characteristics of the base flow and perturbations in the transition region. In particular, it describes saturation of the growth of steady and traveling modes and the deformation of the velocity profiles in the boundary layer initiated by these modes (see Figure 1, b, c). This amplitude method of transition prediction is rather simple and does not require large amount of computations. It can be used in future for operative prediction of transition location instead of e^N method.

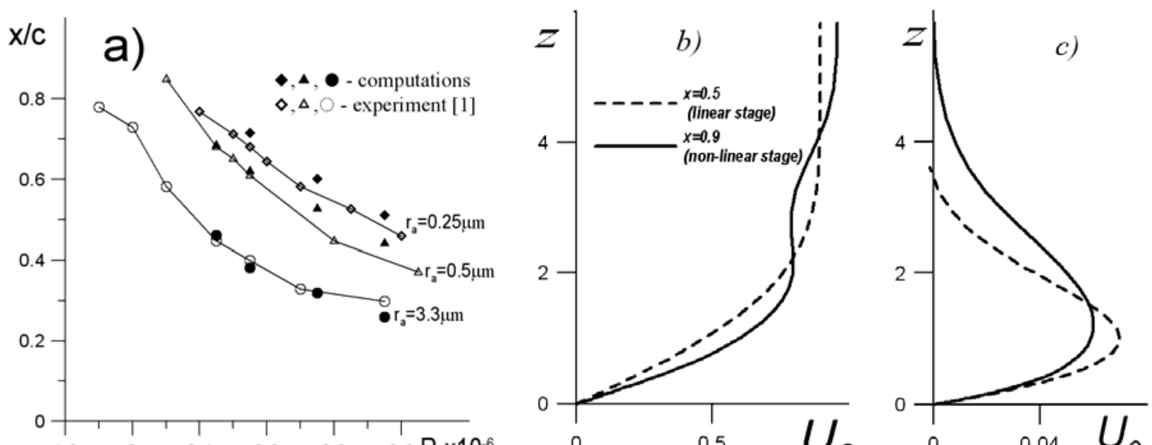

Figure 1. Transition location at the swept wing as function of Reynolds number: comparison of computations with experiment [1] (a). Deformation of profiles of tangential (b) and cross-flow (c) velocity in the boundary layer in the transitional region (computations).

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IS IT POSSIBLE TO COMBINE GOOD AERODYNAMICS AND LOW ACOUSTIC NOISE IN THE SLAT?

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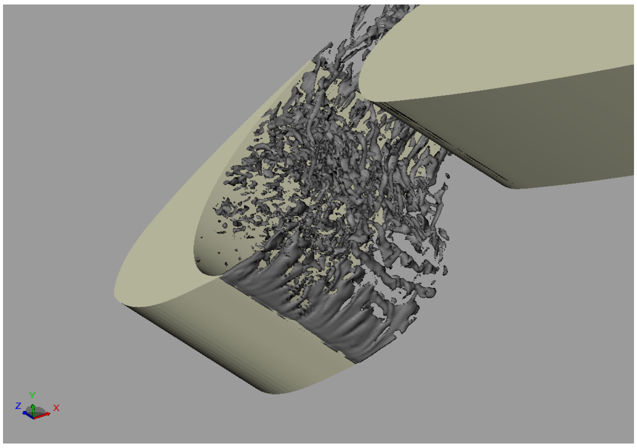
Slat is a high lift devices placed at the leading edge of wings which acts by reducing the main element suction peak at high AoA. It Is an important noise generator and raises important environmental concerns. The spectrum of slat noise is dominated by low-frequency narrowband peaks. The research to be presented initiated by acoustic wind tunnel experiments with microphone arrays and beamforming techniques. A number of slat configurations was tested. Numerical simulations were then carried for selected cases and good agreement with acoustic results was obtained. Next, the numerical data were used to investigate the noise generation mechanisms. Proper Orthogonal Decomposition revealed that the tonal peak frequency selection mechanism is associated with Kelvin-Helmholtz instability resembling open cavity Rossiter modes. The noise generation is associated with 2D structures. The path and evolution of the POD structures explain that two-dimensionality is enhanced by optimal aerodynamic design of the slat.



THE NEW USP-EESC CLOSED-SECTION WIND-TUNNEL

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Experimental investigations on laminar-turbulent transition and on flow-induced sources of sound require an adequate environment of low-turbulence flow and low-background acoustic noise. Many wind-tunnels have been developed for the study of aeroacoustic noise, whereas advances in noise measurement techniques for anechoic wind-tunnels were achieved in the last decades [1, 2, 3, 4]. Moreover, the research community possess installations with capabilities suitable for boundary-layer stability and transition studies [5], and low-turbulence tunnels applied for turbulence and transition researches [6]. This paper introduces the new low-turbulence, low-background-acoustic-noise, closed-circuit wind-tunnel of the University of Sao Paulo, Sao Carlos School of Engineering (USP-EESC), Fig. 1.

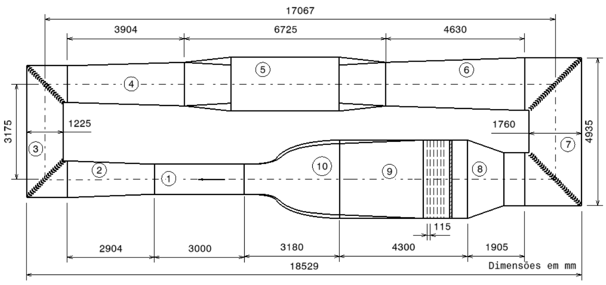

Figure 1: Wind-tunnel aerodynamic circuit. (1) test-section, (2) diffuser 1, (3) corners 1 and 2, (4) diffuser 2, (5) fan, (6) diffuser 3, (7) corners 3 and 4, (8) diffuser 4 / wide angle diffuser, (9) settling chamber and (10) contraction.

The facility includes features to improve the flow-quality through the reduction of turbulent and acoustic disturbances, which suit the facility for pure aerodynamic characterization and for aeroacoustic experiments, as a special contraction shape and a long settling chamber containing a honeycomb and up to seven nylon screens. A rail and drawer mechanism is employed to dock the screens and honeycomb on the settling chamber and to facilitate maintenance/removal procedures, including individual adjustment of the screens tensioners and its cleaning. Turning vanes are filled with insulation, aiming at reduction and absorption of unwanted noise, whereas dense foam were installed on the corners walls, floor and ceiling to provide secondary means of background noise suppression.

The wind-tunnel has a closed test-section of 1000×1000 mm cross-sectional area and 3000 mm length, with $7:1$ contraction ratio. A variable-speed DC motor powers a 13-bladed axial fan and the top freestream speed in the test-section currently goes up to 30 m/s. Preliminary results show the flow turbulence level at 20 m/s freestream speed is approximately 0.13%. The instrumentation includes Particle Image Velocimetry, hot-wire anemometry and phased array microphone systems. Following steps will include a full flow quality characterization, after the operationalization of a traverse gear for the hot-wire anemometry system, which enables turbulence level and flow uniformity measurements at different points in the test-section.

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THE EFFECT OF A BULB SEAL ON THE SOUND EMITTED BY THE SLAT ANALYZED BY PROPER ORTHOGONAL DECOMPOSITION

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The development of high bypass turbofans, used in commercial airplanes, decreased substantially the noise contribution of motors in last decades, which increased the relative airframe contribution to noise. Significant part of this noise during approximation manuevers are due to high-lift devices, slat and flap. Slat noise is relevant as is spreads along almost whole wingspan [1]. Most of studies related to slat noise, however, consider clean surfaces. Seal slats have excrescences on its surface such as anti-icing tubes and seals. Studies considering a slat cove seal place in the slat cove are presented by [2] and show the seal can affect significantly the sound emission. The seal promotes a strong modification on the flow in the slat cove [3]. Depending on the seal position a secondary bubble is created enhancing the recirculation of the turbulence in the bubble and increasing noise emission. At other positions the sound and the turbulence recirculation is reduced. Previous work [4] studied the slat cove flow using POD technique and related the narrow band peaks of the slat sound with Kelvin-Helmholtz vortices. Here a similar approach is applied to the slat cove flow with seal revealing several aspects of the dynamics of this flow. The analysis includes different seal positions and sizes and different AoA. As an example, preliminary POD results of this study are presented in Figure 2, showing that seal at this position increases the coherent structures at earlier stages of the mixing layer. This could be related to higher noise levels observed in the experiments [2].

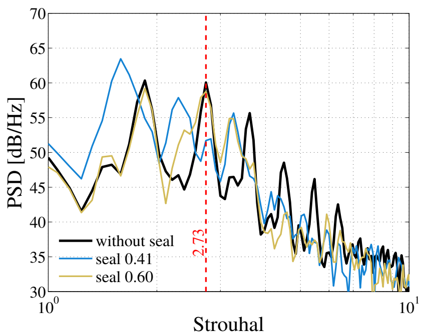
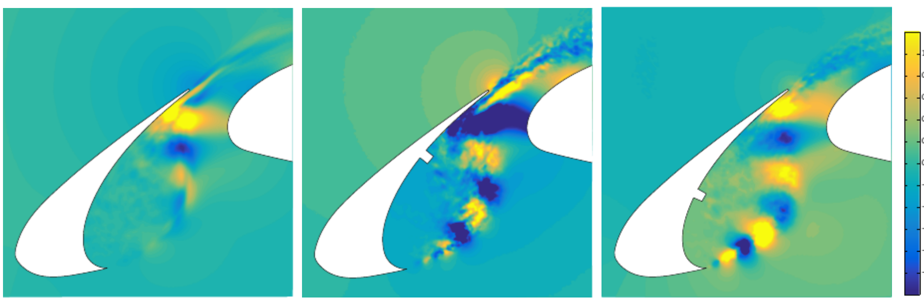


FIGURE 1. *Slat farfield noise spectra for geometries without and with cove seal.*



(a) no seal (b) seal 0.41 (c) seal 0.60

FIGURE 2. *Real part of first POD mode. Farfield pressure inner product (pressure vector). Frequency* 1240 Hz *(*$St = 2.73$*), see Figure 1.*

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REDUCED ORDER MODELS TO ANALYSE WAVEPACKETS IN TURBULENT FLOW OVER AN AIRFOIL

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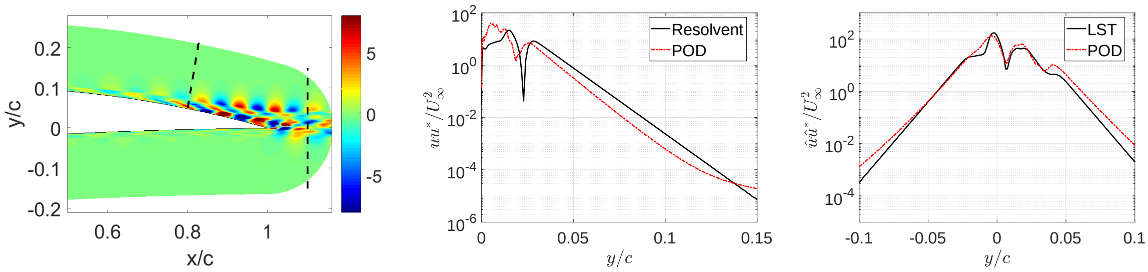
The turbulent flow over a NACA 4412 airfoil with an angle of attack $AoA = 5°$ was analysed using an incompressible direct numerical simulation (DNS) at chord Reynolds number of $Re_c = 4 \cdot 10^5$ [1]. Snapshots of the flow field were analysed using Proper Orthogonal Decomposition (POD) in frequency domain, in order to extract the dominant coherent structures of the flow [2]. Homogeneity in the spanwise direction allows application of a Fourier decomposition in span prior to POD, and focus is given to two-dimensional disturbances, known to be most relevant for aeroacoustics [3]. The leading POD mode show coherent structures forming a hydrodynamic wave, with significant amplitudes in the trailing-edge boundary layer and in the wake, as exemplified in Figure 1(a). To model coherent structures in the turbulent boundary layer, the optimal harmonic forcing and the associated linear response of the flow will be obtained using the singular value decomposition of the linear resolvent operator [4]. Such resolvent analysis is used to show if the leading POD modes can be associated to most amplified, linearised flow responses. Furthermore, coherent structures in the wake are modelled as the Kelvin-Helmholtz mode from linear stability theory (LST).

Figure 1 show results obtained using a Strouhal number $St = 7.93$, defined as $St = fc/U_\infty$, where f is the frequency, c is the aerodynamic chord and U_∞ is the free stream velocity. Figure 1 (a) shows the POD result for streamwise velocity fluctuations u; one can see the coherent structures propagating through the airfoil surface in the boundary layer, with more pronounced amplitudes near the trailing edge. Figures 1(b) and (c) show comparisons of the leading POD mode in the boundary layer and in the wake, respectively, with reduced-order models: optimal response from resolvent analysis for the boundary layer, and Kelvin-Helmholtz mode from LST for the wake. The good agreement in both cases shows that these models allow an accurate description of the relevant flow physics in the trailing-edge region.



(a) POD Mode 1 (b) $x/c = 0.8$ (c) $x/c = 1.1$

FIGURE 1. *Results for $St = 7.93$ and streamwise velocity u, (a) leading POD mode, (b) comparison between POD and resolvent analysis at $x/c = 0.8$ and (c) comparison between POD and LST at $x/c = 1.1$. The black dashed lines in (a) correspond to $x/c = 0.8$ and $x/c = 1.1$, which are the positions analysed in (b) and (c), respectively.*

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LINEAR-QUADRATIC, OUTPUT-FEEDBACK FLOW CONTROL BASED ON REDUCED ORDER MODELS

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In flow dynamics, the discretised system of differential equations is normally of high order. The control of such systems by means of the Linear Quadratic-Gaussian (LQG) approach is numerically possible. However, the observation of all degrees of freedom becomes difficult to implement in a practical application. The high dimensionality of the fluid system requires a step of model reduction. Model reduction techniques based on first principles such as global modes [1] or balanced truncation [2] exploit the underlying dynamics of the system for extracting a reduced projection basis. Unfortunately, having access to the linearised system can be a difficulty in itself when the number of degrees of freedom becomes very large or when experimental data are considered. *A posteriori* techniques become then well suited when collecting an ensemble of realisations of the system permitting to build a basis representative of a subset of states that the system will be further allowed to explore. The choice of the realisations will of course affect the basis. Without any special care, this characteristic is a drawback of the procedure, but it can be exploited for keeping only the states actually active in the instability or oscillation mechanisms. Several reduction techniques exist. The Proper Orthogonal Decomposition (POD) [3] is the most widely used, since it extracts the orthonormal basis minimising the reconstruction error of the realisations.
Even with a POD-based reduced order model (ROM), full ROM-state observation can also be challenging for such a complex system, and may result in high-order controllers. Instead, output feedback in the sense of the Linear Quadratic Regulator (LQR) offers the great advantage of predefining *a priori* the order of the controller [4]. In this paper we apply this concept to augment the stability of a Navier-Stokes flow. Additionally, a new algorithm is proposed to optimise both the gain matrix and the position of the sensors in the sense of the specified quadratic performance index. The technique will be demonstrated for the flow control problem with a rotating cylinder, depicted in figure 1.

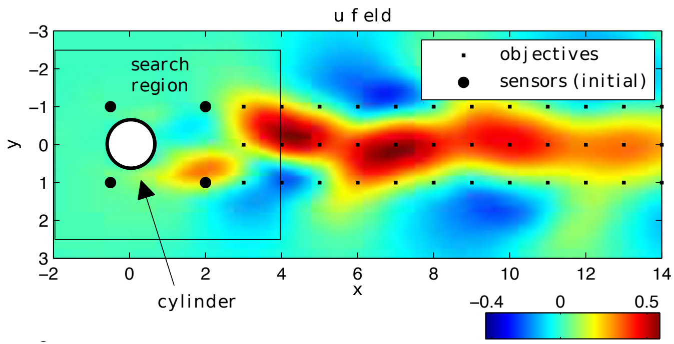

FIGURE 1. *Definition of search region and objectives in the performance index.*

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IMPLEMENTATION OF BOOSTCONV TO ACCELERATE THE OPPOSITELY-SHIFTED SUBSPACE ITERATION (OSSI) METHOD FOR APPROXIMATE OPTIMAL CONTROL WITHOUT MODEL REDUCTION

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The Oppositely-Shifted Subspace Iteration (OSSI) method proposed and described in [1] (to which the reader is referred for details) provides a promising new method for approximate optimal control of large linear (or, linearized) systems, such as those derived from flow stability problems, while bypassing the intermediate (and, as it turns out, unnecessary) step of open-loop model reduction, which can oft be problematical. The OSSI method accomplishes this via:

1) iteratively computating Schur vectors corresponding to the least-stable of the stable eigenvalues of the (block 2×2) Hamiltonian matrix Z corresponding to the optimal control problem in question,

2) block decomposing the top and bottom halves of this set of Schur vectors as, respectively, X and P (corresponding to the state and adjoint components of the Schur vectors computed), then

3) approximately solving the corresponding Algebraic Riccati Equation by forming the product $W = PX^+$, where $()^+$ denotes the Moore-Penrose psuedoinverse.

The OSSI family of method achieves step (1) by implementing subspace iterations with "opposite shifts"; that is, by marching the state part of the approximate Schur vectors one direction in pseudotime, while marching the adjoint part of the approximate Schur vectors the opposite direction in pseudotime. This simple idea tends to identify quickly the central Schur vectors of the Hamiltonian matrix Z as the subspace iterations proceed.

In the case that all of the Schur vectors corresponding to the stable eigenvalues are found via this approach, X is square, $X^+ = X^{-1}$, and $W = PX^{-1}$, so the full optimal control problem is solved. In the case that only a subset of the these Schur vectors are found, the Riccati equation in question (and, the corresponding optimal control problem) is only approximately solved by the value of W computed. The choice to include in this computation the Schur vectors corresponding to the least-stable of the stable eigenvalues is based on the hypothesis that, often, these Schur vectors include the components that are the "most important" in the PDE control problems of interest. By performing the "approximating" step during the Riccati solution, rather than beforehand during a separate model reduction step (based, typically, solely on open-loop criteria), the control objective itself is accounted for during the approximation.

The BoostConv method proposed and described in [2] (to which, again, the reader is referred for details) provides an accelerated iterative procedure, inspired by Krylov-subspace methods, to solve certain PDE-based subproblems, such as those involved in computing the Schur vectors described above. BoostConv is based on the minimization of a residual norm at each iteration step with a projection basis updated at each iteration rather than at periodic restarts like in the classical GMRES method. This powerful idea is able to stabilize any dynamical system without increasing the computational time of the original numerical procedure used to solve the governing equations. Moreover, it can be easily inserted into a pre-existing relaxation procedure, such as OSSI, with a call to a single black-box subroutine.

The application of BoostConv to accelerate OSSI (that is, subspace iteration methods with opposite shifts implemented) for the approximate solution of flow stability and control problems will be discussed at the conference.

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OPTIMAL GUIDANCE OF BUOYANCY-CONTROLLED BALLOONS IN TURBULENT FLOWS USING A NON-QUADRATIC OBJECTIVE AND DISCONTINUOUS ACTUATION

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Meteorological forecasting of extreme phenomena like hurricanes could strongly benefit from sensor-laden vehicles (typically, balloons) that could be guided to remain in the geographical area of interest for a few days at a time, rather than a dozen minutes or so as is the case with today's free-flying balloons and dropsondes. A promising energy-sparing technology consists of balloons with mechanically-adjustable volume [1] which can reversibly provide increased or decreased buoyancy and move to an altitude where the prevailing wind blows in the desired direction. In previous work we have shown that a) guidance of balloons in specified orbits, and even in orderly formations, can numerically be achieved in realistic hurricane simulations [2], and b) a control objective proportional to the absolute value of the inflation rate, more representative of required electric power than its square, leads to the choice of a discontinuous control law where the balloon is left most of the time at a constant volume and only inflated or deflated for abrupt short periods (ideally, in a discontinuous way) [3, 4].

Whereas the optimal control of a linear system, disturbed by white noise, towards a quadratic objective can be mathematically proved to require a linear feedback control and to lead to gaussian statistical distributions of all the quantities involved, a non-quadratic objective removes all these nice mathematical properties, and in particular the optimal controller can no longer be assumed to be linear even when the system to be controlled is linear. In this context, result (b) mentioned above was achieved by extremely simplifying the dynamics, to the point that the entire turbulent flow was replaced by a white noise with its spectral amplitude as the only tunable parameter. A more realistic approximation must at least involve a spectrum that more closely resembles a turbulent flow. It is an almost forgotten result that the lagrangian correspondent of the Kolmogorov $k^{-5/3}$ spatial spectrum of turbulent energy is a temporal spectrum proportional to ω^{-2} [5]. An ω^{-2} power spectrum implies an ω^{-1} amplitude spectrum, and is quite easy to achieve in a lumped numerical simulation by passing white noise through an integrator.

The simplest abstract model of the motion of a balloon in a hurricane is then a two-degree-of-freedom mechanical system disturbed by once-integrated white noise. The power spent to inflate and deflate the balloon is proportional to the absolute value of vertical velocity, and its integral is the energy to be minimized. This nonquadratic objective makes even such a simplified system nontrivial to analyze; its optimization implies solving a partial differential Fokker-Planck equation for the statistical distribution function of position and velocity, a mathematical technique often referred to as dynamic programming. The numerical solution of this problem and the resulting discontinuous, stepwise optimal control strategies will be discussed at the conference.

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ROLE OF KLEBANOFF MODES IN ACTIVE CONTROL OF LAMINAR SEPARATION BUBBLES

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Previous studies have shown that active flow control that exploits the shear-layer instability is both effective and efficient for controlling laminar separation bubble at low-Reynolds numbers. In addition to reducing the extent of the separated flow region, Embacher & Fasel [1] have shown that control using 2D disturbance with a properly chosen frequency and amplitude can suppress the secondary absolute instability and thus delay transition, and may even relaminarize the flow downstream of reattachment.

For airplane applications, it is reasonable to assume that surface roughness and free-stream turbulence (FST) can provide the disturbance environment that influence laminar-turbulent transition. Both have to be considered when investigating separation and separation control for practical applications. Building on our previous research, the present work was aimed at investigating whether FST affects the stunning effectiveness of the 2D harmonic excitation for transition delay and relaminarization. Towards this end, very low-amplitude isotropic FST velocity and vorticity fluctuations are introduced at the inflow boundary of the computational domain and a response of separated flow to the forcing is investigated.

The effect of the forcing on the LSB without and with FST is demonstrated in Figure 1 which shows instantaneous perspective views of iso-surfaces of the λ_2-criterion colored by the streamwise velocity together with the contours of the spanwise-averaged spanwise vorticity in $x-y$ plane. The visualizations for the zero FST cases reveal that the flow is completely "locking on" to the forcing signal and that spanwise "rollers" are shed at the forcing frequency. Moreover, transition to turbulence is delayed significantly. In fact, transition does not occur within the integration domain and the flow remains completely laminar in the entire domain. In contrast to the zero FST case where 3D disturbances have extremely low amplitude (due to the very low "numerical noise") upstream of the separation location, the amplitude level of the 3D disturbances is elevated in the presence of FST (orders of magnitude higher than in the zero FST case). As a result, the primary vortex cores become modulated sinusoidally in the spanwise direction due to the secondary instability of the periodic controlled baseflow as shown in Figure 1b. Contours of spanwise-averaged spanwise vorticity (plotted in $x-y$ plane in Figure 1b) reveal that in the presence of FST, the strong spanwise structures break-up into smaller scales soon after their first appearance such that transition to turbulence is initiated immediately. In fact, prior to transition only three spanwise structures are still visible. We have found that the observed lateral wavelength of the modulation is identical to the spanwise spacing of the Klebanoff modes, i.e. $\lambda_z = L_z/7$. "Clean" simulations where the FST is negligible (zero FST) is extremely difficult to accomplish in practical wind tunnel experiments. However, in extremely low FST levels in free flight, the relaminarization strategy may still be advantageously employed. The presented results are an important finding as they advance our fundamental physical understanding of the effect of FST on the separation and separation control.

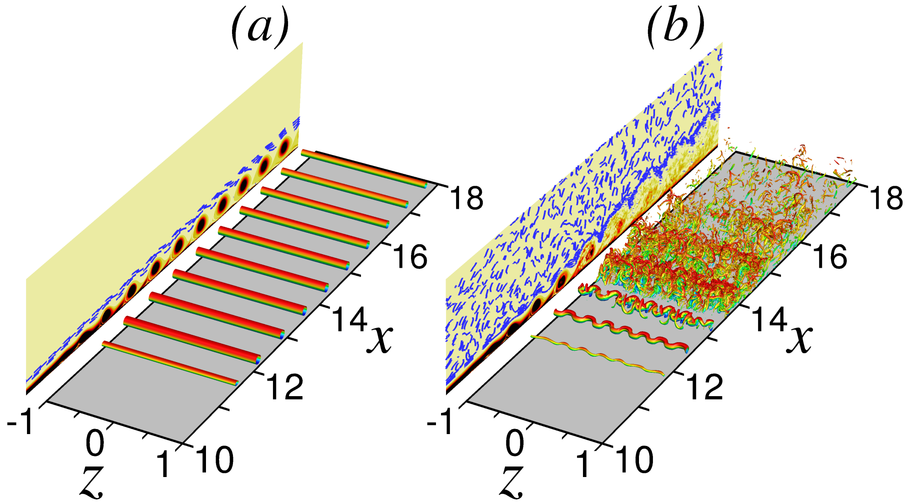

FIGURE 1. *Instantaneous flow visualization for controlled flow. (a) zero FST; (b)* $Tu = 0.005\%$.

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EXPERIMENTAL STUDY ON ESTIMATION AND CONTROL OF NATURAL TS-WAVES

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This work reports on the development of a novel physics-based (white) compensator method for estimation and control of TS-waves. Wind tunnel experiments have been conducted on a natural laminar flow over a flat plate in low-freestream turbulence conditions. Based on recent work [1], an LQG compensator is designed and synthesised from the linearised Navier-Stokes equations. The approach combines state-space discretisation of the governing equations [2] with balanced truncation to synthesise a reduced-order compensator. A Kalman filter is used to estimate the effect of upstream disturbances based on pressure information from a single microphone embedded in a cavity within the body of the plate. The estimates obtained from the Kalman filter are compared with experimental data obtained from PIV. Preliminary results are shown in figures 1 and 2, which compare the reconstructed pressure signal and the estimated perturbation field with the measured data. The Kalman filter is able to filter the measurements and to estimate the spatio-temporal behaviour of the natural perturbation field in the presence of unknown disturbances. This information is used within a state-feedback control law to cancel the perturbations using a surface DBD plasma actuator. The performance of the compensator is analysed in comparison with open-loop continuous forcing. An additional reduction of 60% in the r.m.s. of the pressure fluctuations is measured 9 cm downstream of the plasma actuator.

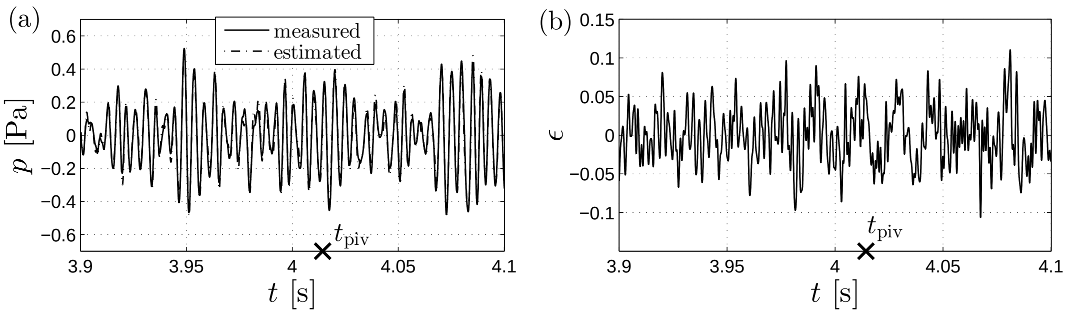

FIGURE 1. *Filtering of the microphone signal. (a) The measured pressure and the estimated pressure. (b) The estimation error.*

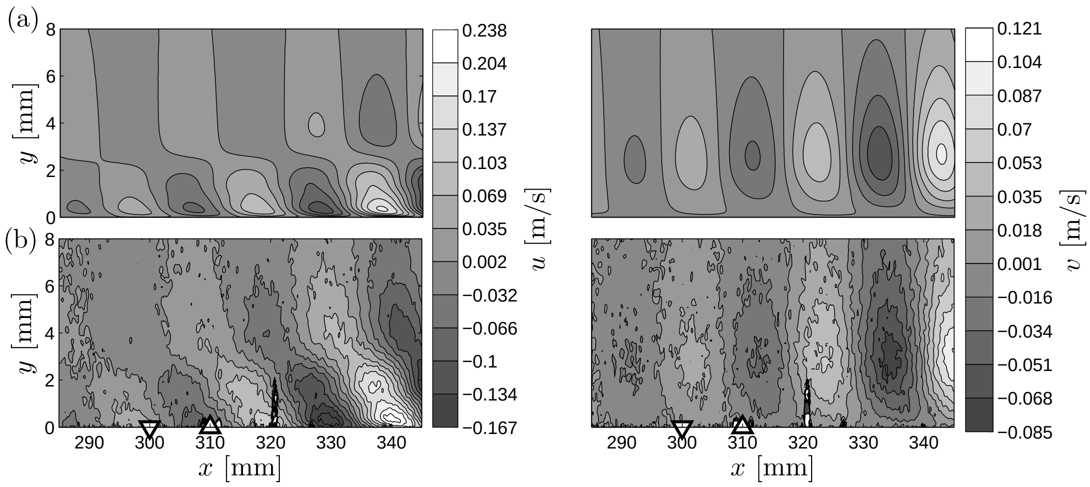

FIGURE 2. *Estimation of the natural perturbation field at an instant in time ($t = t_{piv}$). (a) Estimated using a linear Kalman filter. (b) Measured with PIV. The triangles indicate the position of the microphone (▽) and the plasma actuator (△).*

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