ERCOFTAC
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12th ERCOFTAC SIG 33 Workshop

Progress in Flow Instability, Transition and Control

Certosa di Pontignano, Italy, June 19-21, 2017

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Organisers:

Flavio Giannetti (Univ. Salerno)
Ardeshir Hanifi (KTH)

Monday, June 19

13:00		Lunch
14:30	Michael Gaster	THE INFLUENCE OF SANDPAPER ROUGHNESS ON THE GROWTH OF TOLLMIEN-SCHLICHTING WAVES *M. Gaster*
14:50	Hui Xu	DESTABILISATION AND MODIFICATION OF TOLLMIEN-SCHLICHTING DISTURBANCES BY A THREE DIMENSIONAL SURFACE INDENTATION *H. Xu, S. Mughal, E. Gowree, C. Atkin, S. Sherwin*
15:10	Emma Cooke	MODELLING THE EFFECT OF SMALL EXCRESCENCES ON WING PERFORMANCE *E. Cooke, S. Mughal, R. Ashworth, S. Sherwin*
15:30	Heinrich Lüdeke	Direct TS-wave Simulation in a laminar boundary layer over suction-slots *H. Luedeke*
15:50	Johannes Zahn	STUDY OF BOUNDARY-LAYER SUCTION AT A JUNCTURE FOR SUSTAINED LAMINAR FLOW *J. Zahn, U. Rist*
16:10		Coffee Break
16:30	**Peter Jordan**	**MEAN-FLOW STABILITY FRAMEWORKS FOR MODELLING, ESTIMATION AND CONTROL OF COHERENT STRUCTURES** *P. Jordan, A. Cavalieri*
17:15	David Fabre	THE WHISTLING JET INSTABILITY : EXPERIMENTAL INVESTIGATION AND GLOBAL STABILITY MODELLING OF A BIRCALL *D. Fabre, S. Marragou, R. Longobardi, D. Lo Jacono1, P. Bonnefis, B. Fry, V. Citro*
17:35	Léopold Shaabani Ardali	SUBHARMONIC INSTABILITY MECHANISMS OF THE BIFURCATION PHENOMENON IN HARMONICALLY FORCED JETS *L. Shaabani Ardali, D. Sipp, L. Lesshafft*
17:55	Lutz Lesshafft	THE MULTIFOLD EFFECTS OF DENSITY ON THE INSTABILITY OF JETS, PLUMES AND PREMIXED FLAMES *L. Lesshafft, R.V.K. Chakravarthy, P. Huerre*
18:15	Traneh Sayadi	EFFECT OF COMBUSTION ON THE FREQUENCY RESPONSE OF JETS IN CROSSFLOW *P. Sashittal, T. Sayadi, P. Schmid*

Tuesday, June 20

08:30	**Dan Henningson**	**Dynamical systems theory and bypass transition in boundary-layer flows** *Dan S. Henningson*
9:15	Onofrio Semeraro	STABILITY AND SENSITIVITY ANALYSIS OF COHERENT STATES IN PLANE COUETTE FLOWS *O. Semeraro, S. Cherubini, F.Giannetti, L. Brandt, P. De Palma*
9:35	Simon Illingworth	LINEAR ESTIMATION OF LARGE-SCALE STRUCTURES IN CHANNEL FLOW AT Re_tau=1000 *S. J. Illingworth, J. P. Monty, I. Marusic*
9:55	Roman Grigoriev	FORECASTING TURBULENCE USING THE GEOMETRY OF INVARIANT SOLUTIONS: EXPERIMENTS, THEORY, AND NUMERICS *R. Grigoriev, B. Suri, J. Tithof, M. Schatz*
10:15	Paolo Luchini	UNIVERSALITY OF THE TURBULENT VELOCITY PROFILE *P. Luchini*
10:35		Coffee break
10:55	Marco Costantini	EXPERIMENTAL ANALYSIS OF STEP-INDUCED TRANSITION IN COMPRESSIBLE HIGH REYNOLDS NUMBER FLOW *M. Costantini, S. Risius, C. Klein*
11:15	Juan Alberto Franco Sumariva	NOLOT-LNS: BOUNDARY-LAYER INSTABILITY ANALYSIS FOR SURFACES WITH PERTURBATIONS USING HARMONIC-LNS *J. A. Franco Sumariva, S. Hein*
11:35	Yury Kachanov	EFFECTS OF SURFACE STEPS ON CROSSFLOWDOMINATED SWEPT-WING BOUNDARY-LAYER TRANSITION IN PRESENCE OF UNSTEADY AND STEADY FREESTREAM VORTICES Y.S. Kachanov, V.I. Borodulin, A.V. Ivanov, J.D. Crouch
11:55	Mattias Brynjell-Rahkola	STABILITY AND SENSITIVITY OF A FALKNER{SKAN{COOKE BOUNDARY LAYER WITH DISCRETE SURFACE ROUGHNESS *M. Brynjell-Rahkola, N. Shahriari, P. Schlatter, A. Hanifi, D. S. Henningson*

12:15	Jeffrey Crouch	GAP EFFECTS ON CROSSFLOW DOMINATED TRANSITION IN THE PRESENCE OF SURFACE ROUGHNESS AND FREE-STREAM TURBULENCE *J.D. Crouch, V.I. Borodulin, A.V. Ivanov, Y.S. Kachanov*
12:35	Guillaume Bégou	NAVIER-STOKES COMPATIBLE FORMULATION OF A DATABASE APPROACH FOR LAMINAR-TURBULENT TRANSITION PREDICTION: EXTENSION TO CROSSFLOW INSTABILITIES *G. Bégou, H. Deniau, O. Vermeersch and G. Casalis*
13:00		Lunch
14:00	**Aimee Morgans**	**SIMULATION AND FEEDBACK CONTROL OF BLUFF-BODY WAKES EXHIBITING BI-MODALITY** *A. S. Morgans, O. Evstafyeva, L. Dalla Longa, G. Rigas*
14:45	Mathieu Marant	OPTIMAL STREAKS IN THE WAKE OF A BLUNT-BASED AXISYMMETRIC BLUFF-BODY AND CONTROL OF VORTEX SHEDDING *M. Marant, C. Cossu, G. Pujals*
15:05	Franco Auteri	CONTROL OF RECIRCULATION BUBBLE IN NLP FRAMEWORK *D. Montagnani, F. Auteri*
15:25		Coffee break
15:45	Ubaid Qadri	AN ASYMPTOTIC APPROXIMATION TO THE NONLINEAR FREQUENCY RESPONSE *U. A. Qadri & P. Schmid*
16:05	Carlo Cossu	SECOND ORDER SENSITIVITY, GINZBURG-LANDAU EQUATION AND THE STABILIZING MECHANISM OF STREAKS ON 2D ABSOLUTE AND GLOBAL INSTABILITIES *C. Cossu*
16:25	Alessandro Bucci	ROUGHNESS-INDUCED TRANSITION BY QUASI-RESONANCE OF A VARICOSE GLOBAL MODE *M. A. Bucci, D. K. Puckert, C. Andriano, J.-Ch. Loiseau, S. Cherubini, J.-Ch. Robinet and U. Rist*
16:45	Jack Brewster	SHAPE OPTIMISATION FOR LINEAR STABILITY *J. Brewster, M. P. Juniper*
17:05		San Gimignano

Wedensday, June 21

09:00	**Nigel Peake**	**TRAILING EDGE NOISE AND THE AEROACOUSTICS OF THE OWL** *N. Peake*
9:45	Peter Schmid	SYNCHRONIZATION IN N-PERIODIC ARRAYS OF FLUID SYSTEMS *P.J. Schmid, M. Fosas de Pando, N. Peake*
10:05	Christopher Davies	ABSOLUTE AND CONVECTIVE INSTABILITY OF WAVEPACKET STRUCTURES IN OSCILLATORY BOUNDARY LAYERS *C. Davies, A. Ramage, C. Thomas*
10:25	Scott Morgan	STABILITY OF OSCILLATORY ROTATING-DISK BOUNDARY LAYERS *S. Morgan, C. Davies*
10:45	Loïc Jecker	A LAMINAR KINETIC ENERGY MODEL BASED ON THE KLEBANOFF MODE DYNAMICS *L. Jecker, O. Vermeersch, H. Deniau, G. Casalis, E. Croner*
11:05		Coffee break
11:25	Matthew Juniper	EXPLOITING EXTREME SENSITIVITY TO PASSIVELY CONTROL THERMO-ACOUSTIC INSTABILITY *M. Juniper, H. Yu, N. Jamieson*
11:45	Simone Camari	FLOW CONTROL OF WEAKLY NON-PARALLEL FLOWS BASED ON ADJOINT METHODS *S. Camarri, F. Viola, E. Pezzica, G. V. Iungo, F. Gallaire*
12:05	Jörn Sesterhenn	ADJOINT-BASED BOUNDARY-DRIVEN CONTROL AND OPTIMISATION OF COMPRESSIBLE FLOWS *M. Lemke, J. Reiss, J. Sesterhenn*
12:25	Jose Miguel Perez Perez	ON LINEAR STABILITY ANALYSES OF HYPERSONIC LAMINAR SEPARATED FLOWS IN A DSMC FRAMEWORK: RESIDUALS ALGORITHM AND THE LEAST DAMPED GLOBAL MODES *O. Tumuklu, J. M. Perez, V. Theofilis, D. Levin*
12:45	Johann Moulin	A DISTRIBUTED LAGRANGIAN MULTIPLIER/FICTITIOUS DOMAIN APPROACH FOR COUPLED FLUID-STRUCTURE STABILITY ANALYSIS *J. Moulin, P. Bonnet, J.-L. P ster, M. Carini, O. Marquet*
13:05	Fabrizio Morlando	A CARTESIAN METHOD FOR COMPUTING THE NUMERICAL JACOBIAN OF TURBULENT FLOWS *F. Capizzano, F. Morlando*
13:25		Lunch

THE INFLUENCE OF SANDPAPER ROUGHNESS ON THE GROWTH OF TOLLMIEN-SCHLICHTING WAVES

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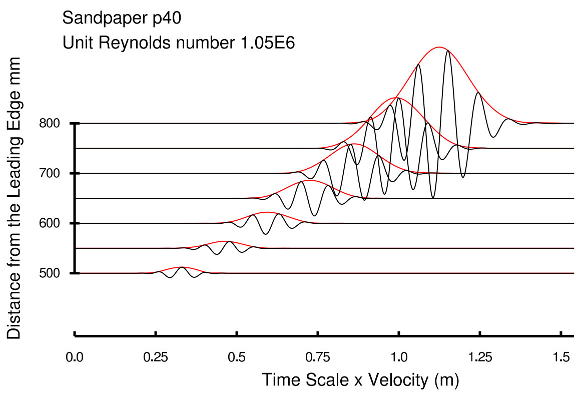
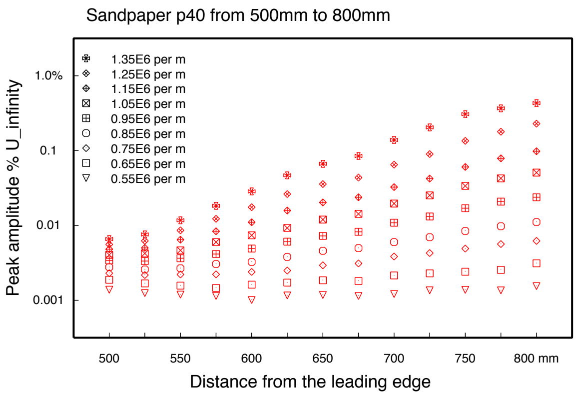
The aircraft industry is increasing concerned about the effects of surface roughness on transition. In particular, attempts are being made to design for small regions of natural laminar flow on flying surfaces and engine nacelles to reduce drag. Although there is a substantial amount of experimental data that can help estimate the effects of surface roughness on the transition location it has not been possible to incorporate these into the E-to-N transition prediction method now favoured for design. Experimental measurements of the amplification rates of artificially generated instability waves over various sandpaper surfaces have been made in the City University Low turbulence wind tunnel. The results of this study will be incorporated into a transition tool for estimating 'N-Factors'.The low turbulence level of the free-stream in the wind tunnel was below 0.007 percent, enabling the forced wave system to remain relatively uncontaminated by system noise.

All experiments were carried out at zero pressure gradient on a flat plate model that had rectangular panels inserted having various sandpapers glued on. Excitation of the wave system was provided by a small acoustic source mounted on the back of plate coupled to the flow through a 0.5mm dia hole. The exciter was driven by short duration pulses that created wavepackets in the boundary layer. Ensemble averaging of the hot-wire signals was used to improve the signal-to-noise of the records. The tunnel set-up had a three-degree of freedom hot-wire traverse that was computer controlled as was the tunnel speed and control of the excitation mechanism and data acquisition. Hot-wire records of the wavepackets were obtained over a range of flow unit Reynolds numbers and sandpaper grit sizes.

One figure shows an example of the wavepacket evolution over a panel covered with p40 grit sandpaper at one unit Reynolds number. These measurements were made at the outer edge of the boundary layer in the region of the outer maximum of typical Tollmien-Schlichting waves. A set of records obtained at various Reynolds numbers provided the amplitude evolutions shown on the second figure. The amplitudes plotted are the peak value of the wavepacket envelope.



Waveform & Envelope over Roughness Panel



Peak amplitudes at various Reynolds numbers

Local amplification rates were obtained from the slopes of these data over the central region of the panel for the three roughnesses at all Reynolds numbers. On the very rough surfaces the highest Reynolds number data could not be used because the disturbances became too large and showed non-linear behaviour or even breakdown to turbulence. The accumulated results from these experiments has been reduced to a simple expression for the added value of amplification rate in terms of the roughness grit size.

The data set was acquired at zero pressure gradient and at virtually zero Mach number. It is clearly important to discover what modifications are needed to cater for more realistic flows.

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DESTABILISATION AND MODIFICATION OF TOLLMIEN-SCHLICHTING DISTURBANCES BY A THREE DIMENSIONAL SURFACE INDENTATION

Hui Xu[1,2], Shahid M. Mughal[1], Erwin R. Gowree[3], Chris J. Atkin[3], Spencer J. Sherwin[2]
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We consider the influence of a smooth three-dimensional (3D) indentation on the instability of an incompressible boundary layer by linear and nonlinear analyses. The numerical work was complemented by an experimental study, to investigate indentations of approximately 11 and 22, δ_{99} width at depths of $45\%, 52\%$ and 60% of δ_{99}. For these indentations a separation bubble confined within the indentation arises. Upstream of the indentation, spanwise-uniform Tollmien-Schlichting (TS) waves are assumed to exist, with the objective to investigate how the 3D surface indentation modifies the two-dimensional (2D) TS disturbance. Numerical corroboration against experimental data reveals good quantitative agreement. Comparing the structure of the 3D separation bubble to that created by a purely 2D indentation, there are a number of topological changes particularly in the case of the widest indentation; more rapid amplification and modification of the upstream TS waves along the symmetry plane of the indentation is observed. For the shortest indentations, beyond a certain depth there are then no distinct topological changes of the separation bubbles and hence on flow instability. The destabilising mechanism is found to be due to the confined separation bubble and is attributed to the inflectional instability of the separated shear layer. Finally for the widest width indentation investigated ($22\delta_{99}$), results of the linear analysis are compared with direct numerical simulations. A comparison with the traditional criteria of using N-factors to assess instability of properly 3D disturbances reveals that a general indication of flow destabilisation and development of strongly nonlinear behaviour is indicated as N=6 values are attained. However $N-$factors, based on linear models, can only be used to provide indications and severity of the destabilisation, since the process of disturbance breakdown to turbulence is inherently nonlinear and dependent on the magnitude and scope of the initial forcing.

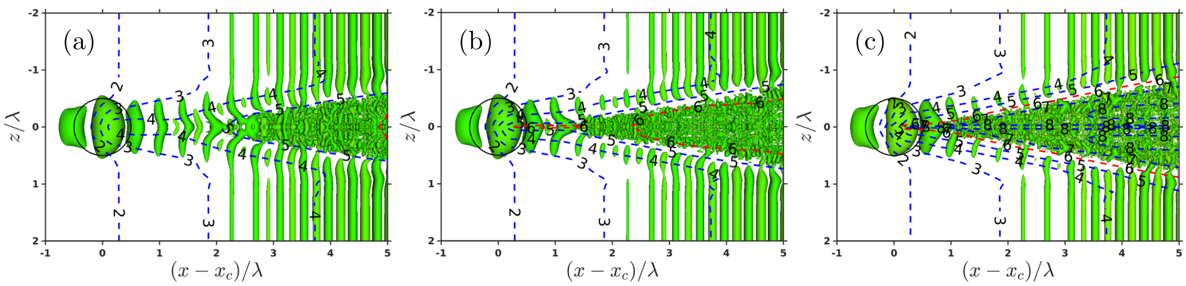

FIGURE 1. *Comparison of laminar-turbulent transition onsets for different h in a large domain. The parameter λ=81mm. (a) h=1.620mm; (b) h=1.895mm; (c) h=2.170mm. The iso-surfaces are generated by pressure fields. The red dashed lines indicate the contour lines with the transition criteria N-factor 6. The solid circles indicate the indentation boundaries $r = \lambda/2$.*

References

[1] H. Xu, S. M. Mughal, E. R. Gowree, C. J. Atkin and S. J. Sherwin. Destabilisation and Modification of Tollmien-Schlichting Disturbances by a Three Dimensional Surface Indentation. *under review.*

MODELLING THE EFFECT OF SMALL EXCRESCENCES ON WING PERFORMANCE

Emma Cooke[1], Shahid Mughal[2], Richard Ashworth[3], Spencer Sherwin[4]
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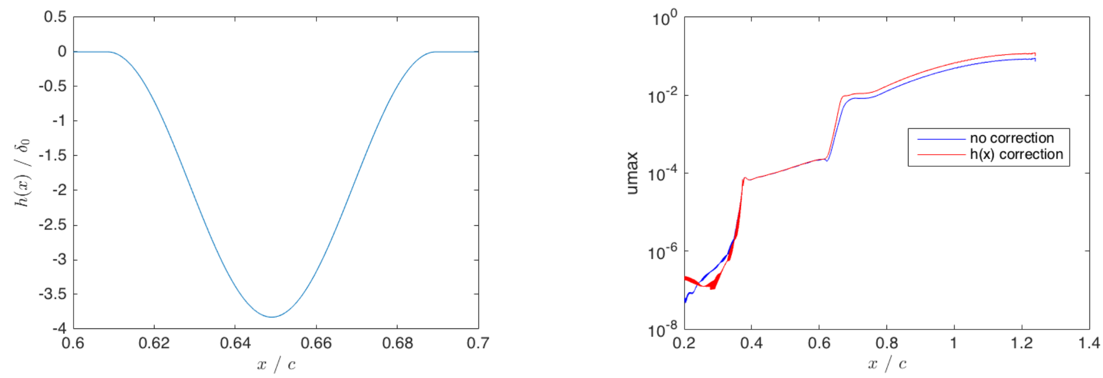
The leading cause of laminar to turbulent transition within the boundary layer of a wing is due to surface imperfections; otherwise known as excrescences. These excrescences could be rivets, due to damage of the wing resulting in small surface indentations, or more specifically where joins occur between two different surfaces, such as leading edge to wing box junction tolerances.

The transition process, although heavily researched, is highly complex and still not fully understood; especially with regard to receptivity. Receptivity is the process of disturbances entering the boundary layer and resonating with the basic flow. This may be though acoustic noise, free-stream turbulence, surface roughness or a combination, causing the perturbation to grow and eventually trip the flow to turbulence. The method adopted by industry for predicting the transition location and linear growth of perturbations is the e^N method. Although this provides reasonably good predictions, and at a fraction of the cost of a DNS solution, it completely neglects important receptivity processes and any nonlinearities. Precisely how linear disturbances are modified as they convect over quite short-scale surface imperfections is an area not well investigated. This is since Parabolised Stability Equations (PSE) models are unable to model such features due to the minimum step-size restriction for achieving stable converged PSE solutions. The objective of this PhD work is to develop advanced models which are inexpensive and better capture the underlying physics of such short-scale variations in the base flow, including where laminar separation bubbles arise.

Contrary to the popular Linear Stability Theory (LST), the Linearised Navier-Stokes (LNS) equations capture much more of the complex flow physics such as, non-parallel effects, surface curvature, capability of modelling weakly nonlinear mode interaction and crucially incorporate receptivity stages of disturbance generation. An excrescence capturing LNS model has been developed and will form the basis of the presentation. Some initial results of the LNSE modelling of a two dimensional excrescence will be discussed. Various test cases have been constructed to compare the original LNS code with the excrescence incorporated LNS model, one being the incompressible 2D surface indentation case as shown in figure (1). Comparisons with DNS solutions and experimental data will be made. Future work consists of trialling this for a swept wing geometry () Saeed et. al. [1]) and further analysis of the effect of separation bubbles on convecting disturbances.



(a) Wall profile

(b) U_{max} profiles, excrescence location at $\approx 0.65\ x/c$

Figure 1: Dimple case $h(x)$ profile and corresponding growth of perturbation for a frequency of 12kHz in a flat plate incompressible regime. Suction generated Tollmien-Schlichting wave around 0.37 x/c.

References

[1] T. I. Saeed, S. M. Mughal, and J. F. Morrison. “The Interaction of a Swept-Wing Boundary Layer with Surface Excrescences”. In: *AIAA* (2016).

DIRECT TS-WAVE SIMULATION IN A LAMINAR BOUNDARY LAYER OVER SUCTION-SLOTS

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Hybrid laminar flow control of TS-waves in attached boundary-layers is generally carried out by suction through a micro-porous surface and a subsequent stabilization of the laminar flow. This micro porousness is usually realized by laser drilled holes with diameters below 100 micron. More advanced manufacturing methods will allow the application of suction by continuous slots in a thin metal-foil, applied on a supporting sub-structure. These slots will allow the same suction-rate at much smaller streamwise slot-dimension, less equivalent surface roughness, and a better production-quality. The use of slots for transition control is not a new approach, it was already proposed by Pfenninger in the 1970's to reduce attachment-line instabilities [1].
The slot-geometry allows 2D-simulations of TS-waves by DNS in given boundary layers and investigations of the interaction between amplified modes and perturbations from the suction-channels. By this way, an applicable number of slots per wavelength and the allowed slot-diameter which does not substantially perturb the TS-modes can be determined. The occurrence of such interactions at deep gaps, resulting from acoustic resonances, was recently shown by Zahn [2] for TS-waves on laminar wings.
For the following study, direct TS-wave simulations are carried out in a prescribed Blasius boundary-layer over suction-slots. The development of acoustic waves, generated by the perturbation-flow of the slots, has been demonstrated by using a high-order implicit Navier-Stokes solver in compressible formulation (Figure 1). The interactions of these perturbations with amplified TS-waves will be investigated by subsequent time-accurate simulations of the flow-field. In addition, the damping of the chosen TS-modes can be directly provided from a post-processing of the results, without an approximation of distributed suction-flow. Furthermore the time-resolved physics inside the slots, including resonance phenomena, are a direct outcome of the study, as demonstrated by Zahn [2].
Simulations at different grid resolution and slot-number are planned for realistic Reynolds-numbers on a flat plate with fully resolved slot-geometries. Slot diameter and corresponding wall-thickness from wind-tunnel models will be modified to demonstrate the impact of these parameters on the interaction-scenario. Comparisons of the suction-rate with steady calculations of cylindrical 3D-holes will be carried out as well.

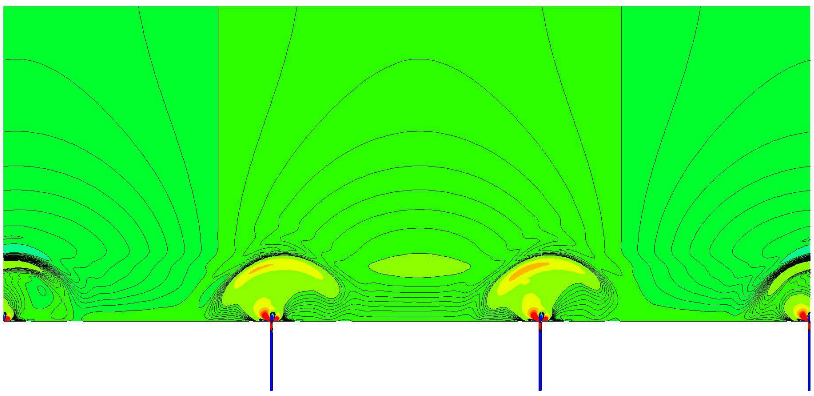

FIGURE 1. *interaction of a temporally growing TS-wave (contour-lines) with acoustic perturbations (color-coded wall-normal velocity) emitted from three suction-slots.*

References

[1] Pfenninger W. *Laminar flow control, laminarization.* Agard report R654, Springer, Berlin, 1977.
[2] Zahn J., and Rist U. *Impact of Deep Gaps on LaminarTurbulent Transition in Compressible Boundary-Layer Flow.* AIAA JOURNAL **54,**, No. 1, 2016.

STUDY OF BOUNDARY-LAYER SUCTION AT A JUNCTURE FOR SUSTAINED LAMINAR FLOW

Johannes Zahn[1], Ulrich Rist[2]
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In present aircraft designs, low fuel consumption is a decisive goal. Due to smaller friction losses compared to turbulent flow, sustained laminar flow on wing surfaces offers a significant potential. However, small steps and gaps that can occur at the juncture between two surface elements adversely influence the location of laminar-turbulent transition. Hence, methods are needed that can eliminate their negative impact on transition. In order to cover the gap and smooth the step occurring at a juncture, fillers as well as tapes are used so far, see e.g. Havar et al. [1]. However, their application is complex with regards to e.g. maintenance and repair of surface elements. In this work, the focus is on the use of local suction to reduce a juncture's impact, see Zahn & Rist [2].

Therefore, two-dimensional, direct, numerical simulations (DNS) are used to study the impact of active and passive suction on laminar-turbulent transition. Suction is applied through the juncture's gap in front of the juncture's forward-facing step that is located in a flat-plate boundary-layer flow without streamwise pressure gradient. A steady base flow is used with a Mach number of 0.6. Subsequently, Tollmien-Schlichting waves are introduced by suction and blowing at the wall, and their growth over the surface imperfection is evaluated by N factors. The investigated step heights h are in the range of one to two times of the local displacement thickness of the smooth flat plate ($3\,000 < Re_h < 6\,000$). Both, sharp and rounded step corners are investigated. Cases with and without suction are compared with the smooth flat plate without suction based on ΔN factors according to the e^N method. Thus, it is shown that suction is capable to compensate or even overcompensate the negative impact of different steps on laminar-turbulent transition. The work concludes with a configuration that allows passive suction in front of a forward-facing step. Here, a significant reduction of the N factor compared to the smooth flat plate without suction is possible. Further estimations indicate that a net drag reduction may be possible as well. Future studies may be dedicated towards profound validations of the applicability of both active and passive suction at junctures on aerodynamic surfaces.

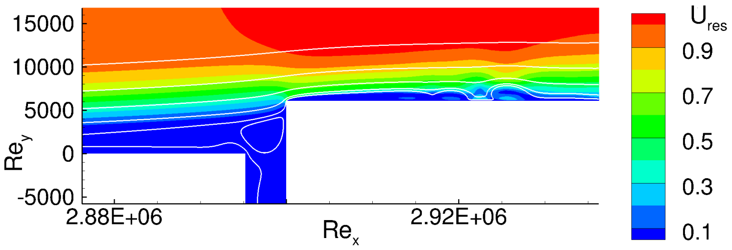

FIGURE 1. *Snapshot of unsteady flow for $Re_h = 6\,000$ and sharp step, no suction.*

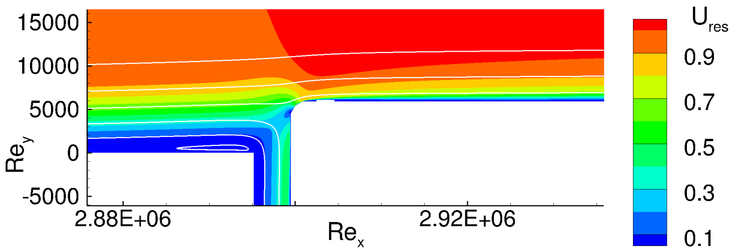

FIGURE 2. *Base flow for $Re_h = 6\,000$ and rounded step, strong suction.*

References

[1] T. Havar, M. Geistbeck, M. Meyer, 0. Rohr, T. Meer. Connection Arrangement for Connecting two Profiled Elements in an Aerodynamically Smooth Manner, Method for Producing Said Connection Arrangement, and Device for Carrying out the Method. *World Intellectual Property Organization WIPO*, Internationales Patent, WO 2013/000447 A1 , 2013.

[2] J. Zahn, U. Rist. Active and Natural Suction at Forward-Facing Steps for Delaying Laminar-Turbulent Transition. *AIAA Journal*, DOI: 10.2514/1.J055122, 2016.

MEAN-FLOW STABILITY FRAMEWORKS FOR MODELLING, ESTIMATION AND CONTROL OF COHERENT STRUCTURES

Peter Jordan[1], André V. G. Cavalieri[2]
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[2]*Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil*

Suspected since the early 1960s, it is now clear that the operator obtained by linearising the Navier-Stokes equations about a turbulent mean flow is a pivotal element for the description of coherent structures in many shear flows. But depending on the modelling objective, the role that the linear operator plays, and the manner therefore in which it is used, may vary. For problems of real-time estimation and control in convectively unstable systems, the operator may best take its place at the heart of a homogeneous linearised system of equations, where unsteadiness is introduced at an upstream boundary. This is also the case for the predictive modelling of supersonic jet noise and the sound radiated by interaction between a turbulent jet and the trailing edge of an airfoil. Where subsonic jet noise is concerned, on the other hand, due to the necessity of greater modelling finesse, the linear operator must be considered under the action of turbulent forcing—the resolvent of the operator then becomes the key element. This is likely to be the case in other situations where higher-order statistical moments are of interest. The reasons behind these different modelling scenarios will be discussed and illustrated by means of a series of examples.

THE WHISTLING JET INSTABILITY : EXPERIMENTAL INVESTIGATION AND GLOBAL STABILITY MODELLING OF A BIRCALL

David Fabre[1], Sylvain Marragou[1], Raffaele Longobardi[2,1], David Lo Jacono[1], Paul Bonnefis[1], Benjamin Fry[1], Vincenzo Citro[2], Flavio Giannetti [2] and Paolo Luchini[2]
[1] *IMFT, Toulouse, France*
[2] *DIIN, Universit di Salerno, Italy*

In this work we explore the so-called hole-tone phenomenon, namely the sound generated by a flow passing through two successive constrictions. This generic situation is encountered in familiar situations such as the whistle of a steam kettle or the birdcalls used by hunters, as well as in many industrial appliances. Early works by Sondhaus, Rayleigh and Bouasse have explored this situation. Very recently, Henrywood & Agarwal have conducted detailed experiments for the configuration of a tea kettle. More recently, Bonnefis and Fabre et al. investigated this situation using a global stability approach and showed that the whistling can be explained by a purely incompressible instability of the jet between the two holes.

In this work we focus on the geometry of a birdcall. At first, we conducted detailed experiments by varying the volumic flow rate and recording the sound signal with a microphone. Time-frequency diagrams allow to characterize the dynamics by identifying the dominant frequencies. We observe several regimes, comprising periodic rgimes, amplitude modulations, period-doubling, chaotic behavior, etc... Furthermore, the transition between the different rgimes often displays strong hysteretic behavior.

Secondly, we continued the global stability approach initiated in Bonnefis for the measured geometry of the birdcall. The results show the existence of several unstable modes whose properties and frequencies are in qualitative agreement with the experimentally observed dynamics.

Finally, we propose a simple model to explain the instability mechanism, which incorporates models for the impedance of both holes and of the spatial instability of the jet. A key ingredient is the fact that as the flow successively passes through the two holes, the pressure first decreases, then increases back.

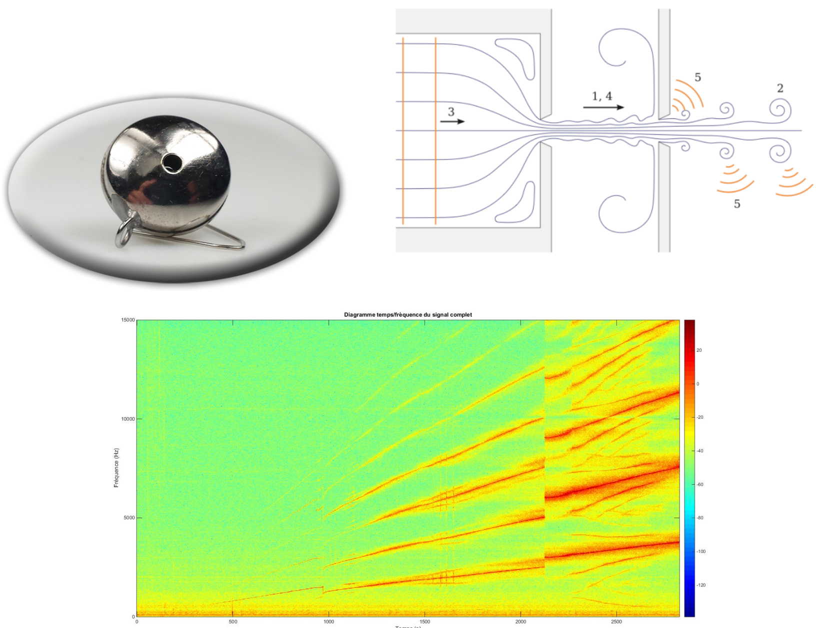

FIGURE 1. (a) : *Birdall used in this work.* (b) *sketch of the flow (according to [?]).* (c) *time-frequency diagram.*

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SUBHARMONIC INSTABILITY MECHANISMS OF THE BIFURCATION PHENOMENON IN HARMONICALLY FORCED JETS

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Experiments [1] and numerical simulations [2, 3] have shown that a round jet excited with a forcing combining both axisymmetric and helical components undergoes a global "bifurcation" which significantly increases the jet spreading and its mixing properties. Axisymmetric forcing alone, at frequency f_a, leads to the formation of vortex rings. When an additional helical forcing at frequency f_h is superposed, these vortex rings are eccentrically displaced. The mutual interaction causes the vortices to further depart from the jet axis in opposite directions, which can lead to a spectacular flaring of the flow, and to a large enhancement of its mixing with the outer flow when turbulence develops.

The final flow behaviour depends on the ratio $r_f = f_a/f_h$. If $r_f = 2$, vortices move to opposite sides of the jet axis in an alternating fashion, leading to a jet with huge spreading in this direction, as shown in Figure 1. This case is called a *bifurcating jet.* If $r_f = 3$, three branches emerge (*trifurcating jet*). If r_f is non-rational, a theoretically infinite number of branches emerges, leading to a strongly flared jet with no preferred spreading direction – this is called a *blooming jet.*

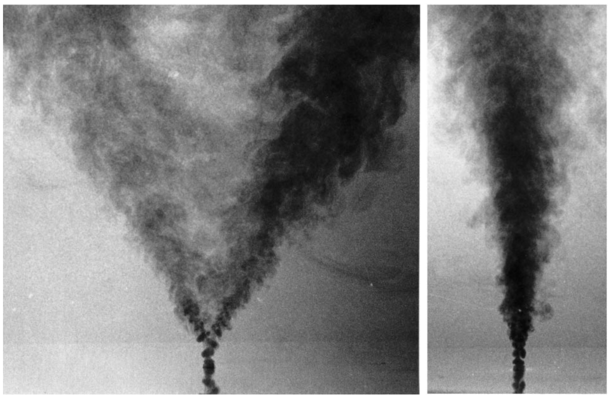

FIGURE 1. *Example of bifurcating jet ($r_f = 2$) in water at Re $\approx$ 20000, published in [1] from experiments carried by Reynolds in 1984: (left) bifurcating plane view, (right) side plane view.*

For a given state of axisymmetrically aligned ring vortices, we identify the optimal helical forcing for provoking the bifurcation scenario. A time-periodic axisymmetric state is computed first, with the aid of a stabilisation routine that inhibits pairing. This axisymmetric state is found to be Floquet-stable with respect to intrinsic helical perturbations. Extrinsic subharmonic forcing ($r_f = 2$) of such perturbations at the inlet however engenders a spatial growth. Optimal linear forcing conditions (subharmonic and helical) are computed such that the downstream eccentricity is maximal. Reynolds and Strouhal numbers are varied, and a physical discussion based on the modulus and phase shifts of the optimal forcing is developed.

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THE MULTIFOLD EFFECTS OF DENSITY ON THE INSTABILITY OF JETS, PLUMES AND PREMIXED FLAMES

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Buoyant jets, plumes and flames are shear flows that share essential features in their velocity fields, and in all three configurations, the instability dynamics are strongly affected by density variations. Unstable eigenmodes obtained for non-parallel axisymmetric base states will be presented, and the role of density in the respective instability mechanisms will be discussed in detail.

It is found that different mechanisms are involved in the instability dynamics in each of the three flow types. Buoyant jets, which are distinguished from plumes by a small Richardson number, may be globally unstable due to baroclinic effects, as has been shown before [1]. Plumes, characterised by large Richardson numbers, display a different dominant mechanism, which is driven by buoyancy [2]. Instability of premixed flames, in one investigated configuration, may involve unsteadiness in the heat release from reaction. At the same time, all of these global instabilities also rely strongly on the base flow shear.

Special emphasis will be placed on the sensitivity analysis that is used to quantify the impact of various terms in the governing equations on the instability characteristics.

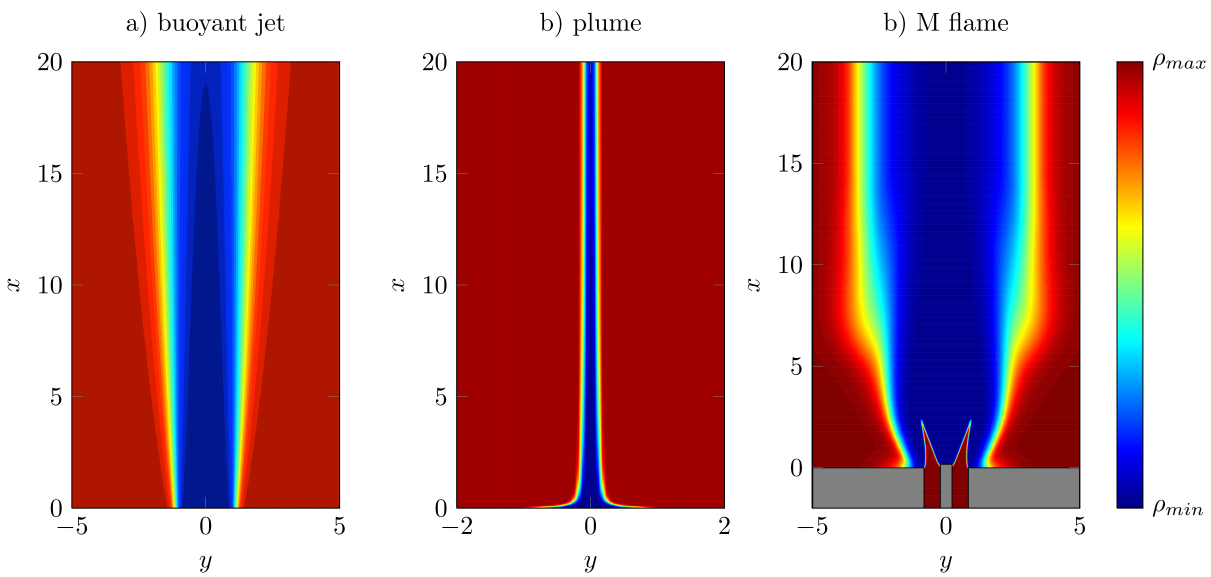

FIGURE 1. *Density distributions in the meridional plane of axisymmetric base flows. Lengths are scaled with the radius of the inlet orifice. a) Jet at $Re = 200$ and $Ri = 10^{-4}$; b) plume at $Re = 200$ and $Ri = 10^3$; c) premixed M-flame at $Re = 950$ and $Ri = 1.6 \times 10^{-4}$.*

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EFFECT OF COMBUSTION ON THE FREQUENCY RESPONSE OF JETS IN CROSSFLOW

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Reacting flows are a recurring flow phenomenon in engineering applications. In order to devise control strategies to optimize and influence their behavior, it is of great importance to understand the character of instabilities such flows are prone to. The objective of this paper is therefore to determine the effect of combustion on these instabilities. To this end, frequency response analysis is performed on reacting and non-reacting jets in crossflow, and their resulting dynamic behavior is compared. In order to perform the parametric sensitivity analysis the method proposed by [1] is employed. The spatial distribution of the optimal forcing field, yielding maximum energy gain at various forcing frequencies, is extracted, and the response map is compared between the two reactive and non-reactive cases. The range of frequencies to be investigated are determined using the energy spectra from the nonlinear simulations.

Apart from a frequency response analysis, in which we find the response of the entire state to forcing in all components of the system, we also perform component-wise input-output analysis which gives us insight into which input-output combinations are specially amplified (or suppressed) by combustion in the flow. This will provide a more mechanistic viewpoint of the role of combustion in the energy transfer processes of the fluid system.

The optimal forcing frequency and fields are extracted using adjoint-based optimization following the approach of [2]. This framework is particularly efficient, since the linearized operators are computed simply by using a local differentiation technique, without explicitly forming the resulting matrices for both forward and adjoint operators.

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DYNAMICAL SYSTEMS THEORY AND BYPASS TRANSITION IN BOUNDARY-LAYER FLOWS

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Dynamical systems theory has contributed a great deal to the understanding of bypass transition in simple shear flow, by elucidating the boundary between the basin of attraction of the laminar and turbulent flows in phase space, showing us what flow structures are associated with the evolution of trajectories on this edge of chaos and giving us information regarding the amplitudes needed for disturbances to reach transition. In this presentation recent work dealing with how to translate this knowledge into open boundary layer flows will be discussed. It is shown that in these more complex flows a dynamical systems picture can also give great insight into the transition process.

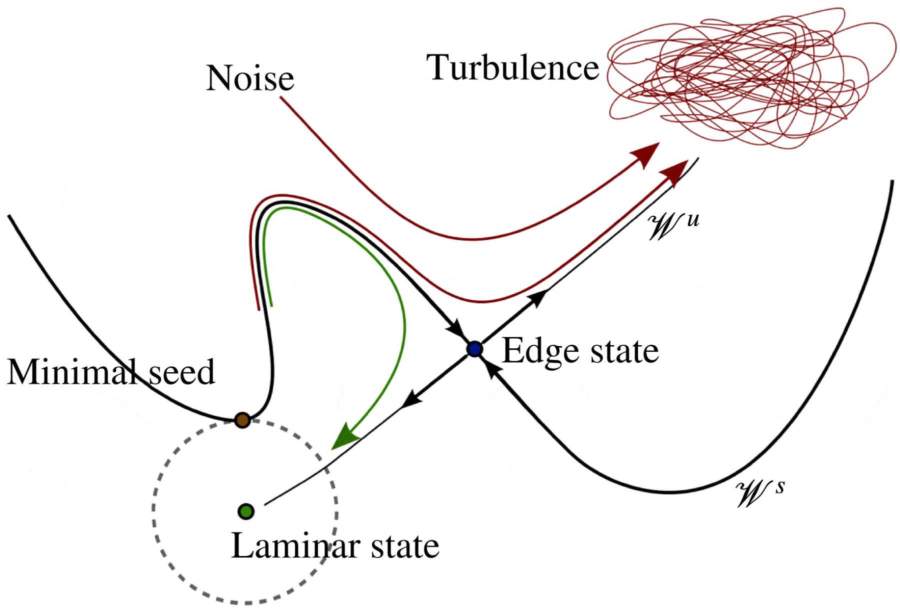

FIGURE 1. *Sketch of the state space. The basin boundary coincides with the stable manifold $\mathscr{W}^s$ of the edge state; $\mathscr{W}^u$ is its unstable manifold and points either towards the laminar state or to the turbulent attractor. The minimal seed is the point on the edge closest to the laminar state in energy norm. The edge state is shown as a point in this representation independent of its temporal dynamics (regular or chaotic).*

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STABILITY AND SENSITIVITY ANALYSIS OF COHERENT STATES IN PLANE COUETTE FLOWS

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In the last decade, shear flows have been analyzed from a dynamical system perspective to gain insight into the transition to turbulence; numerous canonical flows have been analyzed, typically in minimal flow unit, ranging from pipe to plane flows. Phase-space diagrams have been drawn identifying nontrivial solutions and classifying them along the bifurcation branches [3, 4, 5].

Equilibria, travelling waves and periodic orbits have been computed: in our contribution we focus on these non-trivial solutions from a stability point of view. By applying the Floquet analysis [1], we calculate the Floquet multipliers and examine the most unstable modes and the related adjoint modes of solutions belonging to the lower and upper branch. Through this analysis, the sensitivity of the unstable periodic orbits to structural perturbations and baseflow modifications is investigated [6, 2].

The perturbation sensitivity analysis over the orbit period shows that the core of the instability coincides with the region where the streaks are bent, in agreement with previous results. Most of the unstable modes are characterized by this feature. Moreover, we consider the sensitivity of the limit-cycle frequency and amplitude to feedback forcing. Preliminary results show that high sensitivity regions are localized where the velocity of the shear flow is higher.

The final goal of the investigation is to provide indications on how to alter the self-sustaining mechanisms of a turbulent flow and extend the sensitivity framework towards the analysis of nonlinear limit cycles.

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LINEAR ESTIMATION OF LARGE-SCALE STRUCTURES IN CHANNEL FLOW AT RE$_\tau = 1000$

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Given the time-resolved velocity field in a plane at a single wall-normal height, how well can one estimate, using a linear model alone, the time-resolved velocity field at other wall-normal heights? We investigate this question for fully-developed turbulence in a channel at $\mathrm{Re}_\tau = 1000$. The linear model is formed by first performing a triple decomposition of the velocity field, $\tilde{\mathbf{u}} = \mathbf{U} + \mathbf{u} + \mathbf{u}'$. Here $\mathbf{U}$ is the mean velocity, $\mathbf{u}$ represents a large-scale organized motion, and $\mathbf{u}'$ represents small-scale turbulent fluctuations. Following previous work [5, 1, 4], we provide a closure for the terms quadratic in $\mathbf{u}'$ using a simple eddy viscosity model. In contrast to these previous studies, however, we treat the terms quadratic in $\mathbf{u}$ as an unknown forcing after [3]. In this way we obtain a linear model, augmented by an eddy viscosity ν_t, and forced by the remaining nonlinear terms which we label $\mathbf{d}$:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{U}\cdot\nabla)\mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{U} = -\nabla p + \nabla\cdot\left[(\nu+\nu_t)(\nabla\mathbf{u} + \nabla\mathbf{u}^T)\right] + \mathbf{d}. \tag{1}$$

We require two planes of time-resolved velocity data from DNS: (i) the velocity field in a measurement plane which serves as the input for the linear model; and (ii) the velocity field in an estimation plane so that we can compare the linear model's estimate with the truth. This data is taken from the John Hopkins Turbulence database [2], which provides time-resolved DNS data for approximately one channel flow-through time at $\mathrm{Re}_\tau = 1000$. Estimation is performed using a Kalman filter, which provides an estimate of the full state of a state-space model,

$$\dot{x}(t) = Ax(t) + Bd(t), \quad y(t) = Cx(t) + n(t), \tag{2}$$

where d represents unknown disturbances; x is the system state; y is the output; n is sensor noise; and A, B and C are suitably-dimensioned matrices. The estimation problem is then: Given measurements $y(t)$ contaminated by noise $n(t)$, and in the presence of unknown disturbances $d(t)$, generate an estimate of the entire state $x(t)$. The linear system (1) is brought into state-space form (2) by transforming into Orr-Sommerfeld Squire form; taking Fourier transforms in the homogeneous directions; and discretizing in the wall-normal direction (z) using Chebyshev collocation. Thus a Kalman filter must be formed at each streamwise-spanwise wavenumber pair (k_x, k_y) of interest. Preliminary results are shown in figure 1, which compares the linear model's estimate of the velocity field at a wall-normal height of $z^+ = 100$ with the true DNS data. The measurement plane is at $z^+ = 200$. Only wavenumbers satisfying $|k_x| \le 8$, $|k_y| \le 64/3$ are included—for both the DNS data and the linear model—since our interest is in estimating the largest scales. (This is equivalent to only retaining wavelengths satisfying $|\lambda_x^+| \ge 785$, $|\lambda_y^+| \ge 294$.)

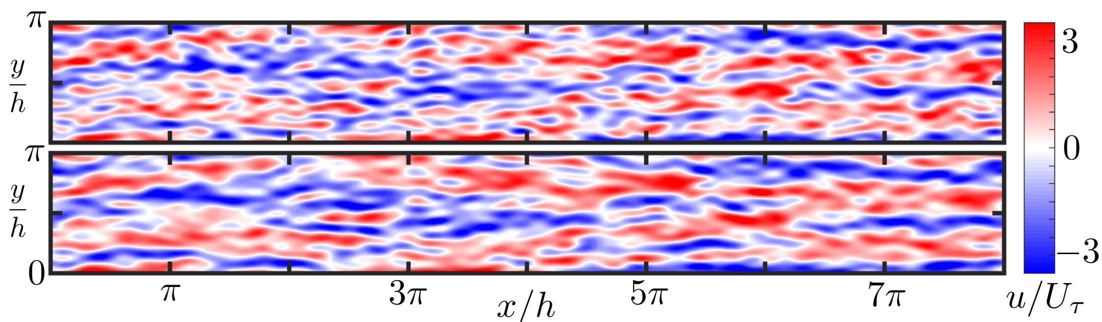

FIGURE 1. *Estimation of the streamwise velocity perturbation at an instant in time at $z^+ = 100$. Top: True DNS velocity field. Bottom: Estimate using linear model.*

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FORECASTING TURBULENCE USING THE GEOMETRY OF INVARIANT SOLUTIONS: EXPERIMENTS, THEORY, AND NUMERICS

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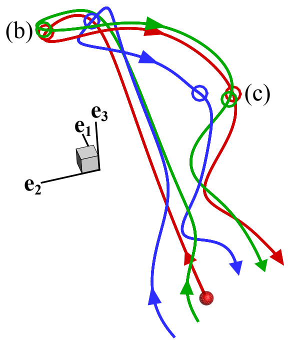
Recent theoretical and experimental studies have approached turbulence from a new perspective, which stems from the observation that turbulent flows often exhibit recognizable transient coherent patterns that recur over time and space. These patterns are related to a class of unstable nonchaotic solutions of the Navier-Stokes equation, called exact coherent structures (ECS). Numerical studies have shown that ECS can serve as building blocks in describing both the statistical [1] and dynamical [2] behavior of fluid turbulence at transitional Reynolds numbers, although experimental evidence of this is scarce at present. Futhermore, the geometrical description obtained by visualizing the evolution of the flow in a high- or infinite-dimensional state space [3] produced a lot of new insights into the dynamical mechanisms of fluid turbulence.

This paper presents a combined numerical and experimental investigation of turbulent flow in a thin, electromagnetically-driven fluid layer [4] intended to test and validate the dynamical description of weak turbulence. We find that the dynamics exhibit clear signatures of numerous ECS, which correspond to unstable equilibrium solutions of Navier-Stokes computed using a combination of flow measurements from the experiment and fully-resolved numerical simulations. We demonstrate the dynamical importance of these solutions by showing that turbulent flows visit their state space neighborhoods repeatedly. Furthermore, we find that unstable manifolds associated with unstable equilibria, or more precisely the submanifolds which correspond to the dominant unstable direction, can be used to predict the evolution of turbulent flow in both experiment and simulation for a considerable period of time. This is illustrated in the Figure 1, which shows examples of trajectories from experiment and from numerical simulations shadowing the submanifold in a low-dimensional projection of the state space and the corresponding flow fields in the physical space.



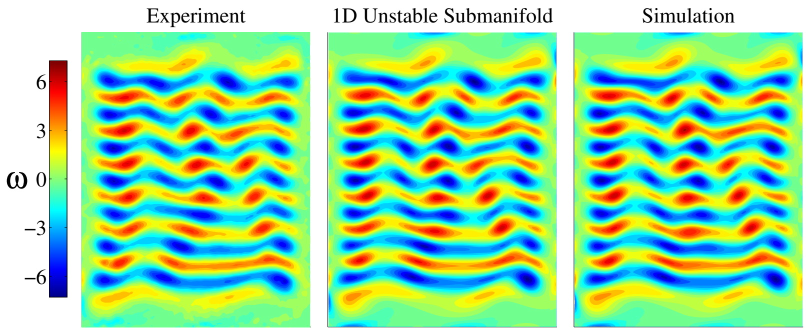


Figure 1: (a) A projection showing an unstable equilibrium (red sphere) with the dominant unstable submanifold (red curve). Experimental (blue curve) and numerical (green curve) turbulent trajectories follow this submanifold as they depart from the neighborhood of the unstable equilibrium. (b) Representative flow fields from the submanifold and two turbulent trajectories (denoted with circles in (a)).

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UNIVERSALITY OF THE TURBULENT VELOCITY PROFILE

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For nearly a century, the universal logarithmic law of the mean velocity profile has been a mainstay of turbulent fluid mechanics and its teaching. Yet many experiments and numerical simulations are not fit exceedingly well by it, and the question whether the logarithmic law is indeed universal keeps turning up in discussion and in writing. Large experiments have been set up in various parts of the world to confirm or deny the logarithmic law and accurately estimate von Krmns constant, the coefficient that governs it. Here, we show that the discrepancy among flows in different (circular or plane) geometries can be ascribed to the effect of the pressure gradient.When this effect is accounted for in the form of a higher-order perturbation, universal agreement emerges beyond doubt and a satisfactorily simple formulation is established.

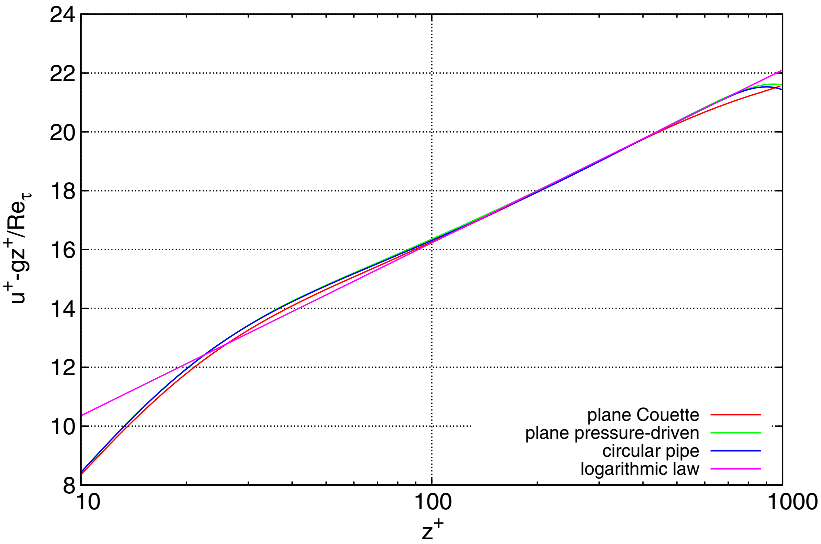

FIGURE 1. *Velocity profile after subtraction of the pressure-gradient term gz^+/Re_τ, compared with the logarithmic law (Luchini [1]).*

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12th ERCOFTAC SIG 33 Workshop, Progress in Flow Instability, Transition and Control
June 19-21, Certosa di Pontignano, Italy

EXPERIMENTAL ANALYSIS OF STEP-INDUCED TRANSITION IN COMPRESSIBLE HIGH REYNOLDS NUMBER FLOW

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Steps at structural joints of aerodynamic surfaces can induce the amplification of existing (or potentially existing) disturbances within the laminar boundary layer as well as the generation of additional instabilities, thus leading to premature transition to turbulence [1]. Most of the previous research on the effect of steps on boundary-layer stability and transition focused on Mach and Reynolds numbers lower than those characteristic of commercial transport aircraft. Numerical studies have been carried out only for flat-plate configurations at zero pressure gradient, whereas only a limited number of pressure distributions have been examined in experiments [2]. The influence of a non-adiabatic surface on boundary-layer stability in the presence of steps has been (numerically) examined in only one single case [3].

The effect of sharp forward-facing steps on boundary-layer transition was systematically investigated in this experimental work in combination with the influence of variations in the following parameters: streamwise pressure gradient, Reynolds number, Mach number, and wall temperature ratio. The experiments were conducted in a quasi-two-dimensional flow at high Reynolds numbers and at both low and high subsonic Mach numbers in the Cryogenic Ludwieg-Tube Göttingen. The cross section of the examined wind-tunnel model is shown in Figure 1a. The adopted experimental setup enabled an independent variation of the aforementioned parameters and allowed a decoupling of their respective effects on the boundary-layer transition. Transition, measured non-intrusively by means of temperature-sensitive paint, was found to move gradually upstream towards the step location with increasing non-dimensional step parameters (i.e., the step Reynolds number and the step height relative to the boundary-layer displacement thickness). Stronger flow acceleration and lower wall temperature ratios led to an increase in the transition Reynolds number even in the presence of forward-facing steps; this favorable influence became, however, less pronounced at larger values of the non-dimensional step parameters. As shown in Figure 1c, the representation of the results using the relative change in transition location with respect to the step location, plotted against the non-dimensional step parameters, gave good correlation. The effect of the steps on boundary-layer transition could thus be systematically investigated, being isolated from the influence of variations in the other parameters. Detailed results will be discussed in the presentation of this contribution.

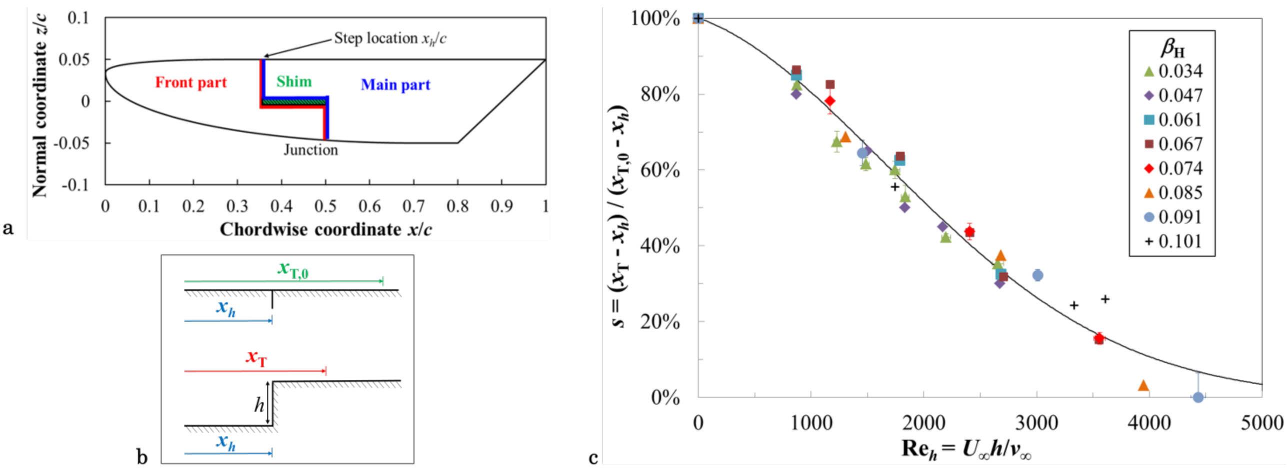

Figure 1. a: *simplified drawing of the construction of the wind-tunnel model (side view) [3]*; b: *sketch of step contour (side view) and definition of the variables;* c: *relative change in transition location as a function of the step Reynolds number* Re_h *at a Mach number* M *= 0.65 and a wall temperature ratio* T_w/T_{aw} *= 1.037-1.057 [3].* U_∞ *and* ν_∞ *are the freestream velocity and kinematic viscosity, respectively, and* β_H *the Hartree parameter characterizing the pressure gradient.*

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NOLOT-LNS: BOUNDARY-LAYER INSTABILITY ANALYSIS FOR SURFACES WITH PERTURBATIONS USING HARMONIC-LNS

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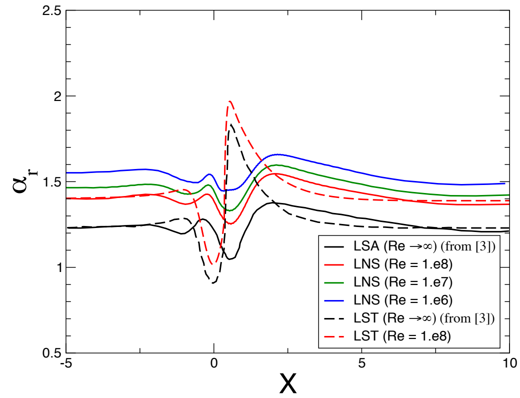
Local (LST) and nonlocal (PSE) stability theories, as implemented in the NOLOT / PSE code [1], have been successfully used to study the growth of convective boundary-layer instabilities in many different scenarios [2]. However, there are surfaces with perturbations where the streamwise variations of the mean flow occur locally over a length scale comparable to the characteristic wavelength of the instability modes. In such cases, the LST and PSE methodologies are not formally applicable, and other approaches, like direct numerical simulations (DNS) or local scattering approach (LSA) [3], need to be considered. Examples of these types of surfaces with perturbations are:

- Isolated or distributed roughness
- Steps, gaps, humps
- Suction, actuators

The harmonic-LNS (linearized Navier-Stokes) methodology [4] presented here can be seen as the natural extension of the nonlocal concept for such types of surfaces. The assumption of 'slowly varying flows in streamwise direction' is no longer considered, and this leads to a fully-elliptic system of equations (as in DNS) but where the harmonic representation of the disturbance is kept (as in PSE). This approach reduces the grid requirements significatively compared with traditional approaches as standard LNS or DNS [5].

The harmonic-LNS is applied for the study of convective instabilities for smooth steps and humps / indentations. In particular, a comparison with LSA for a TS-wave passing a hump is included in Figure 1. In this example, significant differences arise between LST and LNS/LSA. It is also clearly visible that, by increasing the Reynolds number, the harmonic-LNS solution tends to the asymptotic approach [3].



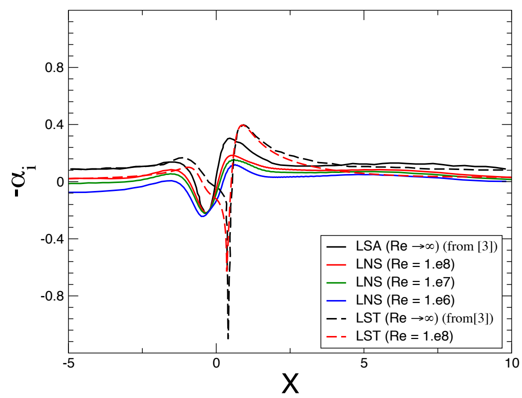


FIGURE 1. *Wavenumber α_r (left) and growth rate -α_i (right) of a TS wave at frequency ω = 3.0 for a hump with height h=2.0 and width d=0.5 located at X = 0.0 on a flat plate.*

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EFFECTS OF SURFACE STEPS ON CROSSFLOW DOMINATED SWEPT-WING BOUNDARY-LAYER TRANSITION IN PRESENCE OF UNSTEADY AND STEADY FREESTREAM VORTICES

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The main goal of the present study is to investigate the influence of spanwise-uniform roughness-elements (such as forward- and backward-facing steps) on the laminar-turbulent transition in a swept-wing boundary layer initiated by crossflow instability modes in the presence of unsteady and steady freestream vortices. The measurements are performed for rectangular (in the spanwise-streamwise plane) roughness strips of various heights (from 82 to 1103 microns) having two widths of either 50 or 150 mm in the chordwise direction. The measurements are performed in 76 different regimes for two different types of free-stream vortical disturbances initiated by grids: (i) primarily unsteady disturbances (grid *G1*) and (ii) mixture of steady and unsteady disturbances (grid *G9*). The measurements are carried out in a low-turbulence wind tunnel of ITAM (Novosibirsk) at low subsonic freestream speeds by means of hot-wire anemometry. The studied range of unit Reynolds numbers $Re_{1rb} = U_{erb}/\nu$ is between $0.687 \cdot 10^6$ and $1.568 \cdot 10^6$ m^{-1}. Here U_{erb} is the potential flow velocity at the boundary-layer edge at the chordwise position of the surface roughness beginning. Two significantly different transition scenarios are observed in the study: (a) evolutionary transition and (a) abrupt transition. (The latter can be either steady or unsteady.) The evolutionary scenario is associated with the gradual amplification of primary crossflow instability modes leading to the appearance of local high-frequency secondary instability, while the abrupt transition is characterized by strong base-flow distortion by the surface steps leading to rapid primary instability of the perturbed flow with a rapid breakdown. The abrupt transition beginning is nearly attached to the steps' locations. The boundary between these two scenarios is determined experimentally in the space of the problem parameters. Shown in Figure 1 are two examples of distributions of the transition location Reynolds number $Re_{2rtr} = x'_{2tr} Re_{1rb}$ versus dimensionless roughness height obtained for various freestream speeds for elevated levels of freestream disturbances generated by grids *G1* (a) and *G9* (b) for roughness-strip width of 50 mm (case *W1*). Here x'_{2tr} is the chordwise distance of the beginning of the laminar flow breakdown measured from the beginning of the surface roughness. The origin of the local high-frequency secondary instability is regarded as the criterion of the transition beginning. It is found that the spanwise-uniform surface steps do not significantly influence the transition onset location if the transition remains characterized as evolutionary. However, steps of sufficient height are able to trigger the abrupt transition scenario with transition jumping forward. The measurements have shown also that the threshold amplitude of the combined disturbances (of about 30 to 33%) found previously [1] remains a good simple criterion for the beginning of the flow transition in all evolutionary regimes studied in the present experiments.

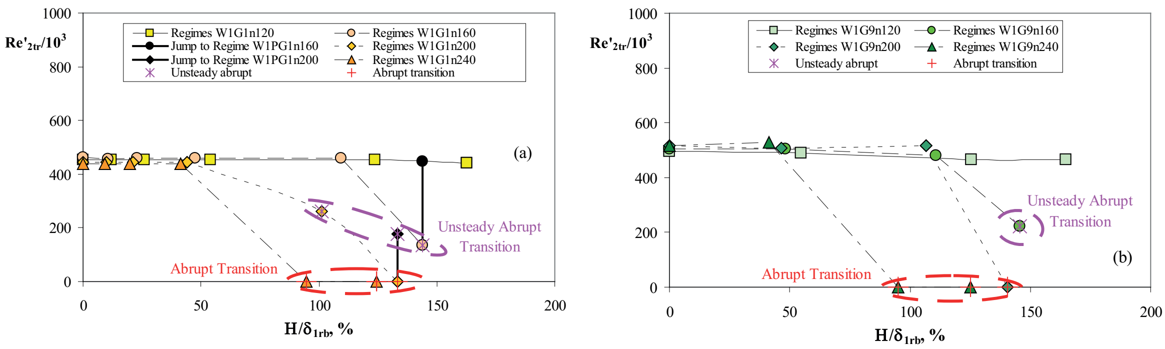

FIGURE 1. *Transitional Reynolds numbers versus dimensionless roughness height obtained for various freestream speeds for elevated Tu-levels generated by grids G1 (a) and G9 (b) for roughness-strip width of 50 mm (case W1).*

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STABILITY AND SENSITIVITY OF A FALKNER–SKAN–COOKE BOUNDARY LAYER WITH DISCRETE SURFACE ROUGHNESS

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With the aim of finding the critical roughness size, a global stability and sensitivity analysis of a three-dimensional Falkner–Skan–Cooke (FSC) boundary layer [1] with a cylindrical surface roughness is performed. The roughness size is chosen such that breakdown to turbulence is initiated by a global version of traditional secondary instabilities of the crossflow (CF) vortices as shown in figure 1, instead of an immediate flow tripping at the roughness. The resulting global eigenvalue spectra of the systems are found to be very sensitive to numerical parameters and domain size.

In order to understand this sensitivity for the present flow case, the ε-pseudospectrum and the energy budget is computed, and an impulse response and a structural sensitivity analysis is performed. The outcome of these analysis will be discussed during the talk. In particular, the results show that while the frequencies remain relatively unchanged, the growth rates increase with domain size (see figure 2), which originates from the inclusion of stronger CF vortices in the baseflow. It is concluded that in contrast to the case with a roughness element in a Blasius boundary layer [2], the onset of global instability in a FSC boundary layer as the roughness height is increased does not correspond to an immediate flow tripping behind the roughness, but occurs for lower roughness heights if sufficiently long domains are considered. However, due to the great sensitivity of the flow, it is not possible to accurately pinpoint the exact parameter values for this instability, and the large spatial growth of the disturbances in the long domains eventually becomes larger than what can be resolved using finite precision arithmetic.

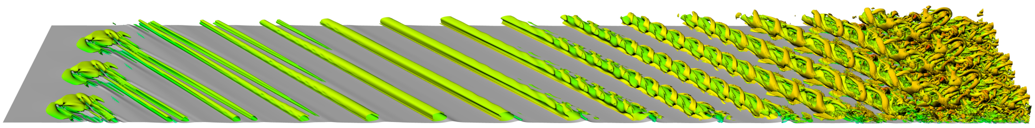

FIGURE 1. *Flow field from a non-linear DNS illustrating the CF vortices and the location of the transition region. Contour of streamwise velocity in light gray and contour of λ_2 colored by streamwise velocity.*

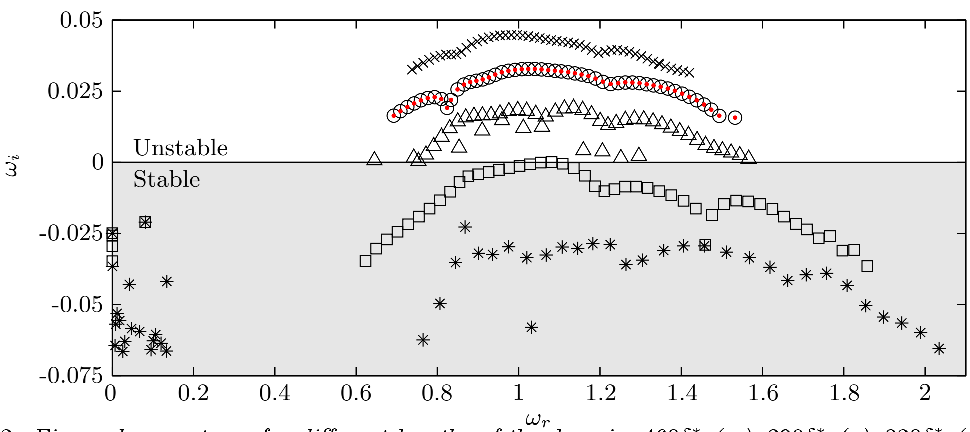

FIGURE 2. *Eigenvalue spectrum for different lengths of the domain,* $460\delta_0^*$ ($\times$), $390\delta_0^*$ ($\circ$), $320\delta_0^*$ ($\triangle$), $250\delta_0^*$ ($\square$), $180\delta_0^*$ ($\ast$), *where* δ_0^* *refers to the displacement thickness at the inlet.*

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GAP EFFECTS ON CROSSFLOW DOMINATED TRANSITION IN THE PRESENCE OF SURFACE ROUGHNESS AND FREE-STREAM TURBULENCE

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The study is devoted to investigations of the influence of spanwise-uniform surface gaps on the cross-flow dominated laminar-turbulent transition in a 35-degree swept-wing boundary layer at low and elevated freestream turbulence levels in the presence of distributed surface roughness. The surface gaps were rectangular in the spanwise-streamwise plane and had various depths (from $0.62\delta_{1rb}$ to $8.33\delta_{1rb}$) and widths (from $2.52\delta_{1rb}$ to $103.81\delta_{1rb}$). Here δ_{1rb} is the boundary-layer displacement thickness. The measurements are performed in 216 different regimes for three different types of free-stream vortical disturbances (two of which were initiated by grids) and two different kinds of distributed surface roughness: (i) low-level "natural" roughness (with rms amplitude between 0.21 and 0.29% of δ_{1rb}) and (ii) weak controlled roughness (with rms amplitude between 3.6 and 5.0% of δ_{1rb}). The measurements were carried out in a low-turbulence wind tunnel of ITAM (Novosibirsk) at low subsonic freestream speeds by means of hot-wire anemometry in a range of unit Reynolds numbers between $0.47 \cdot 10^6$ and $1.44 \cdot 10^6$ m^{-1}. Similar to previous experiments, all observed transition scenarios can be divided into two main groups: (a) evolutionary transition and (b) abrupt transition. (The latter can be either steady or unsteady.) The evolutionary scenario is associated with gradual amplification of primary crossflow instability modes leading to the appearance of local high-frequency secondary instability. The abrupt transition is characterized by strong base-flow distortion from the surface gaps leading to rapid primary instability of the perturbed flow and near-immediate breakdown. The abrupt transition onset occurs very near to the gaps' location. In the majority of studied cases, the transition follows the evolutionary scenario and the spanwise-uniform surface gaps have very little influence on the transition location. However, when the gap characteristics are significant enough to trigger the abrupt scenario the transition jumps forward. The border between these two scenarios is shown in Figure 1 as a function of the dimensionless values of the gap depth and gap width. It is seen that shallow gaps (with $|H/\delta_{1rb}|$ less than 1.5) do not influence the transition at all. Deeper gaps (with $|H/\delta_{1rb}|$ greater than 1.6) are able, in general, to cause the abrupt transition. However, even very deep gaps do not influence the transition location if their width W_r/δ_{1rb} is less than 15. The measurements have also shown that the threshold amplitude of the combined disturbances is about 30 to 33% at transition onset. This is consistent with several previous experiments (see e.g. [1]) and supports the use of this simple criterion for the onset of transition in all evolutionary regimes, including influences of various: surface gaps, turbulence levels and distributed surface roughness.

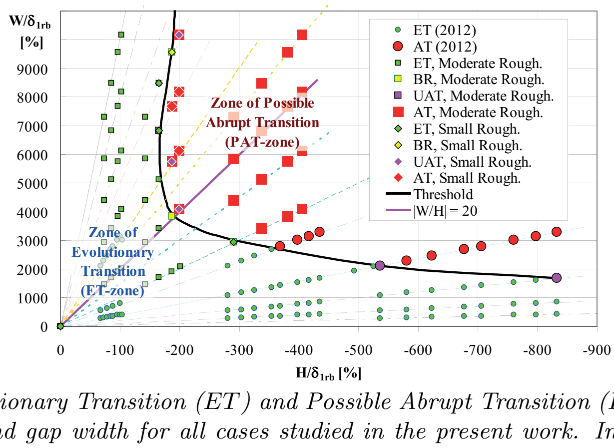

FIGURE 1. *Zones of Evolutionary Transition (ET) and Possible Abrupt Transition (PAT) in plane of dimensionless values of gap depth and gap width for all cases studied in the present work. Inclined lines display constant aspect ratios $|W/H|$ in a range from 0.5 to 100.*

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NAVIER-STOKES COMPATIBLE FORMULATION OF A DATABASE APPROACH FOR LAMINAR-TURBULENT TRANSITION PREDICTION: EXTENSION TO CROSSFLOW INSTABILITIES

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The aerodynamic performances of aircraft are impacted by the natural laminar-turbulent transition of the boundary layer developing on the wings. The present analysis is limited to low environmental perturbations (upstream turbulence, surface roughness). The latter are filtered into a set of normal modes (Tollmien-Schlichting or crossflow) that undergo a linear amplification (local linear stability hypothesis) followed by nonlinear interactions that lead to transition. Its location can be predicted by the N-factor method [1] that consists in integrating the spatial growth rates of each of these modes along the boundary-layer external streamline to get their total amplification. Transition is then triggered for a given value of the envelope of these N-factors. The objective is to recast this method into a RANS-compatible formulation, yielding two major problems:

1. The growth rates of each mode need to be known.
2. The growth rates then need to be integrated along the external streamline.

The first issue is solved in this study *via* a database approach named the Parabolas method [2]. It replaces the exact computation of the growth rates with a set of two half-parabolas whose closed-form expressions depend on some local boundary-layer quantities. The second issue is dealt with by recasting the exact N-factors integration (one per mode) into a set of transport equations that are added to the Reynolds-Averaged Navier-Stokes set. These transport equations are classical convection equations whose source terms correspond to the modes' growth rates. This formulation allows the N-factors to be intrinsically computed along the flow's streamlines (thus avoiding the explicit determination of the external streamline's geometry). The envelope is then computed as the maximum value of the N-factors taken at the boundary-layer edge as shown in figure 1.

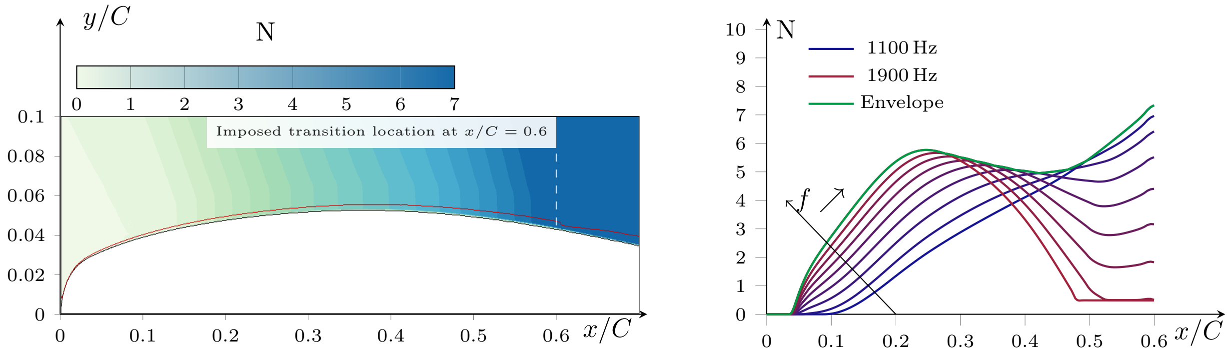

FIGURE 1. *N-factor extraction on an ONERAD (symmetrical) airfoil in 2D subsonic conditions.*
Left: field for the TS mode 1200 Hz and boundary-layer edge (red).
Right: extraction at the boundary-layer edge for 9 TS modes (1100 Hz to 1900 Hz, step: 100 Hz) and envelope.

This method was implemented for 2D flows (TS modes) in Onera's RANS solver *elsA* [3] and successfully validated against experimental data available on an industrial laminar airfoil [4]. The validations of this N-$\sigma_{\mathrm{Parab.}}$ transition model also showed that the transported N-factors are identical to the ones obtained through an exact integration. The extension of the N-$\sigma_{\mathrm{Parab.}}$ model to CF instabilities for 3D flows is presented and its capacity to accurately capture the transition location is firstly evaluated on 2.5D test cases.

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SIMULATION AND FEEDBACK CONTROL OF BLUFF-BODY WAKES EXHIBITING BI-MODALITY

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Recent work on the wakes behind blunt bluff bodies has identified symmetry-breaking behaviour. In the laminar flow regime, as the low Reynolds number is increased, the wake undergoes a sequence of bifurcations [1]. This results in it changing from being spatially symmetric and temporally steady to being spatially asymmetric and temporally unsteady. At the same time, at high, turbulent Reynolds numbers, the wake flow undergoes bi-modal switching between asymmetric states [2, 3, 4]. This bi-modality (or in some cases, multi-modality) occurs over slow and random timescales [5].

It has recently been shown that the asymmetric states at these high, turbulent Reynolds numbers have the same structure as those that result from the bifurcation sequence at laminar Reynolds numbers. The bi-modality (or multi-modality) is then the result of forcing from external disturbances, these originating from turbulent disturbances in the flow [5].

Thus far, this work has been primarily experimental, as the very long bi-modality timescales make simulation expensive. We now present large eddy simulations (LES) which are the first to successfully capture the bifurcation sequence of a squareback Ahmed body wake at low Reynolds numbers [6]. The same LES tools are then applied to blunt bluff body wake flows at high Reynolds numbers, where the separating boundary layer is turbulent. We are able to capture bi-modal switching between asymmetric states. In both the laminar and turbulent regimes, the accessibility of full flow-field data allows us to extract wake flow features that offer new insights.

Finally we apply a linear feedback control strategy to the flow, with a view to reducing the pressure drag of the bluff body. The feedback control is single-input single-output, with body-mounted sensing and actuation for practical applicability. It consists of sensing the base pressure force fluctuations, and actuating a zero-net-mass-flux slot jet just ahead of separation [7, 8]. Linear controller design targets attenuation of base pressure force fluctuations, these being used as a proxy for mean drag. The effect of implementing the linear feedback controller on both the mean pressure drag and the symmetry of the wake are investigated.

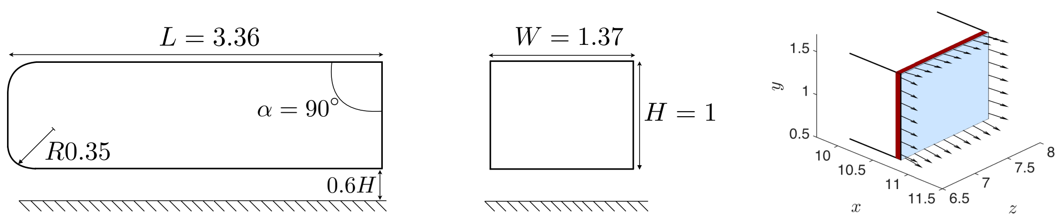

FIGURE 1. *(Left) Side and rear views of simulated squareback Ahmed body. (Right) Schematic of feedback control arrangement, showing sensing (blue) and actuation (red, arrows).*

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OPTIMAL STREAKS IN THE WAKE OF A BLUNT-BASED AXISYMMETRIC BLUFF-BODY AND CONTROL OF VORTEX SHEDDING

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We are interested in the control of global instabilities developing in the wake of a blunt-based axisymmetric bluff-body with an ellipsoidal nose by means of the optimal forcing of large-amplitude steady streaks in the wake, thus extending to three-dimensional wakes the approach used in [1, 2] to control global instabilities in two-dimensional wakes.

Optimal perturbations are forced by means of a radial velocity of azimuthal wavenumber m applied on the lateral skin of the body. The optimal distributions of such a forcing, maximizing the spatial energy growth of steady perturbations in the wake, are computed as in [1, 2] with a scalable adjoint-free subspace expansion method which is found to quickly converge to the optimal solutions. Optimal perturbations with $m \neq 0$ lead to the amplification of streamwise streaks in the wake (see panels a and b in Figure 1) and are obtained with zero mass flux, while $m = 0$ perturbations correspond to a non-zero mass flux.

We find that $m \neq 1$ optimal perturbations forced with finite amplitude have a stabilizing effect on the large-scale unsteady vortex shedding in the wake and that $m = 0$ optimal perturbations are stabilizing only for negative amplitudes (suction). The forcing of $m \geq 2$ modes can significantly reduce the amplitude of the unsteady lift force exerted on the body (see panel c in Figure 1). When combined with low levels of base bleed these perturbations can completely suppress the unsteadiness in the wake with reduced levels of mass injection in the flow.

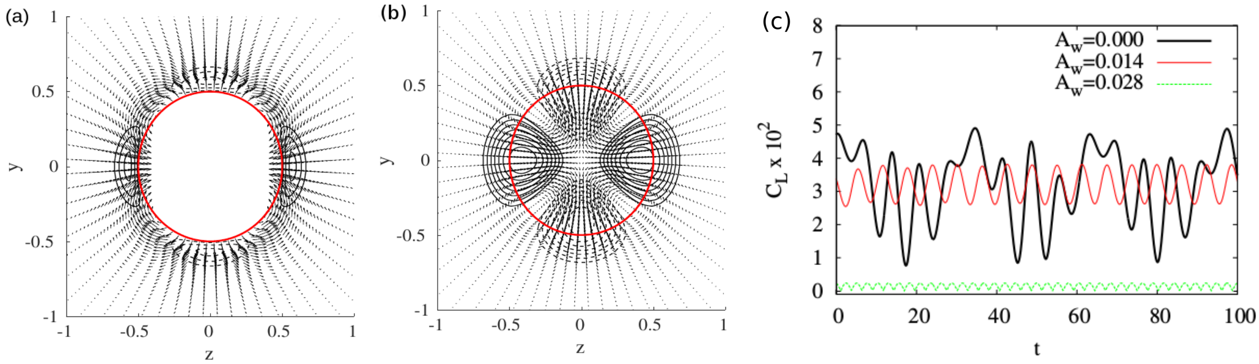

FIGURE 1. *Cross-stream ($y - z$) view of the velocity perturbations forced by the $m = 2$ optimal blowing and suction at the bluff-body stern (panel a) and at the position of maximum streak amplitude (panel b). The scales used to plot the cross-stream v'-w' velocity components (streamwise vortices, arrows) and the streamwise u' component (streamwise streaks, contour-lines) are the same in both panels. The circular cross-section of the bluff-body base is also reported as a (red) circle for reference. In panel c we show the temporal history of the lift coefficient at $Re = 500$ associated to the uncontrolled flow ($A_w = 0$) and to increasing amplitudes A_w of the $m = 2$ optimal blowing and suction.*

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CONTROL OF RECIRCULATION BUBBLE IN NLP FRAMEWORK

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Flow separation occurs in many engineering applications with abrupt changes in the geometry or strong adverse pressure gradients, producing recirculation regions that strongly contribute to the properties of the flow. Such recirculation regions are usefully exploited in a number of practical applications. For instance, swirling flows are often used in burners since they produce an adverse pressure gradient promoting the development of a recirculation region and improve mixing of streams in non-premixed flames.

Unfortunately, the presence of recirculation regions can also lead to undesired effects. The size of the recirculation, a function of the Reynolds number, drives the stability properties of the flow, with strong back-flow and shear stress locally destabilizing the flow. Moreover, perturbations can be amplified in the shear layer delimiting the recirculation region. Both these mechanisms may lead to undesirable low-frequency oscillations. In this respect, control of flow separation emerges as a interesting topic with practical applications.

In the present work, control is applied to the recirculation region occurring in incompressible coaxial swirling jets flow. As the swirl of the outer stream exceeds a critical value, vortex breakdown occurs and a recirculation bubble appears. The problem of controlling the stagnation points of the bubble by means of wall actuation, subject to technological constraints, is set in the nonlinear programming (NLP) framework. The incompressible Navier-Stokes equations are interpreted here as equality constraints. The objective function is defined as a combination of the distance between the actual and the desired position of the stagnation points. The optimization variables determine the intensity of the wall actuation, by modulating prescribed velocity profiles. A limited memory BFGS algorithm [1] is used to minimise the objective function subject to the contraints mentioned above. Sensitivity analysis plays here a major role [2] since it is used both to choose the position and the direction of the wall actuation and to compute the gradient of the cost function w.r.t. the optimization variables required by the BFGS algortihm.

In the figure an example is reported showing the capability of the method to control the position of the stagnation points of a stable flow. Further results as well as the potential and limits of the proposed method will be discussed at the workshop.

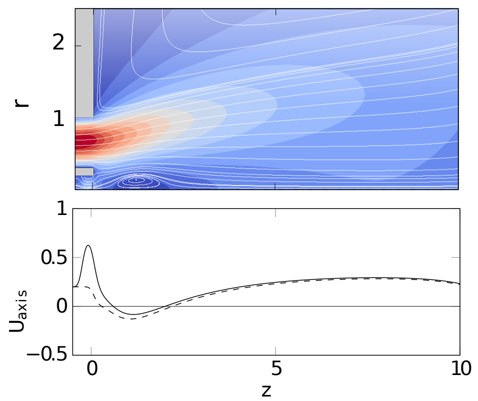

FIGURE 1. *Controlled flow field and comparison between the velocity on the axis of the uncontrolled (dashed) and controlled system.*

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AN ASYMPTOTIC APPROXIMATION TO THE NONLINEAR FREQUENCY RESPONSE

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We study the effect of nonlinearities on the global frequency response of a uniform-density jet [1]. A weakly nonlinear expansion is employed to calculate the higher-order corrections to the linear frequency response for axisymmetric and non-axisymmetric body forcing. In particular, we focus our attention on the axisymmetric ($m = 0$) and asymmetric ($m = 1$) azimuthal modes about frequencies that are optimally excited in experiments, that is, for Strouhal numbers around $St \sim 0.3$.

We find that the expansion coefficients of the weakly nonlinear expansion describe a divergent series. While recognizing the limit in forcing amplitude beyond which the asymptotic expansion is not valid, we derive an integral expression for the sum of the divergent series beyond this limit using a Borel summation. We find that this expression gives a pleasing approximation to the full nonlinear gain up to one order of magnitude beyond the limit of validity of the weakly nonlinear expansion. We have also compared our results with a self-consistent model [2] that takes into account the base flow modification induced by the Reynolds stress terms of the forcing, shown in figure 1. For equal forcing amplitudes, we find that the asymmetric mode dominates over the axisymmetric mode. This suggests that the projection of environmental forcing onto the individual azimuthal modes plays an important role in the preferred dynamics of round jets.

The presented formalism can easily be applied to configurations where the linear frequency response is used to understand other aspects of jet dynamics, for example, the production of noise in high-speed jet flows. In this case, our asymptotic approach could provide a quick estimate of nonlinear effects with minimal computational effort. The asymptotic approach is expected to give better results for flows that exhibit less non-normality – e.g., strongly non-parallel flows at moderate Reynolds numbers, and for flows that exhibit supercritical bifurcations, as observed in, for example, convection.

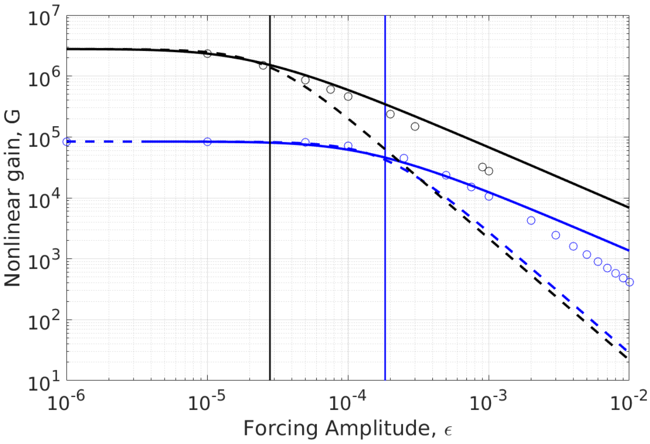

FIGURE 1. *The variation of the gain with forcing amplitude for forcing with $m = 0$ (blue) and $m = 1$ (black) for $St = 0.40$ at $Re = 1000$. The solid lines represent the results of the Borel summation , and the dashed lines represent the weakly nonlinear asymptotic expansion. The circles represent a self-consistent model that correctly predicts the nonlinear behavior. The two vertical lines indicate, for the respective azimuthal wavenumber, the critical forcing amplitudes given by the radius of convergence of the geometric series.*

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SECOND ORDER SENSITIVITY, GINZBURG-LANDAU EQUATION AND THE STABILIZING MECHANISM OF STREAKS ON 2D ABSOLUTE AND GLOBAL INSTABILITIES

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Global and local absolute instabilities of 2D wakes are known to be stabilized by spanwise periodic modulations of the wake velocity [4, 3, 1, 2] but the nature of this stabilizing mechanism is not yet completely understood. Assuming that the leading effect of the spanwise modulations of the wake streamwise velocity profile is associated to the spanwise modulation of the advection velocity of unstable waves, we investigate the effect of spanwise periodic modulations of the wave advection velocity in a generalization of the linear complex Ginzburg-Landau equation, which approximates the spatio-temporal evolution of unstable waves.

We show that the enforced spanwise modulations of the wave advection velocity have a stabilizing effect on the global instability of the non-parallel complex Ginzburg-Landau equation. The growth rate of the unstable global mode is shown to decrease quadratically with the amplitude of the modulations and the global instability is suppressed for large enough modulation amplitudes. It is then shown that a second order structural sensitivity analysis provides accurate predictions of the variation of the growth rate of the unstable global mode with respect to the amplitude of the advection velocity modulations. This second order analysis is then applied to compute the influence of these modulations on the absolute instability growth rate in the parallel case. It is shown that the leading order effect of the advection velocity modulations is to alter the wave diffusivity in the local dispersion relation. This altered diffusivity is associated to a decrease of the absolute growth rate. A straightforward local stability analysis of the global mode stabilization obtained in the non-parallel case shows that at criticality the spanwise advection velocity modulations have reduced the pocket of local absolute instability to the same level that it would have had by reducing the global bifurcation parameter μ_{max} to its critical value μ_c. This confirms that the suppression of the global instability is induced by the reduction of the local absolute instability.

These results, which are in complete agreement with what is found in non-parallel wakes [1, 2], show that the simple spanwise modulation of the advection velocity plays the key role in the stabilization mechanism. As no vorticity is defined in the Ginzburg-Landau equation, this key stabilizing mechanism is simpler and of more general nature than explanations based on the vortex dynamics of wake vortices in the presence of 3D modulations. This stabilizing effect is also more general in the sense that it can probably be applied to other physical systems described by the complex Ginzburg-Landau equation. Spanwise modulations of the advection velocity may e.g. play a role in the analysis of the solar dynamo mechanism [6] or of the cyclogenesis in the atmosphere [5], where the absolute and global instabilities play an important role.

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ROUGHNESS-INDUCED TRANSITION BY QUASI-RESONANCE OF A VARICOSE GLOBAL MODE

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The effect of wall roughness elements on laminar-turbulent transition in boundary-layer flows has recently been the focus of many investigations. Despite their stabilizing effect on TS waves, in certain flow conditions they can induce bypass transition, a detrimental effect for control purposes. In an effort to provide thresholds for transition, von Doenhoff & Baslow [1] compiled a transition diagram correlating the roughness element's aspect ratio to the roughness Reynolds number, Re_h, beyond which the induced flow would transition to turbulence. With the aim of providing a more accurate estimate of the critical Reynolds number for transition, global stability analyses have been recently performed in the case of a cylindrical roughness elements [2].

In this work, the onset of unsteadiness in a boundary-layer flow past a cylindrical roughness element of unitary aspect ratio is investigated both experimentally and numerically at a subcritical Reynolds number. On the one hand, a shedding of spanwise-symmetric hairpin vortices characterized by a pulsation $\omega \simeq 1.05$ and a spatial wavelength $\lambda_x \simeq 5$ is observed experimentally. On the other hand, global stability analyses have revealed the existence of a varicose isolated mode, as well as of a sinuous one, both being linearly stable, whereas unsteadiness is observed during the experiments. Nonetheless, the isolated varicose mode, characterized by a pulsation $\omega = 1.02$, is highly sensitive, as ascertained by pseudospectrum analysis (see Fig. 1). To investigate how this mode might influence the flow dynamics, an optimal forcing analysis is performed [3]. The optimal response at $\omega = 1.02$ consists of a spanwise-symmetric perturbation with wavelength $\lambda_x \simeq 4.7$ inducing dynamics similar to the ones observed experimentally. This indicates that the onset of unsteadiness at subcritical Reynolds number can be due to quasi-resonance of such a varicose global mode, explaining the experimental observations.

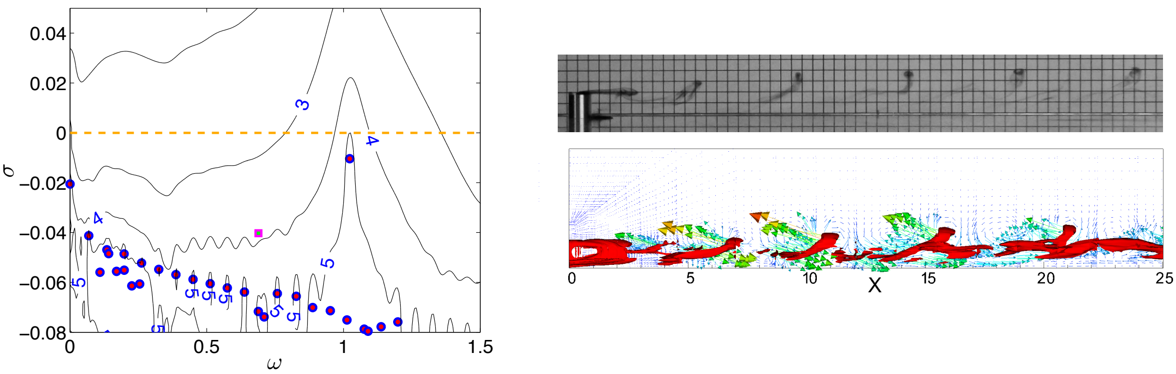

FIGURE 1. *(Left): Eigenspectrum (colored symbols) and pseudospectrum (solid lines) of the linearised Navier-Stokes operator for $(\eta; Re) = (1; 700)$. Circles (squares) represent varicose (sinuous) modes. The iso-lines represent pseudospectrum given by $\log_{10}\left(\varepsilon^{-1}\right)$ contours, with ε ranging from 10^{-6} to 10^{-3}. (Right-top): Flow visualization with potassium permanganate crystals placed upstream of roughness and in recirculation zone with 5 mm grid background.; (Right-bottom): DNS, Instantaneous fluctuation field u associated to the hairpin structure highlighted by the λ_2-criterion.*

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SHAPE OPTIMISATION FOR LINEAR STABILITY

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A linear stability analysis about a solution of the steady incompressible Navier-Stokes equations is performed, generating a set of mode shapes and their corresponding growth rates and frequencies. The Hadamard form[1] for the growth rate of a given mode is then derived. As a model problem, this shape derivative is then used to find the aspect ratio of an ellipse required to suppress vortex shedding at $Re = 90$.

Combining this gradient information with a projection method enables the linear stability of the flow to be used as a constraint during the optimisation procedure. As an example of this, the shape derivative is used to keep a shape marginally stable whilst optimising for a different objective function - the viscous dissipation within the domain (Figure 1). Projecting the search direction into a space where the growth rate is corrected to zero with first order accuracy allows us to ensure the shape remains marginally stable at each iteration.

Finally the framework is extended to a linear stability analysis about the solution to the RANS equations employing the Spalart-Allmaras turbulence model.

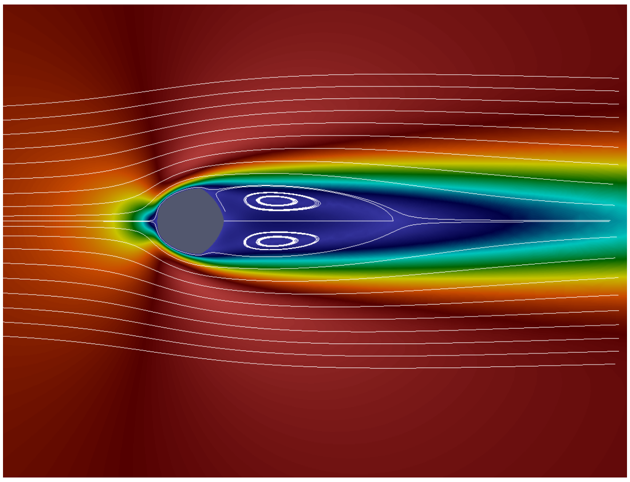

FIGURE 1. *End result of optimisation procedure: viscous dissipation is minimised whilst area is kept constant and growth rate of the leading global mode is held at zero*

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SYNCHRONIZATION IN N-PERIODIC ARRAYS OF FLUID SYSTEMS

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In many applications of technological and industrial interest, the fluid system to be analyzed or controlled consists of a periodic array of n individual, but identical units. Heat exchangers (consisting of cylindrical bundles), ring flame holders (consisting of several combustors in an annular configuration), high-performance turbomachines (consisting of a large number of blade passages) or vortex generators (consisting of a row of roughness elements) are but a few flow geometries where communication across individual units may play a significant role in analyzing the global dynamics of the respective fluid device.

Studying the dynamics (stability, receptivity, sensitivity) of one individual unit, even with periodic boundary conditions, can neither capture a possible cross-unit synchronization nor predict the rise of coherent motion that locks multiple units into a dominant structure. We will present a convenient and easily implementable framework [1] to analyze n-periodic arrays of fluid systems at the cost of a single-unit analysis. We will demonstrate modal, non-modal and direct-adjoint cases, and present tools for the analysis of trans-unit motion and synchronization. The framework relies on spectral properties of block-circulant operators and is akin to Bloch-wave analysis. Examples covering shear flow stabilities (see figure 1 for synchronization effects in an array of wakes), acoustic wave propagation through baffles, and turbomachinery cascades will be presented to illustrate the ease of implementation and the efficacy of the methodology.

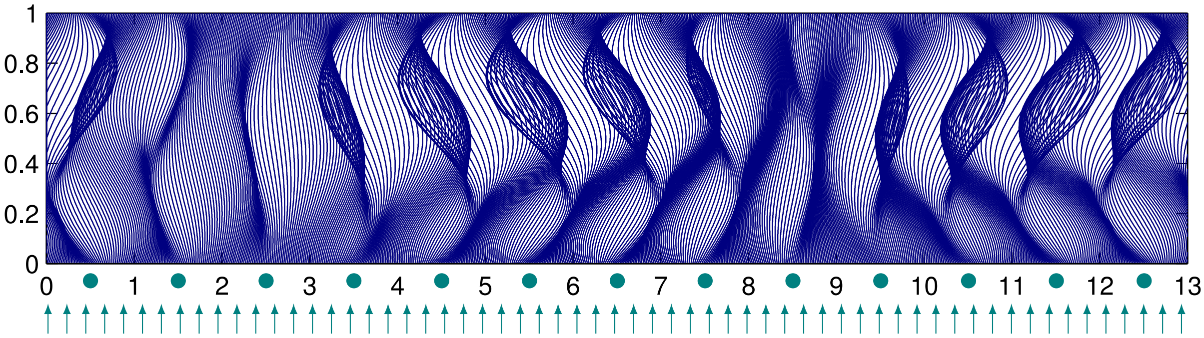

FIGURE 1. *Streaklines (in the x-y-plane) of a wake past 13 cylinders. Visualized is the second least stable mode, showing a synchronization of individual units.*

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ABSOLUTE AND CONVECTIVE INSTABILITY BEHAVIOUR OF WAVEPACKET STRUCTURES IN OSCILLATORY BOUNDARY LAYERS

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A review will be given of some recently discovered effects of base-flow unsteadiness on the development of small amplitude boundary-layer disturbances. We consider boundary layers that are created by time-periodic in-plane motions of a flat plate, which bounds what would otherwise be a stationary body of incompressible fluid. Linearised direct numerical simulations for the impulse response, together with a Floquet stability analysis, have been undertaken.

The simplest possible case, which is what is usually designated as being a Stokes layer, arises when the imposed time-periodic wall motion is taken to be purely sinusoidal, with a spectrum characterised by a single temporal frequency. This may be construed as providing a prototypical configuration for studies of the disturbance behaviour in oscillatory boundary layers. As well as investigating the disturbance evolution for this well-known example, we have also studied cases where high frequency harmonics were incorporated into the temporal periodicity of the wall motion. It was discovered that these harmonics could give rise to surprisingly large effects on the flow stability.

In the numerical simulations that we have conducted, the unsteadiness of the basic state was found to give rise to multiple wavepackets in the response to an impulsively applied excitation [1]. The development of these wavepackets displays an intricate family-tree-like spatial-temporal structure. Within this structure, individual wavepackets can be identified as having been born, in successive generations, at particular phases of the base-flow oscillation cycle. As time progresses, different components of the disturbance are convected to become increasingly separated from each other, by distances which are typically very much larger than the thickness of the boundary layer.

Results obtained from a linear stability analysis, for disturbances with a Floquet mode form, can be deployed to explain many of the important features of the spatial-temporal evolution that were found in the simulations for the impulse response. In particular, it is possible to anticipate the asymptotic temporal growth rate of the maximum of the disturbance amplitude, as well as the most dominant wavenumber exhibited in the spatial spectra. However, the family-tree-like structure that was revealed in the numerical simulations had not been in any way anticipated. Methods for predicting and understanding its overall character are still a matter of active investigation.

It has also been discovered that absolute instability can be displayed in the spatial-temporal structure of the disturbance development. The signature of the absolutely unstable behaviour was found to be strongly enhanced by the introduction of low-amplitude high frequency temporal harmonics into the oscillatory motion of the bounding wall. The flow modifications induced by this change in the wall motion had previously been shown to trigger instability for spatially monochromatic disturbances, when these were analysed using Floquet theory [2]. Nevertheless, it is not at all clear why the incorporation of a relatively weak higher harmonic into the time-periodicity of the base-flow can have a very marked effect in promoting absolute instability. This effect was sufficient to generate global temporal growth that dominated the evolution found in the numerical simulations for impulsively excited disturbances. By contrast, in the absence of any high-harmonic alteration to the unsteadiness of the boundary layer, the exhibition of the absolutely unstable behaviour appeared to be much less pronounced, making it far more difficult to detect.

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STABILITY OF OSCILLATORY ROTATING-DISK BOUNDARY LAYERS

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The rotating disk boundary layer has long been considered as providing an archetypal model for studying the stability of three-dimensional boundary-layer flows. It is one of the few truly three dimensional configurations for which there is an exact similarity solution of the Navier-Stokes equations. The crossflow inflexion point instability mechanism is common to both the rotating disk boundary layer and the flow over a swept wing. Thus the investigation of strategies for controlling the behaviour of disturbances that develop in the rotating disk flow may prove to be helpful for the identification and assessment of aerodynamical technologies that have the potential to maintain laminar flow over swept wings.

We will consider the changes in the stability behaviour that arise when the rotating disk base-flow configuration is altered by imposing a periodic modulation in the rotation rate of the disk surface. This modulation is utilised in order to induce a small level of oscillatory flow into the otherwise steady boundary layer. In effect, a time-periodic oscillatory Stokes layer is added, which has an alignment along the circumferential flow-direction. Thomas et. al. [2] have previously demonstrated that Tollmien-Schlichting waves can be stabilised when a similarly induced Stokes layer is conjoined to a plane channel flow.

Preliminary results indicate that the addition of a temporally oscillatory component to the rotating disk boundary layer can lead to significant stabilising effects, over a range of the parameters that have so far been considered.

Current work encompasses three distinct investigatory approaches. Linearised direct numerical simulations have been conducted, using the vorticity-based methods that were first adopted by Davies & Carpenter [1]. These simulations are complemented by a local in time linear stability analysis, that is made possible by imposing an artificial frozen base-flow approximation. This localised analysis is deployed together with a more exact global treatment based upon Floquet theory, which avoids the need for any simplification of the temporal dependency of the base-flow.

With laminar flow control techniques and suppression of crossflow vortices on swept wings foremost in mind, we will focus our presentation on the favourable results that have been discovered for stationary forms of disturbance.

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A LAMINAR KINETIC ENERGY MODEL BASED ON THE KLEBANOFF MODE DYNAMICS

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In 1997, Mayle & Schulz introduced the Laminar Kinetic Energy (LKE) concept, popularised in 2008 by Walters & Cokljat (WC) with their $k_T - k_L - \omega$ pattern [1]. WC wrote their formulation using the Boussinesq hypothesis for both turbulent and laminar velocity fluctuations (with two different eddy viscosities), separating the "large" coherent eddies from the small turbulent scales.
The aim of this study is to build a new bypass transition model. We have chosen to reuse the LKE concept, but based on the streak dynamics for the laminar zone in order to represent the Klebanoff mode (or streak) energy. The transport equation for the LKE k_L is built on the optimal disturbance equations (Andersson [2] and Luchini [3]) written for the longitudinal velocity fluctuation: the laminar fluctuation model is thus anisotropic. The k_L production rests on the lift-up phenomenon, described in 1980 by Landahl, which consists in the interaction between the Free-Stream Turbulence (FST), filtered by the "shear sheltering" phenomenon described by Jacobs & Durbin [4], and the boundary-layer shear.
Streak destabilisation can occur according to several scenarios, such as those presented in [5] and [6]. In our model, the transition is detected using a criterion comparing the streak energy to the mean shear flow. This criterion is consistent with DNS results from the literature (Jacobs & Durbin [5]). Once detected, the transition dynamics is controlled by an energy transfer from the laminar kinetic energy k_L to the turbulent one k_T.

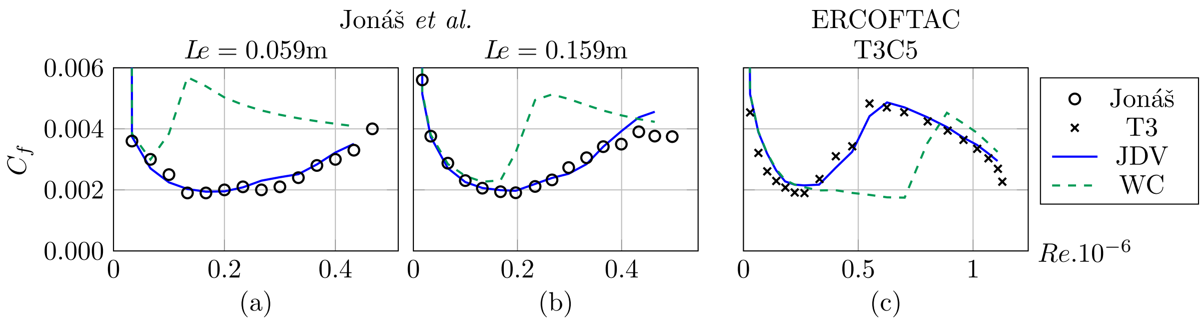

FIGURE 1. *Skin friction coefficient for 2 of the 6 cases from Jonáš et al. [7] (Tu = 3% with different integral length scales Le) and for the ERCOFTAC T3C5 case, with adverse pressure gradient.*

Figure 1 depicts the skin friction coefficient predicted by the Walters & Cokljat model (WC) and our model (JDV) for two of the Jonáš *et al.* cases [7] (a and b) and for the ERCOFTAC T3C5 case, with adverse pressure gradient (c). In their paper, Jonáš *et al.* aimed to show the influence of the turbulence dissipation scale *Le* on the bypass transition. These cases enable us to show the great improvement in term of transition detection and transition dynamics brought by our model. Additionally, in the ERCOFTAC T3 cases our model showed satisfying behaviour for various FST levels and in adverse pressure gradient.

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EXPLOITING EXTREME SENSITIVITY TO PASSIVELY CONTROL THERMO-ACOUSTIC INSTABILITY

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Thermoacoustic oscillations in combustion chambers occur when fluctuations in the flame's heat release rate become synchronized with acoustic oscillations in the chamber. If, each cycle, instants of higher heat release rate coincide with instants of higher pressure then thermal energy is converted to acoustic energy and the oscillation amplitude grows.

Nine decades of rocket engine and gas turbine development have shown that thermoacoustic oscillations are difficult to predict, but can usually be eliminated with relatively small ad hoc design changes. This paper explains why thermoacoustic instability is so sensitive to parameters such as operating point, fuel composition, and injector geometry, and therefore why thermoacoustic oscillations are difficult to predict but can be eliminated with small design changes. These changes can, however, be ruinously expensive to devise. For example, the small changes required to stabilize the F1 engines of the Apollo missions required 2000 full engine tests.

This paper proposes a more systematic approach, which requires: (i) a model that can reliably predict linear thermoacoustic behaviour; (ii) a cheap way to obtain the sensitivity of the linear growth rate to all parameters of the model; (iii) combination of this sensitivity information with practical constraints to find the optimal passive control mechanism.

Regarding (i), the extreme sensitivity to parameters introduces considerable systematic error in the prediction of thermoacoustic instability. To reduce this systematic error, model parameters can be tuned using inverse uncertainty quantification on tens of thousands of datapoints from automated experiments. Parameters learned on highly-instrumented and automated laboratory rigs can then become priors for, and be updated on, increasingly realistic rigs.

Regarding (ii), adjoint-based sensitivity analysis of the thermoacoustic model shows, in a single calculation, how the growth rate and frequency of thermoacoustic oscillations are affected by every parameter of the model, including shape parameters. This information can be used in a gradient-based optimization process in order to design a stable system. This presentation will outline the adjoint approach in thermoacoustics and then show results from a series of automated experiments that, with tens of thousands of datapoints, enable careful improvement of the model and therefore higher confidence in its predictions.

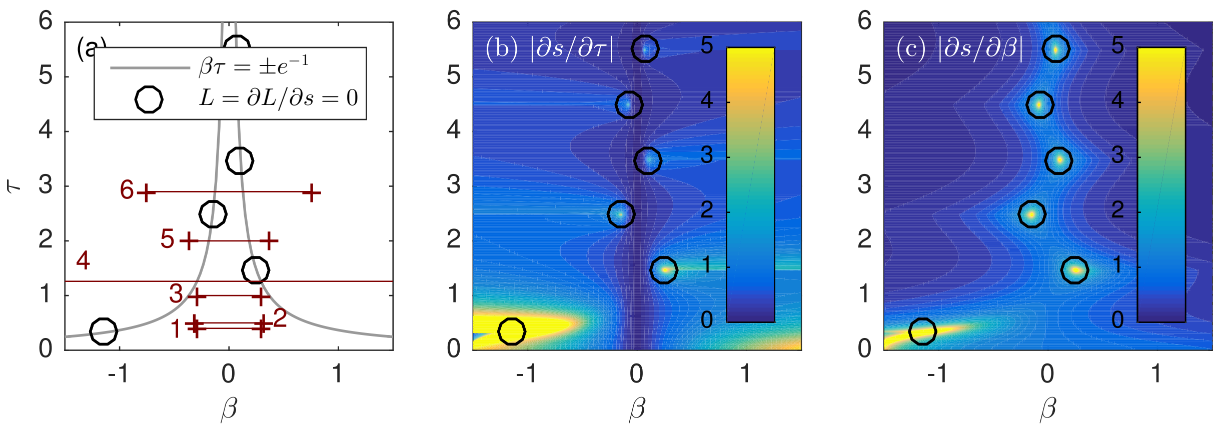

FIGURE 1. *(a) Points of extreme sensitivity (circles) calculated analytically as a function of heat release rate (β) and flame time delay (τ). The red lines show the ranges of (β, τ) for practical thermoacoustic systems. (b) Numerically-calculated $|\partial s/\partial \tau|$ and (c) $|\partial s/\partial \beta|$, showing that the eigenvalue, s, is indeed very sensitive to the parameters around the circled points. The sensitivity of the eigenvalue to every model parameter is calculated cheaply with adjoint methods.*

FLOW CONTROL OF WEAKLY NON-PARALLEL FLOWS BASED ON ADJOINT METHODS

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A general formulation is proposed to control the integral amplification factor of harmonic disturbances in weakly non-parallel amplifier flows [1]. The sensitivity of the local spatial stability spectrum to a base-flow modification is first determined, generalizing the results of [2]. This result is then used to evaluate the sensitivity of the overall spatial growth to a modification of the inlet flow condition. This formalism is applied here to a non-parallel Batchelor vortex which is a well-known model for trailing vortices generated by a lifting wing [3, 4]. The resulting sensitivity map indicates the optimal modification of the inlet flow condition so as to stabilize the helical unstable modes. It is shown that the control, formulated using a single linearization of the flow dynamics around the uncontrolled configuration, successfully reduces the total spatial amplification of all convectively unstable modes in the considered flow case.

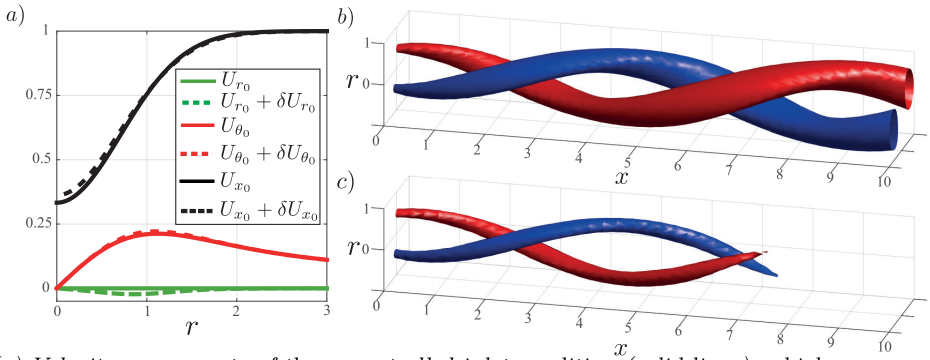

FIGURE 1. *(a) Velocity components of the uncontrolled inlet condition (solid lines), which correspond to a Batchelor vortex profile, and inlet condition perturbed by the application of the control (dashed lines). Isosurfaces of the maximum axial vorticity of the corresponding global spatial mode are shown in (b) for the uncontrolled case and in (c) for the controlled case.*

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ADJOINT-BASED BOUNDARY-DRIVEN CONTROL AND OPTIMISATION OF COMPRESSIBLE FLOWS

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The control of boundary conditions of fluid dynamics problems allows an effective control of the flow, in particular for convective problems. We will present an adjoint-based boundary-driven control/optimisation approach for the compressible Navier-Stokes equations. The modification of the boundary conditions allows for different control goals. Examples using acoustic and fluid-dynamic actuators will be presented.

Framework For the sake of clarity, the adaptation of non-reflecting boundary conditions is just indicated for one dimension. Application to more dimensions is straightforward and will be presented on site.
In general boundary conditions can be formulated as $q(x=0,t)=l(t)$ and $q(x=L,t)=r(t)$, with q as system state and l respectively r as boundary values in time. In linearised form they can be added to the Lagrangian function giving rise to the adjoint equations as an additional constraint with separate multipliers l^* and r^*.

$$\delta J = \ldots - {l^*}^T \left(\delta q(x=0) - \delta l(t)\right) - {r^*}^T \left(\delta q(x=L) - \delta r(t)\right) \tag{1}$$

Partial integration of these additional terms and combination of independent boundary variations from the general adjoint derivation results in

$$\left[\delta q^T \left(-\left(B^T + C^T\right) q^* - l^*\right)\right]_{x=0} = 0 \qquad \left[\delta q^T \left(+\left(B^T + C^T\right) q^* - r^*\right)\right]_{x=L} = 0 \tag{2}$$

with B and C as linearised operators of the governing equations. As both terms have to vanish

$$\frac{\delta J}{\delta l} = l^* = -\left(B^T + C^T\right) q^*(0,t) \approx \nabla_l J \qquad \frac{\delta J}{\delta r} = r^* = +\left(B^T + C^T\right) q^*(L,t) \approx \nabla_r J \tag{3}$$

results. The adjoint solution q^* on the boundary can be interpreted as gradient for optimal change of the direct boundary conditions. The framework is applied in iterative manner until a considered objective is sufficiently small.

Examples The framework is validated by means of an acoustic problem. The test aims at creation of a pressure pulse centered in the computational domain by modification of the surrounding non-reflecting boundary conditions. Different cases are considered: no flow, a constant base flow and the presence of a wall. The objective function is defined by $J = \iint (p - p_{\mathrm{tar}})^2 \sigma_t \mathrm{d}\Omega$ with p_{tar} as Gaussian distribution with an amplitude of 500 Pa. The weighting function σ_t is chosen as Dirac distribution $\delta_{t^n, t^{\mathrm{end}}}$.
Results for the setup with base flow are shown in Fig. 1. The adjoint framework is applied for 25 loops using a shape based gradient method. Due to the adaptation, from all boundaries curved pressure waves enter the domain. A circular pressure distribution is formed resulting in the demanded pressure pulse at the end of the computational time, as desired.

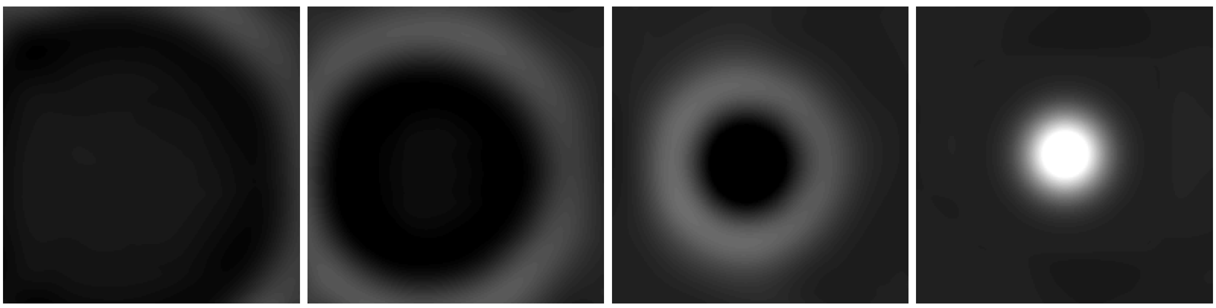

FIGURE 1. *Pressure evolution in time. The adapted boundary conditions form the desired pressure pulse.*

On site applications of the framework on a transitional problem and a data assimilation task will be presented.

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ON LINEAR STABILITY ANALYSES OF HYPERSONIC LAMINAR SEPARATED FLOWS IN A DSMC FRAMEWORK: RESIDUALS ALGORITHM AND THE LEAST DAMPED GLOBAL MODES

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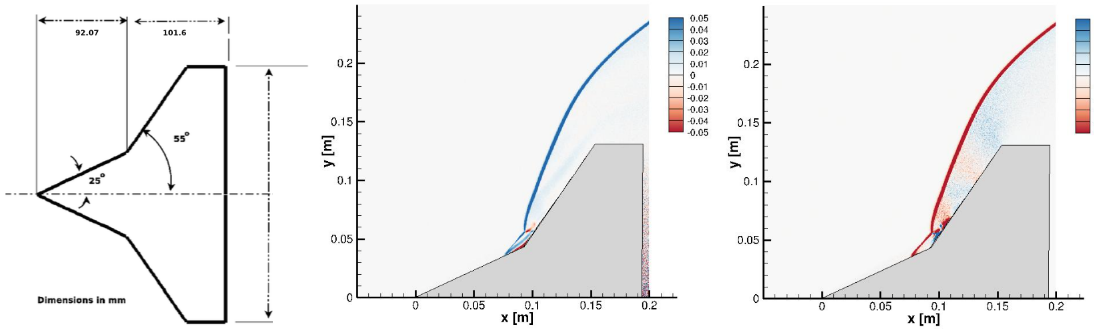
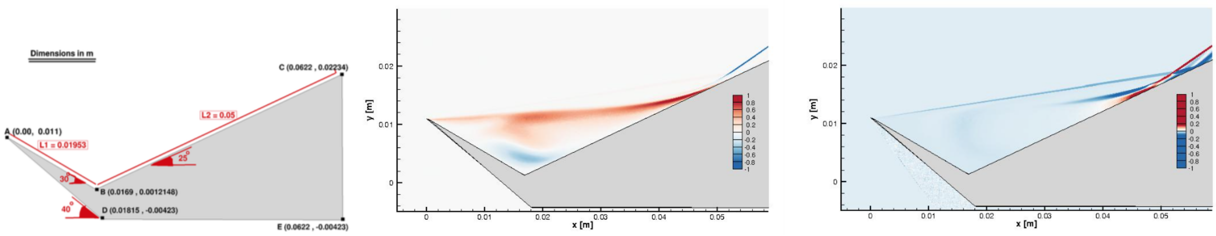
Linear global instability analysis of hypersonic laminar separated flows over a double cone and a tick configuration is performed (see figures 1 and 2). Statistical analysis of unsteady Direct Simulation Monte Carlo (DSMC) data [2, 3] yields the average damping rates of the respective least damped perturbations. The residuals algorithm [4] is then used to predict the converged steady state at a fraction of the DSMC computational effort, as well as identify the amplitude functions of the underlying global modes of shock-dominated laminar separated flow. It is seen that the main flow features, such as the shape and location of the shock, the triple point and the entire laminar separated region, are clearly reflected in the amplitude functions of the global modes. First steps are taken toward self-consistent instability analysis of DSMC-based hypersonic flows, based on linearization of the probability distribution function. The viability of the approach is demonstrated in incompressible global stability analysis computations based on the Lattice Boltzmann method [5].



(a) (b) (c)

Figure 1: (a) CUBRC sharp double-cone geometry [1]. Amplitude functions of least-damped linear global mode; (b) $\hat{u}$ and (c) $\hat{p}$.



(a) (b) (c)

Figure 2: (a) Tick geometry. Amplitude functions of least-damped linear global mode; (b) $\hat{u}$ and (c) $\hat{p}$.

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A DISTRIBUTED LAGRANGIAN MULTIPLIER/FICTITIOUS DOMAIN APPROACH FOR COUPLED FLUID-STRUCTURE STABILITY ANALYSIS

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The understanding and accurate prediction of coupled fluid-structure instabilities is of crucial importance in several engineering applications. The most classical approach to deal with the numerical simulation of fluid-structure interaction (FSI) problems is the Arbitrary Lagrangian-Eulerian (ALE) method [1]. Although this formulation has been widely used in unsteady FSI simulations, it results in quite expensive computation when adapted to the linear stability analysis of the fully coupled fluid-structure problem. This is essentially due to the more complicated form assumed by the fluid equations once written on the reference domain and linearised with respect to both flow perturbations and domain deformation.

In the present work we investigate an alternative approach to coupled fluid-structure stability analysis which is based on a Fictitious Domain (FD) formulation of the original FSI problem, and on the use of Distributed Lagrangian Multipliers (DLM) to properly handle the coupling between the fluid and the solid at their common interface, [2, 3]. Compared to the ALE description, the so-called DLM/FD formulation has the main advantage of keeping the linearised fluid equations in the same form of classical hydrodynamic stability analysis, being solved on a fixed Eulerian domain and with the solid elastic body "immersed in it". However, unlike the ALE approach, the fluid and the solid grids are in general not conforming, which could affect the local accuracy of the solution.

The DLM/FD technique is applied here to a low Reynolds number model problem representative of a strongly coupled fluid-structure system. The considered configuration features an elastic splitter plate attached to a rigid circular cylinder in cross-flow, as already investigated in [4, 5]. For selected values of the nondimensional governing parameters, the fluid-structure dynamics is characterised by the onset of an unstable oscillating mode, which is represented in Figure 1. The temporal frequency and the structural deformation of this mode are close to those of the first natural vibration mode of the elastic plate. A comparison of the obtained linear stability results with the ALE approach will be presented, discussing their numerical performance as well as the dependence of the DLM/FD results from the use of conforming/non-conforming fluid-structure meshes.

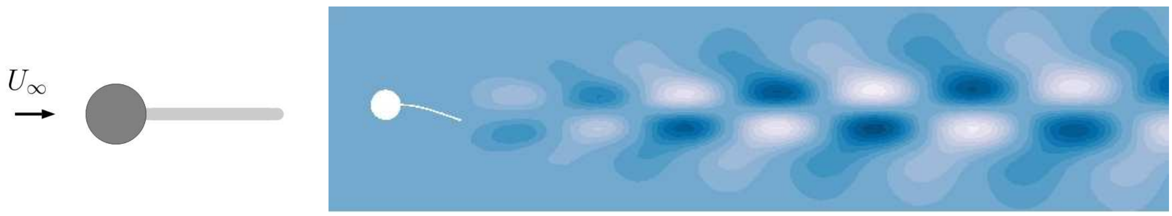

FIGURE 1. *FSI stability analysis. Left panel: sketch of the considered fluid-structure configuration. Right panel: unstable fluid-structure global mode represented by the contours of its streamwise velocity component and the corresponding shape of the structure displacement.*

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A CARTESIAN METHOD FOR COMPUTING THE NUMERICAL JACOBIAN OF TURBULENT FLOWS

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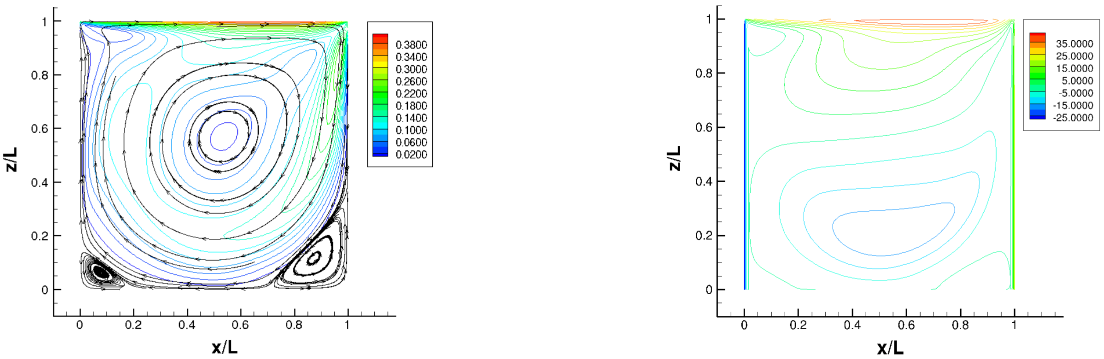
We report on our ongoing effort aimed at developing a numerical methodology to compute the sparse flux Jacobian matrix of a viscous flow. A global formulation is adopted to allow analyses of two- and three-dimensional complex flows. The linearization of the discrete Navier-Stokes equations around a baseflow is obtained by using first-order finite differences in a fully discrete framework[1, 2]. The proposed strategy allows to compute the matrix terms by means of repeated evaluations of the residual function $\mathcal{R}$. The CIRA simulation system based on Cartesian grids and an immersed boundary (IB) technique is applied both to extract the baseflow and to carry out the residual evaluations[3]. The present method may be naturally applied for accurate linear stability analyses of compressible turbulent flows and for gradient-based aerodynamic design optimization in a spirit similar to the work of [2, 4, 5] to name just a few. An example of numerical Jacobian analysis is shown in fig. 1. It refers to a compressible flow[6] at $Mach_\infty = .5$ and $Re_\infty = 900$ inside a close square-cavity of $L = 1$ wide whose upper wall is moving with a constant tangential velocity of $u/U_\infty = 1$. A constant temperature of $T/T_\infty = 1$ is fixed at each side of the cavity.



(a) Contour lines colored by Mach number.

(b) Contour lines colored by $\frac{\partial \mathcal{R}_{(\rho u)}}{\partial \rho u}$.

FIGURE 1. *Lid-driven cavity flow at* $Mach_\infty = .5$ *and* $Re_\infty = 900$.

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