17th ERCOFTAC SIG 33 Workshop

Progress in Flow Instability, Transition and Control

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Book of Abstracts

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Vigo, 36212, Spain

Conference Organizers:

Dr. Andrea Nóvoa– Imperial College London (chair)

Prof. Luca Magri – Imperial College London (co-chair)

Prof. Ardeshir Hanifi – KTH Royal Institute of Technology

Prof. Flavio Giannetti – Università di Salerno

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ERCOFTAC European Research Community On Flow, Turbulence And Combustion

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Tim Colonius

Tim Colonius is the Frank and Ora Lee Marble Professor of Mechanical Engineering and Medical Engineering at the California Institute of Technology. He is also the Executive Officer for Mechanical and Civil Engineering and holds the Cecil and Sally Drinkward Leadership Chair. He received his B.S. from the University of Michigan in 1987 and M.S and Ph.D. in Mechanical Engineering from Stanford University in 1988 and 1994, respectively. He and his research team use numerical simulations and data-driven analysis to study a range of problems in fluid dynamics, including aeroacoustics, reduced-order modeling, flow control, instabilities, shock waves, and multiphase flow. He also investigates medical applications of ultrasound and cavitation. Prof. Colonius is a Fellow of the American Physical Society and the Acoustical Society of America. He was the recipient of the 2018 AIAA Aeroacoustics Award, the 2021 APS-DFD Stanley Corrsin Award, and he was the 2022 ASME Freeman Scholar. He is an author of more than 350 publications, and he is the former editor-in-chief of the journal Theoretical and Computational Fluid Dynamics.

OWNS, NOWNS, and Unknowns: Efficient and robust tools for transition prediction

Accurately predicting instability and transition to turbulence in boundary layers is critical for aerodynamic design yet remains difficult for complex geometries and hypersonic flows where global stability methods are computationally prohibitive. We introduce the One-Way Navier–Stokes (OWNS) equations—a fast, streamwise-marching framework for modeling linear disturbance evolution in free-shear and boundary layers. OWNS eliminates key limitations of quasi-parallel approaches such as the parabolized stability equations (PSE) while maintaining high efficiency. We further extend the method to nonlinear interactions (NOWNS), enabling prediction of early-stage transition dynamics. OWNS also supports inverse stability analysis to identify optimal disturbances when initial conditions are unknown. In addition, we present a new receptivity framework—applicable to OWNS and global solvers—that uses optimization to determine combinations of acoustic, vortical, and entropic free-stream disturbances that maximize boundary-layer amplification. Together, these advances provide a powerful and computationally efficient toolkit for tackling instability, receptivity, and transition in realistic, high-speed aerodynamic configurations.

Jacob Page

Jacob Page is a Reader (Associate Professor) in Applied and Computational Mathematics at the University of Edinburgh. He was previously the Sultan Qaboos Research Fellow in mathematics at Corpus Christi College, University of Cambridge, and obtained his PhD from Imperial College London in 2016. He is interested in the nonlinear dynamics of both Newtonian and non-Newtonian fluids and uses ideas from modern dynamical systems theory combined with data-driven techniques and machine learning to study transitional and turbulent flows. His group's recent work has focused on the utility of "online learning" techniques in a variety of problems related to the dynamical systems view of shear flow turbulence. His work is/has been supported by an ERC Starting Grant, EPSRC and the Met Office.

Differentiable flow solvers and online learning for the dynamical systems view of turbulence

Online learning is a technique in which a differentiable flow solver is included inside the training loop for a neural network. One common use case in fluid mechanics is subgrid scale parameterizations in turbulence. In that problem, online learning produces schemes that are more stable than their "offline" counterparts, but the approach can also be used in a variety of other problems, including solution discovery and state estimation. In this talk I will describe three problems rooted in a "dynamical systems" view of fluid motion in which differentiable solvers play a critical role. First, I will show how the search for unstable periodic orbits – exact solutions of the Navier-Stokes equations which contain a particular recurrent process relevant to the chaotic flow – can be framed as an optimization problem. A scalar loss function which measures the distance between the state and its location a time T later is minimized using a combination of differentiation through the solver in combination with a high-dimensional optimizer. The approach converges an order of magnitude more solutions in a two-dimensional Kolmogorov flow than have been computed by earlier methods. In the second problem, I will present an online-learning algorithm for super resolution. Super resolution refers to the prediction of a high-resolution flow snapshot (usually with a neural network) given coarse-grained observation. In contrast to the usual approach, our method does not require a library of high-resolution snapshots: the loss function is a modification of the variational 4DVar algorithm for state estimation and seeks to match the coarse-grained evolution of the predicted state to measurements. I will compare the performance to classical 4DVar and assess the impact of known limiting length scales for assimilation. Finally, I will describe a method to learn mappings between a family of dynamical systems, with a training algorithm motivated by the definition of topological equivalence. The resulting neural networks allow for continuation of arbitrary solutions of the governing equations and extend the standard dynamical systems toolbox which can follow statistically steady states only.

Marios Kotsonis

Marios Kotsonis is Professor of Flow Control at Delft University of Technology, Faculty of Aerospace Engineering. His interests cover laminar-turbulent transition, flow instabilities, flow control and flow actuators, using theoretical, numerical and experimental techniques. He is recipient of the Veni and Vici grants of the Dutch Research Council and Starting, Proof-of-Concept and Consolidator grants of the European Research Council.

From wall impedance to fluidic crystals: Metamaterials for Controlling Boundary Layer Instabilities

Metamaterials are engineered composite structures, able to invoke resonant and dispersive wave phenomena in classical fields such as optics, acoustics, and electrodynamics. Their resulting dynamic properties go beyond (i.e. meta) what is considered possible in nature. Such a key property of interest is the so-called “bandgap", a range in which waves are suppressed when interacting with the Metamaterial. In this talk, a recent idea is explored, namely the use of Metamaterial-derived concepts for the control and attenuation of wave-like boundary layer instabilities, such as Tollmien-Schlichting waves. Recent numerical, theoretical and experimental work from the group of Flow Control at TU Delft will be discussed, followed by an outlook of current challenges and future directions.

Shervin Bagheri

Professor Bagheri's research explores the interaction between flowing fluids and materials to control and sense transport phenomena. His work spans laminar and turbulent flows over rough, porous, and lubricant-infused surfaces; biofilm growth and resistance in fluid environments; and flow through porous materials for energy and life-science applications. He earned his PhD in fluid mechanics at KTH on modal decomposition of transitional flows and later expanded into flow–material interactions. A Wallenberg Academy Fellow, SSF Future Research Leader, and ERC Consolidator Grant recipient, he leads the Fluids and Surface Group at KTH and coordinates the national initiative FLUX bringing together Swedish fluid mechanics researchers to address key challenges in science and technology.

Model reduction and control of Flows over complex and responsive Surfaces

Flows over complex surfaces exhibit rich physics that offer opportunities for control—such as drag reduction or heat transfer enhancement—but can also lead to detrimental effects like increased drag from roughness or contamination by bacterial biofilms. In some systems, surfaces (such as rough or porous materials) passively modify momentum transfer without being significantly affected by the flow. In others, including bacterial biofilms or lubricated walls, the surface evolves dynamically under flow, resulting in strong coupling and feedback between surface and flow. This talk presents recent progress toward reduced-order and data-driven models that efficiently capture these interactions. For passive surfaces, homogenization and machine-learning approaches are used to represent their effective influence on the flow. For responsive surfaces, models describe and eventually enable control of the coupled surface–flow evolution. Together, these advances provide new ways for predicting and controlling flow–surface interactions across physical and biological systems.

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"Reduced-order modeling and control of a shock-laden scramjet isolator"
Daniel J. Bodony, C. Errico, A. Padovan (U. Illinois Urbana-Champaign)

ATTACHMENT-LINE TRANSITION AND RELAMINARIZATION ON A HEATED LEADING EDGE

K.A.Goc[1], J.D. Crouch[1]
[1] *The Boeing Company, Seattle, U.S.A.*

Surface heating effects can alter the state of the attachment line, potentially impacting targeted downstream benefits of either laminar or turbulent flow. For aircraft incorporating hybrid-electric propulsion, the potential to offload heat through the wing surface can result in a loss of laminar flow and reduced aerodynamic performance [1]. In other applications, turbulent flow may be desired for providing better handling characteristics [2] or for surface cooling to limit potential overheating due to wing anti-ice operation during dry air conditions. For the adiabatic-wall attachment-line boundary layer, if $\bar{R} = W\delta_r/\nu$, is below $\bar{R} \approx 260$ the flow will be laminar, and if it is above $\bar{R} \approx 580$ the flow will be turbulent (where W is the edge velocity along the attachment line, ν is the kinematic viscosity, and $\delta_r = \sqrt{\nu/(dU/ds)|_{s=0}}$). Between these Reynolds numbers, the state of the flow is dependent on initialization from any form of stochastic and deterministic excitations.

For non-adiabatic wall conditions, results of [3] show a significant reduction in the critical $\bar{R}$ for instability as a result of surface heating, with $\bar{R} = 356$ at $T_w/T_e = 1.1$ as compared to $\bar{R} = 583$ at $T_w/T_e \approx 1$. The analysis of [2] considered a wide range of surface temperature ratios, and showed a reduction in the critical Reynolds number for instability to $\bar{R} \approx 250$ for $T_w/T_e \approx 1.28$, and to $\bar{R} \approx 150$ for $T_w/T_e \approx 1.68$. These higher temperature ratios show instability for $\bar{R}$ values below the relaminarization threshold for adiabatic wall conditions and suggests these conditions could have turbulent attachment-line flow. However, it remains to be seen if the relaminarization boundary also shifts toward lower values of $\bar{R}$ with increasing T_w/T_e – and if so, what $\bar{R}$ values are required to relaminarize the flow.

We utilize wall-resolved large eddy simulations to investigate the attachment-line flow in the presence of elevated surface temperature to determine if the onset of instability is sufficient to produce turbulent flow. The results show a more complex behavior than observed under adiabatic conditions. At a given $\bar{R}$, increasing T_w/T_e leads to a transition from a laminar steady state to an unsteady finite-amplitude equilibrium state. Further increases in T_w/T_e result in turbulent bursting. An increase in $\bar{R}$ leads to a turbulent attachment-line flow. These four flow conditions are demonstrated in figure 1.

The talk will discuss the effects of surface heating on the instability and relaminarization boundaries and on the potential downstream impacts to transition when the attachment line remains laminar.

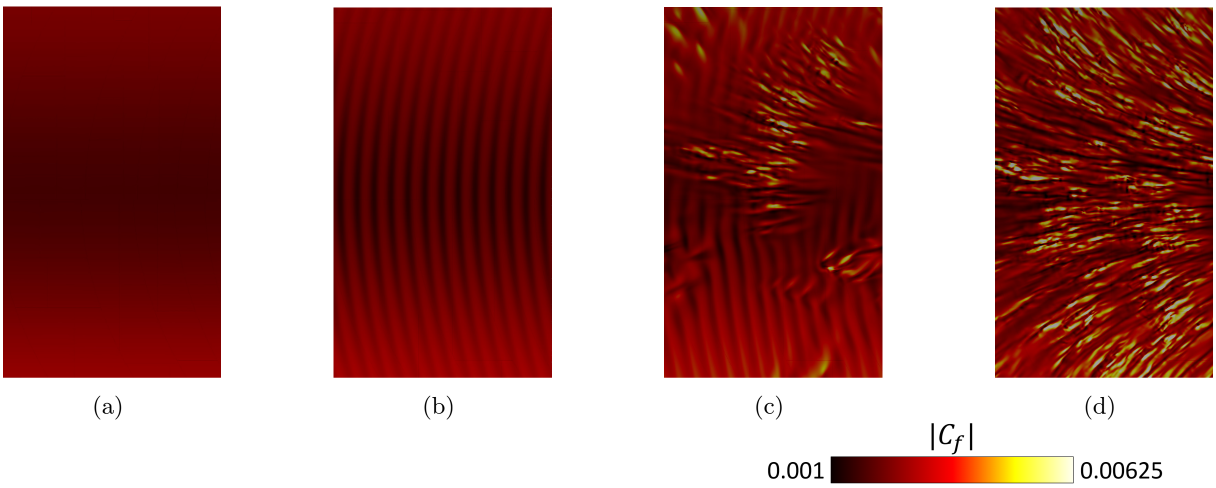

Figure 1: Skin friction on the attachment line, showing: (a) laminar flow at $\bar{R} = 263, Tr = 1.2$, (b) unstable equilibrium flow at $\bar{R} = 263, Tr = 1.3$, (c) unstable flow with turbulent bursting at $\bar{R} = 263, Tr = 1.4$, and (d) turbulent flow at $\bar{R} = 286, Tr = 1.4$. Flow is into the page from right to left.

References

[1] M. Barahona, T.A.F.van de Weijer, A.F. Rius-Vidales and M. Kotsonis. Impact of a heated wall on the laminar-to-turbulent transition of crossflow vortices: an experimental study. AIAA Paper 2024-0695, 2024.

[2] H.L. Reed and W.S. Saric. Attachment-line heating in a compressible flow. *J. Eng. Math.*, 84(1):99–110, 2014.

[3] D.G. Lasseigne, T.L. Jackson and F.Q. Hu. Temperature and suction effects on the instability of an infinite swept attachment line. *Phys. Fluids A*, 4(9):2008–2012, 1992.

BEYOND EDDY VISCOSITY: USING A TRANSPORT MODEL TO IMPROVE LINEAR ANALYSIS

S.J. Knechtel[1], K. Oberleithner[1]
[1] *Laboratory for Flow Instabilities and Dynamics, Technical University Berlin*

In recent years, linear mean-field analysis has played an important role in the calculation of coherent structures of turbulent flows as well as in stability analysis and control. However, the resulting linear operator, which is derived directly from the mean flow, leads to erroneous results in many flow configurations. The use of an eddy viscosity significantly improves the results and is extensively discussed in the research community.
This talk will be in two main parts. In part I we assimilate the ideal mean operator from data by using constraints that follow the inherent Lie symmetries of the system. In addition to an eddy viscosity, these constraints lead to a linear velocity transport as model parameter[1]. We show first results for the flapping (laminar) cylinder flow by analyzing two quantities: First, the sensitivity to a constant volume forcing is investigated. We show that an eddy viscosity alone cannot be used to calculate the correct sensitivity with the mean linear operator. Due to its isotropic nature, it satisfies too many symmetries and therefore cannot represent directional effects due to the Reynolds stresses. In addition, near the recirculation zone of the cylinder, we observe counter gradient transport that cannot be modeled by a diffusive expression. In contrast, the assimilated linear transport velocity can almost perfectly reproduce the sensitivity (see Figure 1, left column). Secondly, we will take a look at the mode shape of the leading eigenmode. Here, the eddy viscosity as a model parameter has the same shortcomings as in the sensitivity case. An additional linear transport improves the results significantly (see Figure 1, right column).
Part II of the talk will be about getting the model quantities from the mean flow alone. We introduce a linear mean flow equation that takes higher averaging moments (like the Reynolds stresses) into account and compare it to a "mean flow consistent" approach, which fits the model quantities to the nonlinear Navier-Stokes equations.

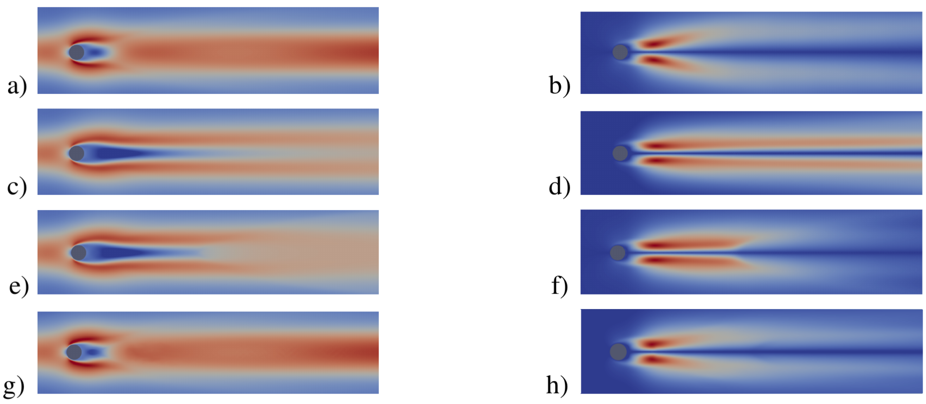

FIGURE 1. *Sensitivity to constant volume forcing (left column) and total value of stream-wise component of the leading eigenmode (right column). From top to bottom: a) true solution and b) FFT result, both computed with time resolved data; c-d) solution generated with the mean linear operator without modeling; e-f) with an eddy viscosity; g-h) with linear transport & eddy viscosity.*

References

[1] D. Klingenberg, M. Oberlack, and D. Pluemacher. Symmetries and turbulence modeling. *Phys. Fluids* 32(2):025108, 2020.

TURBULENT SPOT CHARACTERISTICS IN FREE-STREAM TURBULENCE INDUCED TRANSITION

İmge Yığılı[1], Jens H.M. Fransson[2]
[1] *KTH Royal Institute of Technology*
[2] *KTH Royal Institute of Technology*

The mechanism of growth and spreading of turbulent spots in boundary layers is of interest for understanding the boundary layer transition from laminar to turbulent flow due to free-stream turbulence (FST). The reported values for the leading and trailing edge speeds of a turbulent spot are around 0.88% and 0.5% of the free-stream velocity (U_∞), respectively [1]. The lateral half spreading angle (α) is reported to be $8 - 11°$. However, unstedy streamwise elongated streaks appearing due to FST is shown to affect the development of turbulent spots and consequently, the relative length of the transition zone [2]. So far, turbulent spot data in FST induced transition is very limited. This study is focused of turbulent spot measurements in a flat plate boundary layer subjected to FST generated by several passive grids.
Multiple turbulence generating passive grids with different geometrical properties are used to systematically vary the turbulence intensity (Tu) and integral length scale (Λ_x) of the FST. Individual turbulent spots are then tracked using a novel experimental setup. The setup consists of 25 spanwise microphone arrays, which are mounted on the flat plate with increasing distance in the streamwise direction. Each microphone array consists of 53 individual wall-mounted microphones that can be sampled with a frequency of 5 kHz. Four microphone arrays can be sampled simultaneously. This allows the tracking of individual turbulent spots in the streamwise and spanwise plane in a non-intrusive manner. Two-point cross-correlation measurements with two single hot-wire sensors are performed to measure the spacing (λ_z) of the unsteady streamwise streaks introduced due to FST.
Over 5×10^4 individual turbulent spots have been tracked using wall-pressure fluctuation signals measured by the microphones. The signals are post-processed using an in-house developed MATLAB code to identify the turbulent spots. The advantage with this technique is that, all the statistical properties such as the ensemble averages, standard deviation and probability density function distributions for all important spot quantities are obtained for each FST case.
Initial analyses show that the growth rate ($\mathcal{G} = (U_{LE} - U_{TE})\tan(\alpha)$) increases with increasing Reynolds number based on streak spacing (λ_z), i.e. with $Re_{\lambda_z} = U_\infty \lambda_z/\nu$. The data shown in Figure 1 is the ensemble average of more than 1000 spots for each FST case. The error bars are within the markers. An interesting finding is that turbulent *patches* can sporadically spread faster than U_∞.

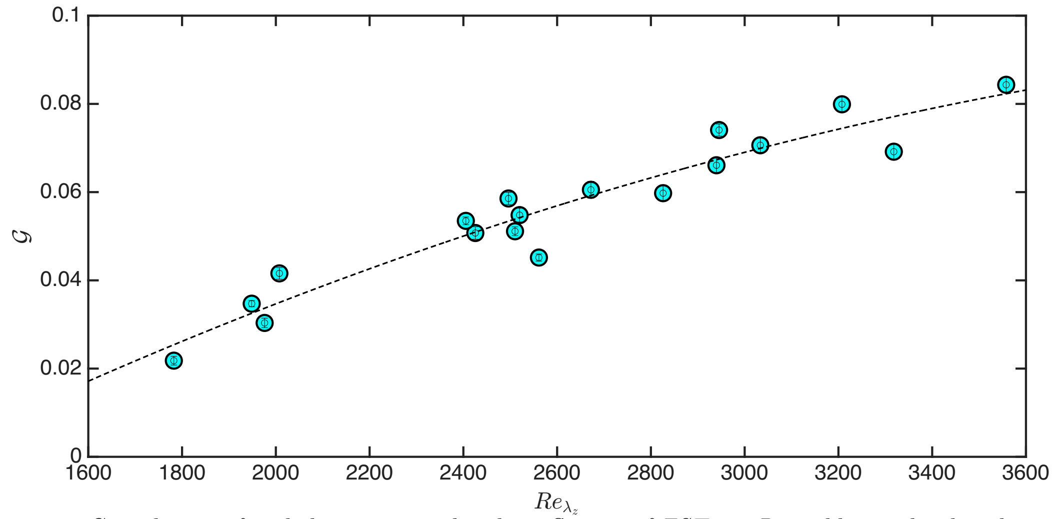

FIGURE 1. *Growth rate of turbulent spots under the influence of FST vs. Reynolds number based on streak spacing. $U_\infty = 6$ m/s.*

References

[1] X.Wu. *New Insights into Turbulent Spots. Annu. Rev. Fluid Mech.*, 55:45–75, 2023.
[2] J.H.M. Fransson. *Turbulent spot evolution in spatially invariant boundary layers. Phys. Rev. E.*, 81(3):035301, 2010.

ON THE INFLUENCE OF FREE-STREAM TURBULENCE ON ROUGHNESS-INDUCED BOUNDARY-LAYER TRANSITION

Tristan M. Römer[1], Markus Kloker[1], Ulrich Rist[1], Christoph Wenzel[1]
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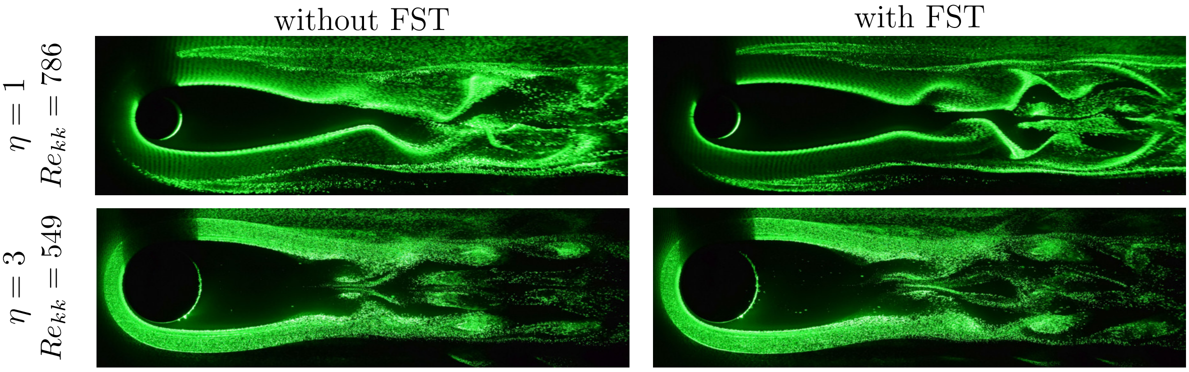

Cylindrical roughness elements have become a canonical configuration serving as a benchmark for testing how well current theoretical and numerical models capture the complex wake dynamics they produce, to the extent that they have even been used for boundary-layer stabilisation [1]. While advances in computational methods have greatly improved our ability to analyse and predict the flow physics of roughness-induced transition – such that the underlying mechanisms are understood in considerable detail for idealised conditions – experimental studies and real-world applications are almost invariably affected by external disturbances, most notably free-stream turbulence (FST). Consequently, FST can substantially modify both the observed flow phenomena and the dominant transition pathways. Discrepancies between theoretical predictions and experiments can therefore rarely be attributed unambiguously to either modelling assumptions or uncontrolled external perturbations. This motivates a closer examination of precisely how FST influences roughness-induced transition.

This study experimentally examines the alteration of roughness-induced transition by FST in a laminar water channel by exposing cylindrical roughness elements of diameter-to-height ratios $\eta = 1, 2, 3$ to three distinct turbulence levels ($Tu \approx 0.05\%,\ 1.15\%,\ 1.55\%$). The investigation utilises hydrogen-bubble flow visualisation, particle image velocimetry (PIV), and hot-film anemometry. Although the roughness Reynolds number Re_{kk} is varied solely via the free-stream velocity, a detailed characterisation of the incoming FST and the resulting Klebanoff modes demonstrates that their variation remains moderate, thereby enabling a controlled assessment of FST effects.

FST consistently promotes earlier transition for all η at subcritical global-instability Reynolds numbers; however, its influence on the underlying instability mechanisms depends strongly on the aspect ratio.

The top figure presents exemplary hydrogen-bubble visualisations of a thick ($\eta = 3$) and a thin ($\eta = 1$) cylinder positioned at $x = 400\,\text{mm}$ downstream of the leading edge. The images depict supercritical Reynolds numbers, comparing conditions without FST and with elevated FST ($Tu \approx 1.15\%$). For the 'thick' cylinder ($\eta = 3$), the global instability remains remarkably robust: the dominant varicose mode shows virtually no sensitivity to FST. In contrast, the 'thin' cylinder ($\eta = 1$) exhibits an extreme susceptibility: already moderate FST suppresses the sinuous mode otherwise predicted by global stability theory (see e.g. [2]) at supercritical Reynolds numbers. Furthermore, spectral analysis reveals that the dominant frequencies are also significantly affected by FST in the $\eta = 1$ case.

These findings provide a clear, experimentally grounded explanation for why global stability predictions often fail to materialise the structures in real, turbulence-contaminated environments and establish FST as a decisive factor governing whether, when, and how roughness-induced instabilities manifest.

References

[1] C. Cossu and L. Brandt. Stabilization of Tollmien–Schlichting waves by finite amplitude optimal streaks in the Blasius boundary layer. *Phys. of Fluids*, 14(8):L57-L60, 2002.

[2] M. A. Bucci, D. K. Puckert, C. Andriano, J.-C. Loiseau, S. Cherubini, J.-C. Robinet and U. Rist. Roughness-induced transition by quasi-resonance of a varicose global mode. *J. Fluid Mech.*, 836:167-191, 2018.

INFLUENCE OF MACH NUMBER AND 3D INSTABILITIES ON THE TRANSITION MECHANISMS OF LAMINAR BOUNDARY LAYERS OVER GAP DISCONTINUITIES

Víctor Ballester Ribó[1], Jeffrey Crouch[2], Yongyun Hwang[1], Spencer Sherwin[1]
[1] *Department of Aeronautics, Imperial College London, UK* [2] *The Boeing Company, USA*

In this work we investigate the linear stability of laminar boundary layers encountering a gap discontinuity. The gap is modeled as a rectangular cavity of width w and depth d embedded in a flat plate aligned with the flow. The depth of the cavity is varied within the range $d/\delta^* \in [0.5, 4]$, while the width is set to $w/\delta^* \in [5, 100]$. The Reynolds number considered is $\mathrm{Re}_{\delta^*} = 1000$, where δ^* denotes the displacement thickness measured at the upstream edge of the gap on a smooth surface that is free of discontinuities. High-fidelity simulations for both incompressible and compressible flows are performed using the spectral/*hp* element method implemented in Nektar++ [1]. Under incompressible or low-Mach-number conditions, previous experimental studies [2] have shown that narrow gaps amplify Tollmien–Schlichting (TS) waves, leading to transition downstream through the primary instability pathway, as illustrated in Figure 1. In contrast, sufficiently wide gaps promote a bypass transition originating near the downstream edge of the gap. In incompressible simulations, for fixed gap depth d, a Hopf bifurcation emerges as the gap width exceeds a critical value $\mathcal{H}(d)$. The periodic orbit emerges as a form of self-sustained oscillation near the downstream edge of the gap. The critical width for this bifurcation increases as the gap depth decreases and disappears for shallow gaps ($d/\delta^* < 1.25$), which remain globally stable. The functions $d \mapsto \mathcal{B}(d)$ (bypass threshold) and $d \mapsto \mathcal{H}(d)$ show good agreement. We further extend the analysis to examine the effects of Mach number ($\mathrm{M} \in (0, 1)$) and three-dimensional gap geometries on the bifurcation behavior. Results indicate that increasing Mach number lowers the critical width $\mathcal{H}(d)$, suggesting that compressibility promotes bypass transition.

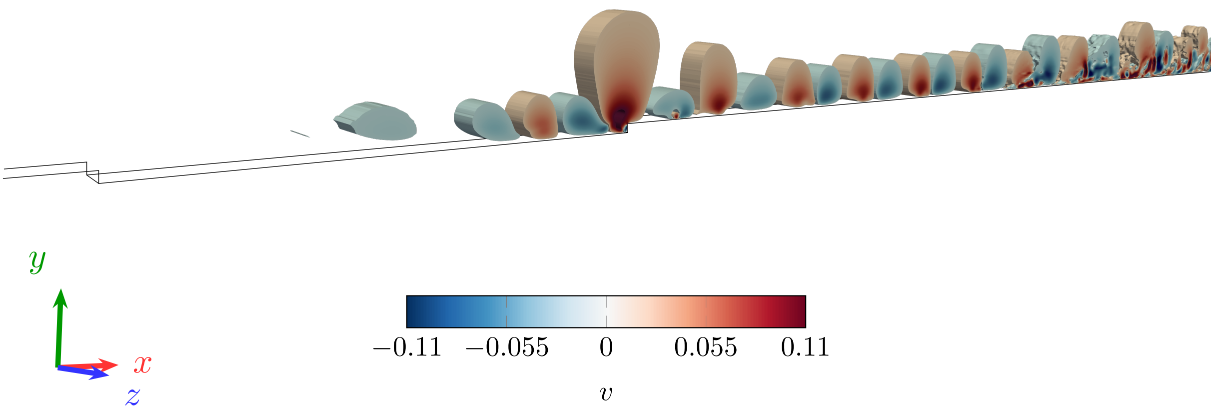

FIGURE 1. *Wall-normal velocity isovolumes showing the over-amplification of TS waves due to the presence of a 3D gap discontinuity of depth* $d = 1.5\delta^*$ *and width* $w = 80\delta^*$*, and transition to turbulence downstream of the gap.*

References

[1] C. D. Cantwell, S. J. Sherwin, R. M. Kirby, and P. H. J. Kelly. Nektar++: An open-source spectral/*hp* element framework. *Comput. Phys. Commun.*, 192:205–219, 2015. DOI: 10.1016/j.cpc.2015.02.008.

[2] J. D. Crouch, V. S. Kosorygin, M. I. Sutanto, and G. D. Miller. Characterizing surface-gap effects on boundary-layer transition dominated by Tollmien–Schlichting instability. *Flow*, 2:E8, 2022. DOI: 10.1017/flo.2022.1.

SUPERSONIC RECEPTIVITY TO SURFACE ROUGHNESS

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The development of future hypersonic vehicles presents several technological challenges, one of the most critical being the control of laminar-turbulent transition in boundary layers ingested by the air intakes. This issue stems from the reliance of hypersonic propulsion systems on shock-wave systems to decelerate the incoming flow before combustion, as their interaction with a laminar boundary layer can trigger large-scale flow separations and reduce engine efficiency. A promising strategy to mitigate this problem is to trigger an early laminar-turbulent transition of the boundary layer upstream of the shock interactions. The present study investigates the receptivity of supersonic boundary layers to three-dimensional disturbances originating from free-stream perturbations and surface roughness, with the goal of identifying the ones who are amplified the most. The configuration considered is a two-dimensional flat plate with a rounded leading edge, subject to a uniform inflow at $Ma_\infty = 4.5$ and $Re_{unity} = 3.4e6\ m^{-1}$.
The influence of surface roughness (periodic in the spanwise direction z), is accounted with a linear model by imposing non-homogeneous boundary conditions at the wall [1], enabling calculations on the mesh of the smooth geometry. The in-house code BROADCAST [2] is employed to compute the two-dimensional base flow, and to determine the "optimal" 3D perturbations, i.e. the roughness shape and the spanwise wavenumber that yield the most energetic perturbation. This optimization is performed via a resolvent-based approach, permitting the roughness to assume any shape in the x-y plane. Analyzing results for different nose radii, we show that the leading edge is the most sensitive zone to roughness receptivity. The perturbation thus generated impacts the shock and is then able to generate streaks downstream (Figure 1).
We also investigate, using a linear framework, the case in which the sources of disturbances are freestream perturbations (acoustic waves, vortical perturbations) superposed on the inflow. Furthermore, their interaction with the roughness is evaluated with a weakly nonlinear analysis.

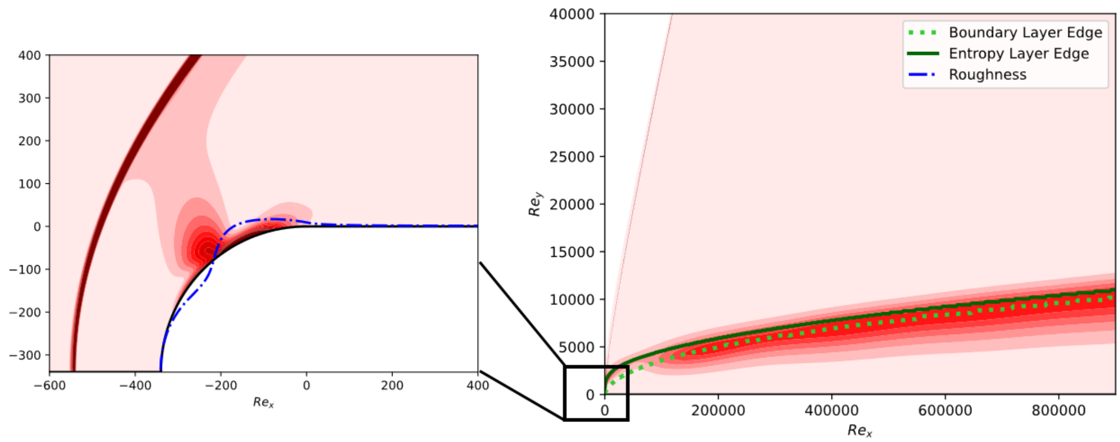

FIGURE 1. *Energy evolution of the perturbation induced by the "optimal roughness" for spanwise wavenumber $\beta = 1.0e-4$ on the plate with leading edge radius $R_n = 0.1mm$.*

References

[1] E. Kitzinger, D. Sipp, O. Marquet, E. Piot. Receptivity of swept-aerofoil flows to small-amplitude wall roughness using a transfer function from wall displacements to induced velocity perturbations. *Flow. 2023;3:E41*
[2] A. Poulain, C. Content, D. Sipp, G. Rigas, E. Garnier. BROADCAST: A high-order compressible CFD toolbox for stability and sensitivity using Algorithmic Differentiation. *Computer Physics Communications, Volume 283, 2023, 108557, ISSN 0010-4655.*

GEOMETRICAL OPTIMISATION OF RECTANGULAR MINIATURE VORTEX GENERATORS

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Numerical simulations [1] and experiments [2] have shown that miniature vortex generators (MVGs) can create spanwise mean velocity gradients (SVG), which effectively attenuate the growth of Tollmien–Schlichting waves. This mechanism is capable of delaying the transition from laminar to turbulent flow in a boundary layer under low-turbulence conditions.

A recent parametric study [3] revealed that the vortex generator configurations measured in the aforementioned experiments were not optimal. Consequently, our objective has been to determine the optimal geometric parameters for MVGs for a given far-field velocity and streamwise position.

The methodology follows an efficient modeling framework, which has been validated with the experiments [2]. It combines a three-dimensional CFD and the Boundary Region Equations (BRE) for the base flow calculation and the BiGlobal spatial stability equations for stability analysis. The resulting eigenvalues are then used in the e^N method to predict the streamwise location of the transition.

The optimization aims to find the furthest streamwise location of the laminar-turbulent transition focusing on the attenuation of the TS waves, while keeping the growth rate of high frequency disturbances low. A Bayesian approach [4], is employed to optimize the geometric properties of the MVGs. Two optimisation campaign were conducted, a smaller scale one, with three varied parameters, to check the viability of the method, and a larger scale one, where every geometric parameter other than the MVG's width was varied.

Finally, the most promising points chosen from the Pareto front are further analysed to better understand the underlying physical mechanisms which improve the effectiveness of this strategy.

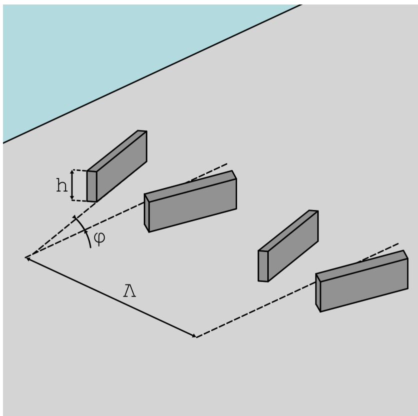

FIGURE 1. *Schematic drawing of two MVG pairs with their varied parameters in the case of a three variable optimisation, namely the height (h) and angle (φ) of the MVG-s and the distance (Λ) between MVG pairs.*

References

[1] L. Siconolfi, S. Camarri, J. H. M. Fransson. Stability analysis of boundary layers controlled by miniature vortex generators. *Journal of Fluid Mechanics*, 784:596-618, 2015.

[2] S. S. Sattarzadeh, J. H. M. Fransson. On the scaling of streamwise streaks and their efficiency to attenuate Tollmien-Schlichting waves. *Experiments in Fluids*, 56, 2015.

[3] A. Szabó, P. T. Nagy, G. De Baets, M. Vanierschot, Gy. Paál. Stability analysis of a streaky boundary layer generated by miniature vortex generators. *Computers and Fluids*, 269:106-123, 2024.

[4] S. Ament, S. Daulton, D. Eriksson, M. Balandat, E. Bakshy. Unexpected Improvements to Expected Improvement for Bayesian Optimization. *NIPS '23: Proceedings of the 37th International Conference on Neural Information Processing Systems*, 20577–20612, 2024.

WEAKLY NONLINEAR RESOLVENT ANALYSIS IN AN AXISYMMETRIC SUDDEN EXPANSION

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Flows in sudden symmetric planar expansion are known to undergo a symmetry-breaking bifurcation at low Reynolds numbers ($\leq$ 300 for expansion ratios greater than 2), which are well predicted by linear stability analysis[1]. In its axisymmetric counterpart, early experimental studies show a periodic time-breaking bifurcation for Re between 600-1600 for a 1:2 outlet to inlet ratio, prior to the transition to turbulence[2]. More recent work suggests the existence of a low-Re steady symmetry breaking[3]. Classical linear stability analysis, however, seems to fail to capture both of these bifurcations and predicts a critical Re of 3600 for a periodic symmetry-breaking perturbation [4]. Evidence of large transient growth has been brought to light for Re $\leq$ 1200, showing the sensitivity of this system to experimental noise and imperfections due to its non-normality[5].
In order to reconcile these observations, we propose to investigate the axisymmetric expansion by means of a resolvent analysis. Using the optimal frequency response and forcing for different azimuthal wavenumbers, we derive a weakly-nonlinear equation to predict the saturated state in the presence of external volume or inlet forcing as well as in the presence of geometry imperfection. This provides useful insights on the impact of experimental imperfections in this system, as well as a better physical understanding of its dynamics.

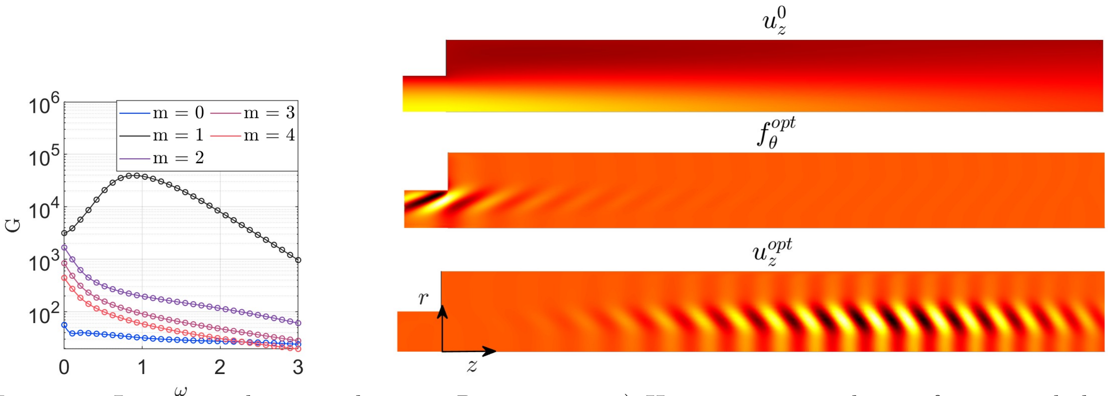

Figure 1: Linear resolvent analysis at $Re = 1200$. a) Harmonic optimal gain for azimuthal numbers $m \in [0, 4]$. b) top: streamwise velocity of the base flow, middle and bottom: azimuthal component of the optimal forcing and response for $\omega = 0.94$, $m = 1$.

References

[1] T. Hawa, and Z. Rusak. Viscous flow in a slightly asymmetric channel with a sudden expansion. *Phys. Fluids*, 12:2257–2267, 2000.
[2] K. R. Sreenivasan, and P. J. Strykowski. An instability associated with a sudden expansion in a pipe flow. *Phys. Fluids*, 26:2766-2768, 1983.
[3] T. Mullin, and J. R. T. Seddon, and M. D. Mantle, and A. J. Sederman. Bifurcation phenomena in the flow through a sudden expansion in a circular pipe. *Phys. Fluids*, 21:014110, 2009.
[4] E. Sanmiguel-Rojas, and C. del Pino, and C. Gutiérrez-Montes. Global mode analysis of a pipe flow through a 1:2 axisymmetric sudden expansion. *Phys. Fluids*, 22:071702, 2010.
[5] C. D. Cantwell, and D. Barkley, and H. M. Blackburn. *Transient growth analysis of flow through a sudden expansion in a circular pipe. Phys. Fluids*, 22:034101, 2010.

CHARACTERISATION OF NONLINEAR FORCING IN THE RESOLVENT FRAMEWORK FOR A SELF-SIMILAR ADVERSE-PRESSURE-GRADIENT TURBULENT BOUNDARY LAYER AT THE VERGE OF SEPARATION

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Resolvent analysis expresses the linearised Navier–Stokes equations as a transfer function between forcing representing the non-linear interactions and response, and has become a widely used framework for flow-structure extraction and control in turbulent flows. In self-similar adverse pressure gradient turbulent boundary layers (SS-APG-TBLs) at the verge of separation, strong non-parallelism in the mean flow motivates a bi-global formulation that retains streamwise and wall-normal inhomogeneity [1]. An open question is the structure of the nonlinear forcing that drives the linearised dynamics, in particular, whether the forcing is effectively broadband ("white") or organised in space and across scales ("coloured"), and how this organisation relates to the most amplified resolvent modes [2]. We present a DNS-based characterisation of the full Reynolds-stress–gradient forcing in a SS-APG-TBL [3]. Time-resolved three-dimensional DNS fields are used to compute all nine mean-removed Reynolds-stress–gradient terms, which constitute the three-component forcing vector. Spectral statistics are averaged in the streamwise direction in self-similar coordinates, and studied as a function of spanwise wavelength, temporal frequency and wall-normal location. Spectra of the three forcing components exhibit comparable amplitudes and closely matched spectral distributions, indicating an absence of a preferred forcing direction in this flow. The forcing intensity peaks at $\lambda_z/\delta_1 \approx 0.1$ and $\omega\delta_1/U_e \approx 35$, which occur at substantially shorter spanwise wavelengths and higher temporal frequencies than those associated with the maximum bi-global resolvent gain reported for this flow by Soria et al. [1]. The spanwise-wavenumber spectra as a function of wall-normal position at the peak forcing frequency further indicate that the strongest forcing occurs at $y/\delta_1 \approx 1.2$, farther from the wall than the peak turbulent kinetic energy and approximately coincident with the inflection point of the mean streamwise velocity profile. The pronounced spectral mismatch between the natural forcing and the resolvent gain suggests an opportunity for targeted actuation to control the flow, as the highest-gain modes are weakly forced by natural nonlinear interactions [4].

Acknowledgements The authors acknowledge computational resources provided by the National Computational Infrastructure (NCI), allocated through the National Computational Merit Allocation Scheme (NCMAS) and the Monash University–NCI partnership scheme. This research was funded by the Australian Government through a Australian Research Council Discovery Project.

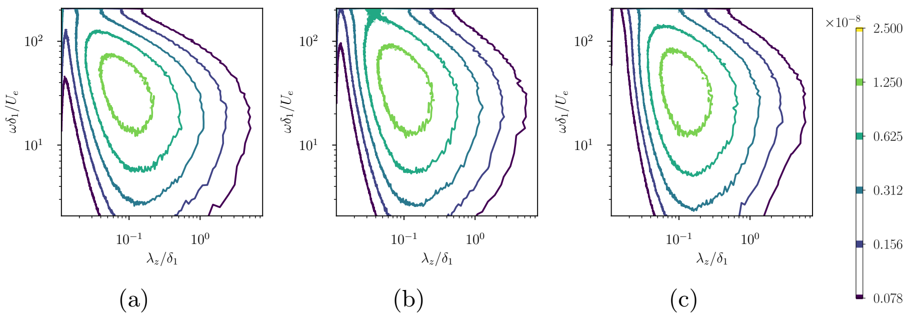

Figure 1: Pre-multiplied spanwise-frequency spectra of the non-linear forcing terms integrated in wall-normal direction: (a) streamwise (b) wall-normal and (c) spanwise components. The forcing peaks at $\lambda_z/\delta_1 \approx 0.1$ and $\omega\delta_1/U_e \approx 35$, separated from resolvent gain maximum reported for SS-APG-TBL [1].

References

[1] J. Soria, A. Matas, K. Liu, S. R. Gomez, T. Jaroslawski, and B. J. McKeon. Biglobal resolvent analysis of a self-similar adverse pressure gradient turbulent boundary layer at the verge of separation. In *Center for Turbulence Research Proceedings of the Summer Program 2024*, Stanford, December 2024.

[2] Armin Zare, Mihailo R. Jovanović, and Tryphon T. Georgiou. Colour of turbulence. *Journal of Fluid Mechanics*, 812: 636–680, February 2017. ISSN 0022-1120, 1469-7645. doi: 10.1017/jfm.2016.682.

[3] V. Kitsios, A. Sekimoto, C. Atkinson, J. A. Sillero, G. Borrell, A. G. Gungor, J. Jiménez, and J. Soria. Direct numerical simulation of a self-similar adverse pressure gradient turbulent boundary layer at the verge of separation. *Journal of Fluid Mechanics*, 829:392–419, October 2017. ISSN 0022-1120. doi: 10.1017/jfm.2017.549.

[4] B. Sun, K. Liu, A. Matas, C. Atkinson, and J. Soria. Characterization of the Fluctuating Reynolds-Stress Gradients and Their Implications for Bi-Global Resolvent Analysis in an Adverse-Pressure-Gradient Turbulent Boundary Layer. *Journal of Physics: Conference Series*, (In press).

SYMMETRY-FREE PERIODIC ORBITS OF TURBULENT PIPE FLOW

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Fluid turbulence is one of the key examples of chaotic dynamics. Applying deterministic concepts from dynamical systems theory to the study of fluid flows has hence a long history [1], in competition with the more statistical approaches favoured in high Reynolds number (Re) regimes. One of the halllmarks of deterministic chaos is the idea that the chaotic attractor of an autonomous system is structured around an infinite set of *unstable periodic orbits* (UPOs) [2]. We present several families of such UPOs [3, 4, 5, 6] and travelling wave solutions (TWs) [7, 8, 9] of the three-dimensional Navier–Stokes that have been identified numerically in the cylindrical pipe geometry by recurrence analysis. Contrarily to all former studies, no discrete spatial symmetry were imposed. The solutions found are linearly unstable, they have short temporal periods and are also free from any discrete symmetry. Their statistics predict reasonably well the turbulent characteristics at equivalent parameters, except for the most dissipative events. Numerical continuation was performed in the axial wavenumber and in the Reynolds number (Re).

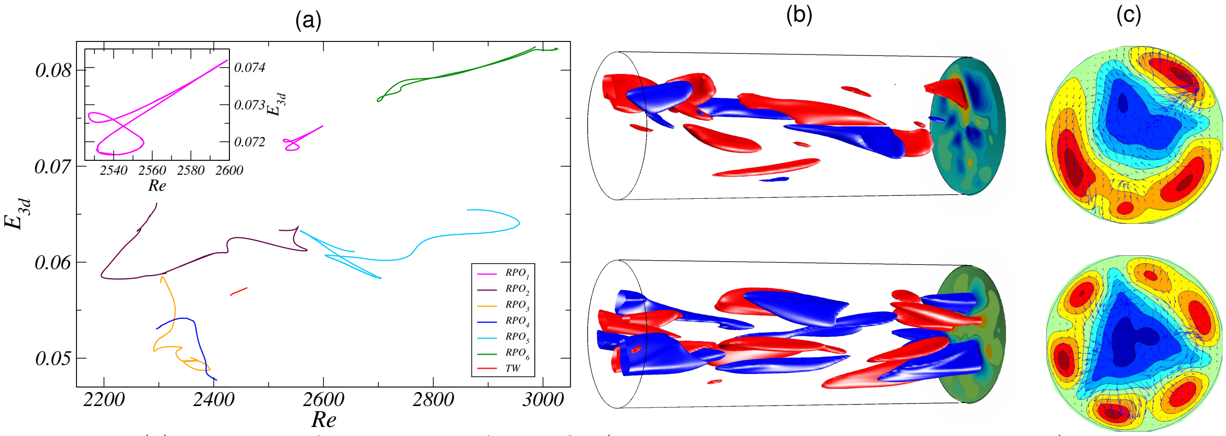

FIGURE 1. *(a) Variation of E_{3d} with Re for RPOs (index numbers represent the period time) and TWs as indicated. Flow visualization of (*top*) RPO_1 ($\tau = 6.511$) ($Re = 2550$) and (*bottom*) TW ($Re = 2450$); Shown are streamwise velocity $u_z = \pm 0.4U$ (red is positive and blue is negative; flow from left to right) and space-time averaged cross section perpendicular to the pipe axis. The downstream velocity relative to the parabolic laminar profile is shown in color ranging form red (fast) to blue (slow). In-plane velocity components are indicated by vectors.*

The solutions turn out to exist only below $Re = 3000$ (Fig. 1), at which standard flow statistics do not match the asymptotic high-Re dynamics. This suggests that these unstable short-period orbits of pipe flow, although crucial as building blocks of the underlying dynamical system, become less relevant for statistical predictions of high-Re multiscale turbulence.

References

[1] D. Ruelle, Turbulence, strange attractors, and chaos. World Scientific, 16, 1995.
[2] P. Cvitanovic, R. Artuso, R. Mainieri, G. Tanner, G. Vattay, N. Whelan, and A. Wirzba, ChaosBook, Niels Bohr Institute, Copenhagen 69, 25, 2005.
[3] G. Kawahara and S. Kida. Periodic motion embedded in plane Couette turbulence: regeneration cycle and burst. Journal of Fluid Mechanics 449:291, 2001.
[4] P. Cvitanovic and J. Gibson, Geometry of the turbulence in wall-bounded shear flows: periodic orbits Physica Scripta T142:014007 (2010).
[5] A. P. Willis, P. Cvitanovic, and M. Avila. *Revealing the state space of turbulent pipe flow by symmetry reduction.* J. Fluid Mech, 721:514, 2013.
[6] M. Avila, F. Mellibovski, N. Roland, and B. Hof. *Streamwise-localized solutions at the onset of turbulence in pipe flow.* Phys. Rev. Lett., 110:224502, 2013.
[7] H. Faisst and B. Eckhardt. *Traveling waves in pipe flow.* Phys. Rev. Lett., 91:224502, 2003.
[8] C. C. T. Pringle and R. R. Kerswell. *Asymmetric, helical, and mirror-symmetric travelling waves in pipe flow.* Phys. Rev. Lett., 99:074502, 2007.
[9] H. Wedin and R. R. Kerswell. *Exact coherent structures in pipe flow: travelling wave solutions.* J. Fluid Mech, 508:333, 2004.

PARAMETRIC SPECTRAL SUBMANIFOLDS CAPTURING HOPF BIFURCATIONS WITH APPLICATIONS TO FLUID DYNAMICS

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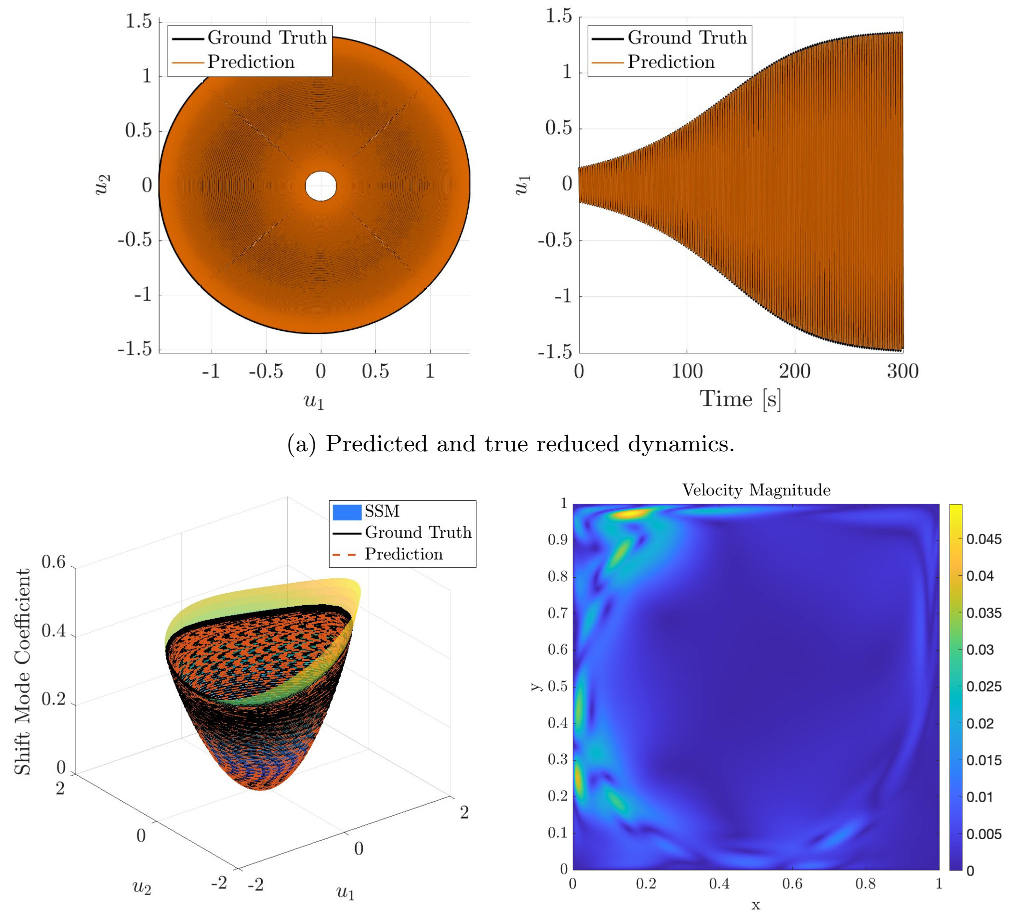
We investigate the persistence and regularity of spectral submanifolds (SSMs, [1]) in high-dimensional parametric dynamical systems undergoing a Hopf bifurcation. By analyzing how resonances in the linearized spectrum near bifurcation points limit the existence and smoothness of SSMs, a phenomenon that has been somewhat overlooked in the past, we show that low-order Taylor coefficients of the SSM expansion and the associated reduced dynamics persist smoothly through the bifurcation. This analysis generalizes to any local bifurcation and provides a clear estimate of the parameter ranges over which a parametric SSM model can be justified, thus illustrating how globally the model can be extended despite the presence of resonances near criticality. We demonstrate these findings on multiple examples, including a data-driven SSM approach to the lid-driven cavity flow (See Figure 1), where we construct a parametric reduced-order model that accurately captures the full transition to periodic dynamics and the critical Reynolds number. These results provide a rigorous foundation for robust data- and equation-driven model reduction of fluid flows across bifurcations, enabling an accurate prediction of nonlinear dynamics across critical parameter regimes.



(a) Predicted and true reduced dynamics.

(b) SSM plotted against the shift mode. (c) Predicted perturbation from fixed point.

Figure 1: Parametric SSM predictions for the lid-driven cavity flow at an unseen Reynolds number.

References

[1] G. Haller. *Modeling Nonlinear Dynamics from Equations and Data — with Applications to Solids, Fluids, and Controls.* Society for Industrial and Applied Mathematics, Philadelphia, PA, 2025. https://doi.org/10.1137/1.9781611978353

RELAMINARISING TURBULENT PIPE FLOW: UPPER EDGE BISECTION AND NONLINEAR OPTIMISATION

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Recent experimental studies [1, 2] have suggested several large-scale control strategies for completely relaminarising turbulent flows in pipe flow. Counter-intuitively, many of these strategies involve initially increasing the flow's turbulent kinetic energy before it fully decays. This points to the dynamical systems concept of the 'upper edge' [3], separating turbulent flows from high energy initial conditions that relaminarise.

We aim to expand the application of dynamical systems theory, which has previously been successful in describing the transition *to* turbulence, to the transition *from* turbulence. Firstly, we adapt the classical bisection algorithm to the upper edge in order to investigate the upper edge state. We find that not only do upper edge trajectories rapidly decay in energy, but that the upper edge state is precisely identical to the previously well-studied (lower) edge state.

Furthermore, we adapt nonlinear optimisation methods [4] used for studying the minimal seed - the smallest amplitude perturbation to laminar flow that does not decay - to find the smallest perturbation to a given turbulent flow that does decay. We find that these relaminarising perturbations can reach energies five decades lower than the turbulent flow they modify. The perturbations are generally composed of near-wall small-scale structures (see Figure 1) that weaken the strength of streamwise vorticies.

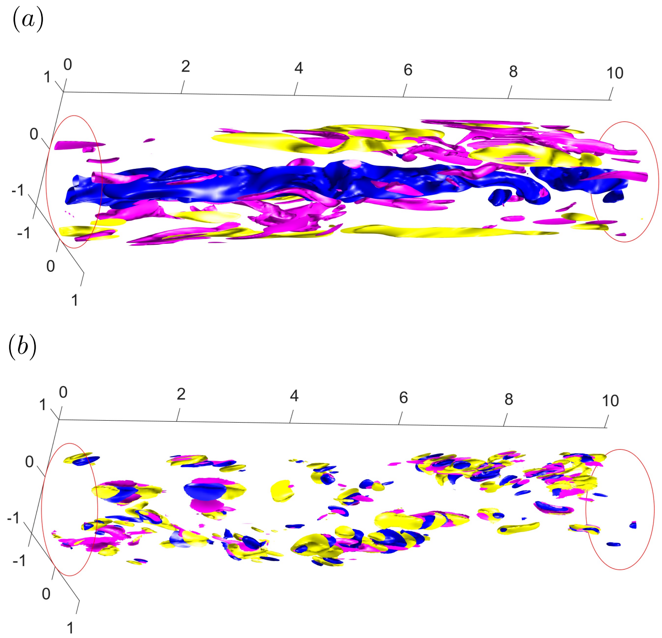

FIGURE 1. *Isosurfaces of (a) a turbulent flow and (b) the corresponding relaminarising perturbation. In (a), isosurfaces are of streamwise perturbation velocity at $+0.3U$ (yellow), $-0.3U$ (blue), and of streamwise vorticity at $\pm 1U/R$ (magenta). In (a), isosurfaces are of streamwise perturbation velocity at $+0.001U$ (yellow), $-0.001U$ (blue), and of streamwise vorticity at $\pm 0.05U/R$ (magenta). Quantities are non-dimensionalised by the centreline velocity of laminar flow U and the pipe radius R.*

References

[1] J. Kühnen and B. Song and D. Scarselli and N. B. Budanur and M. Riedl and A. P. Willis and M. Avila and B. Hof. *Destabilizing turbulence in pipe flow. Nat. Phys.*, 14:386–390, 2018

[2] J. Kühnen and D. Scarselli and M. Schaner and B. Hof. *Relaminarization by steady modification of the streamwise velocity profile in a pipe. Flow Turbul. Combust.*, 2018.

[3] N. B. Budanur and E. Marensi and A. P. Willis and B. Hof. *Upper edge of chaos and the energetics of transition in pipe flow. Physical Review Fluids*, 5(2):023903, 2020.

[4] R. R. Kerswell. *Nonlinear nonmodal stability theory. Annu. Rev. Fluid Mech.*, 50(1), 2018.

LOCALIZING SCREECH CLOSURE VIA KH–GUIDED SCATTERING

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Screech in imperfectly expanded supersonic jets is sustained by a feedback loop that couples a downstream-propagating Kelvin–Helmholtz (KH) wavepacket with an upstream-travelling guided jet mode ([1-2]). Loop closure hinges on the interaction of the KH wave with the shock-cell system: when a triadic matching between KH, guided and shock wavenumbers is satisfied, part of the convecting instability is scattered into an upstream guided component, which can convey phase-coherent feedback to the nozzle region. While resonance models and absolute-instability formalisms capture frequency selection ([2-3]), they often rely on idealized periodic shock patterns and do not directly quantify where, within a finite and decaying shock train, the KH-to-guided conversion is strongest.

Here we target (i) the identification of the *axial closure region* of the screech loop and (ii) the quantitative extraction of the guided-mode amplitude generated by KH scattering on weak shocks. We combine shock-removal filtering, local stability analysis, and a weak-scattering formulation applied to RANS and URANS data. The unstable RANS base flow or the time-averaged URANS flow, both computed with a modified $\kappa - \epsilon$ model ([4]), are decomposed into a filtered slowly varying shock-free base flow and a compact rapidly varying residual that represents weak shock modulation. This filtered base supports a well-posed local stability problem for KH and guided branches, while the residual is treated as a compact scattering inhomogeneity. On the filtered base flow we compute direct and adjoint eigenmodes and evaluate a scattering expression derived via Green's identity that yields the upstream guided-mode coefficient at the entrance of the shock region under forcing by an incident KH wave. Stationary-phase analysis of the resulting axial integral provides automatic localization of the dominant coupling location within the finite shock-cell system. Theoretical predictions are validated against an independent estimate extracted directly from a URANS simulations of the screech by projecting fluctuations onto the adjoint guided mode, providing the guided-mode amplitude as a function of axial position. The combined outcome is a data-driven localization of the effective loop-closure region and a quantitative estimate of KH-to-guided scattering efficiency for weakly imperfectly expanded jets.

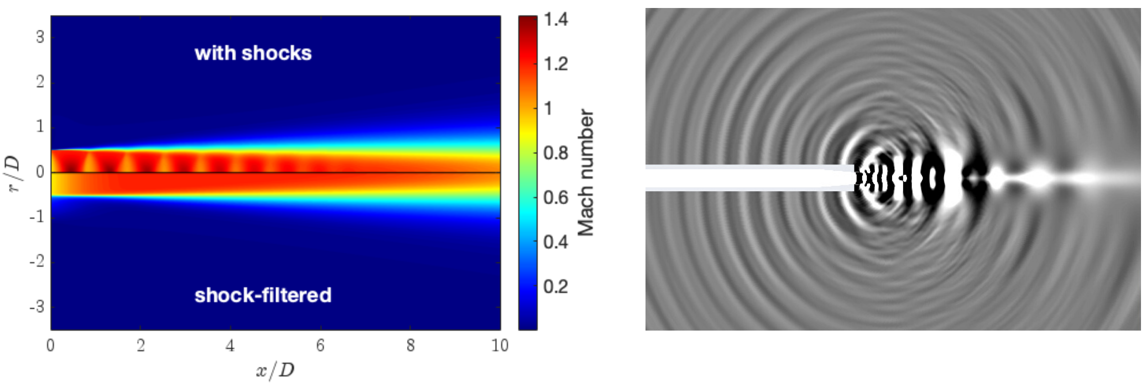

FIGURE 1. *(Left) Mach-number distribution for a nominally $M_j = 1.2$ underexpanded jet case: original field (top) and shock-filtered field (bottom) used for the linear stability analysis. (Right) Instantaneous pressure-fluctuation field $\Delta p = p - p_a$ from URANS simulations at $M_j = 1.2$.*

References

[1] D. Edgington-Mitchell, T. Wang, P. A. S. Nogueira, O. Schmidt, V. Jaunet, D. Duke, P. Jordan, and A. Towne. Waves in screeching jets. *J. Fluid Mech.*, 913:A7, 2021.

[2] M. Mancinelli, E. Martini, V. Jaunet, P. Jordan, A. Towne, and Y. Gervais. Reflection and transmission of a Kelvin–Helmholtz wave incident on a shock in a jet. *J. Fluid Mech.*, 954:A9, 2023.

[3] P. A. S. Nogueira, P. Jordan, V. Jaunet, A. V. G. Cavalieri, A. Towne, and D. Edgington-Mitchell. Absolute instability in shock-containing jets. *J. Fluid Mech.*, 930:A10, 2022.

[4] H. Shen and C. K. W. Tam. Numerical simulation of the generation of axisymmetric mode jet screech tones. *AIAA Journal*, 36(10):1801–1807, 1998.

SENSITIVITY ANALYSIS AND CONTROL OF IMPINGING JET NOISE

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In this work, we investigate the generation and control of tonal noise from a high subsonic impinging jet. A previous study [1] showed that, for an impinging jet with $M_j = 0.9$, tonal noise arises from a feedback mechanism between downstream-propagating Kelvin–Helmholtz (K–H) wavepackets and trapped upstream-travelling guided jet waves. This feedback loop can be captured through global linear stability analysis. As shown in figure 1, there is a strong similarity between the SPOD modes and the corresponding global mode shapes. With the aid of a local stability analysis, we further showed that an unstable resonance condition is established when the combined effect of the growth rate of the unstable K–H wave and the reflection coefficients at the two turning points yields a net gain greater than unity. The resonance condition was also found to be highly sensitive to the flow conditions inside the nozzle.

To systematically investigate the relationship between mean-flow modifications (via changes in reflection coefficients) and the influence of turbulent flow inside the nozzle, an impedance boundary condition is applied at the impinging wall. This approach enables us to track the resulting variations in the global and adjoint mode structures. Furthermore, a resolvent analysis is expected to carry out to examine the receptivity and amplification characteristics associated with changes in the boundary condition and the resulting mean-flow variations across different Reynolds numbers.

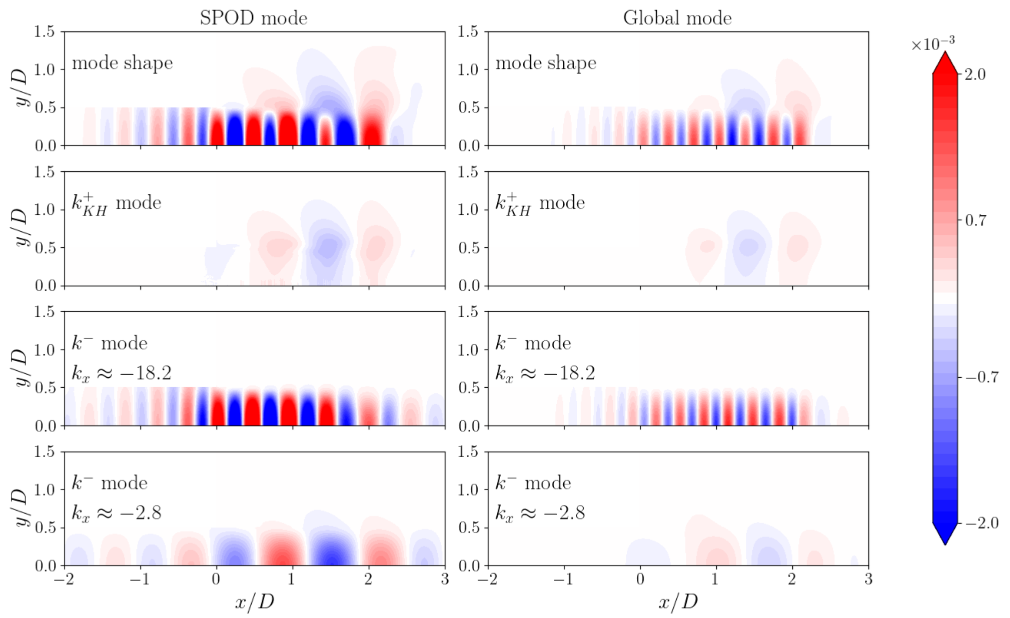

FIGURE 1. *The comparison between the SPOD and global mode shapes. A Fourier filter is applied to extract downstream (superscript +) and upstream (superscript -) propagating waves with different wave numbers.*

References

[1] Z. Yuan and V. Jaunet and P. Jordan and A. V.G. Cavalieri and A. Hanifi. Sensitivity of impinging jet noise to flow conditions inside the nozzle. *16th ERCOFTAC SIG 33 Workshop, Progress in Flow Instability, Transition and Control*, 2025.

GLOBAL INSTABILITIES OF A PLANAR JET FROM A FLEXIBLE NOZZLE

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We characterize the stability properties of an incompressible planar jet flow exiting from a flexible nozzle composed of two identical cantilever plates, whose dynamics are governed by the elasticity equation [1]. We propose this configuration as a prototype of a typical fluid-structure interaction (FSI) that occurs in several natural or bio-mimetic propulsion mechanisms [2, 3]. Moreover, the stability of free jets is one of the fundamental problems in fluid mechanics and research has focused on the convective instabilities that characterize their dynamics [4]. However, in realistic configurations, free jets are often confined by solid walls which may be compliant. We present evidences that the presence of a flexible nozzle can lead to self sustained global instabilities for this flow. To show it, we perform a linear stability analysis [5], dealing with the FSI problem by an Arbitrary Lagrangian-Eulerian method, discretized thanks to the finite element open-source library *GetFEM* [6]. We firstly characterize the base flow, discussing the effect of the Reynolds number — based on the bulk velocity and channel height — in the range $[50, 200]$ and of the Young's modulus of the compliant nozzle on its deformation and in the jet flow development. Moreover, exploiting an idea first proposed in [7], we write a quasi-1D model capable of predicting the static displacement of the flexible nozzle even in cases of large deflections. Secondly, the stability analysis reveals that the interaction of the flow with the flexible structure leads to single mode flutter instabilities of discrete structural bending modes of the cantilever, compliant nozzle. The instabilities arise in two different families of global modes: sinuous modes (Figure 1a,b) and varicose modes (Figure 1c,d). The spatial structure of the sinuous (varicose) mode is anti–symmetric (symmetric) and the two plates of the nozzle oscillate *in-phase* (*out-of-phase*). The emergence of a sinuous or a varicose flutter instability depends on each different discrete structural mode we investigate. Finally, two dimensional time marching simulations of the non-linear FSI system have been performed to reveal the supercritical nature of the first bifurcation. At a fixed Reynolds number, we track the squared amplitude of the limit cycle that linearly fits the set of the investigated Young's moduli close to the critical one, confirming the supercriticality.

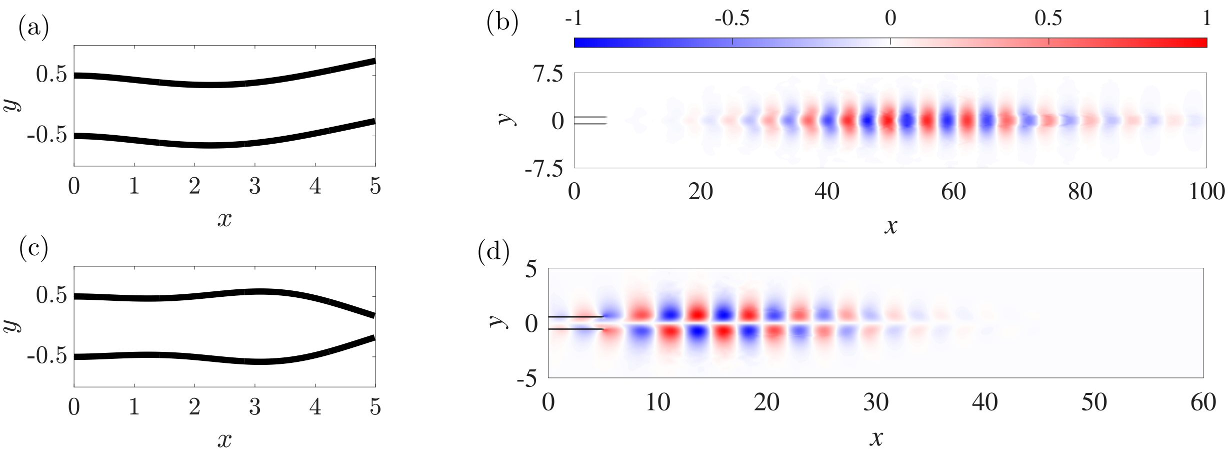

FIGURE 1. *A sinuous (a,b) and a varicose (c,d) global mode. Structural deformation (a,c) and the vertical component of the fluid velocity (b,d) for the real part of the eigenvector. The coulour bar denotes the values of the vertical component of the fluid velocity normalized by its maximum absolute value in the domain.*

References

[1] Cruciani S., Citro V., Fournié M. & Auteri F. Global instability in a plane jet with flexible nozzle. *J. Fluid Mech.* 2026.
[2] Choi, D. & Park, H. Flow–structure interaction of a starting jet through a flexible circular nozzle. *J. Fluid Mech.*, 2022.
[3] Zhang, J., Ren, Z., Hu, W., Soon, R. H., Yasa, I. C., Liu, Z. & Sitti, M. Voxelated three-dimensional miniature magnetic soft machines via multimaterial heterogeneous assembly. *Sci. Robot.*, 2021.
[4] Huerre, P. & Monkewitz, P. A. Local and global instabilities in spatially developing flows. *Annu. Rev. Fluid Mech.,* 1990.
[5] Fabre, D., Citro, V., Ferreira Sabino, D., Bonnefis, P., Sierra, J., Giannetti, F. & Pigou, M. A Practical Review on Linear and Nonlinear Global Approaches to Flow Instabilities. *Appl. Mech. Rev.,* 2019.
[6] Renard, Y. & Poulios, K. Getfem: Automated FE modeling of multiphysics problems based on a generic weak form language. *ACM Trans. Math. Softw.,* 2020.
[7] Luchini, P. & Charru, F. Consistent section-averaged equations of quasi-one-dimensional laminar flow. *J. Fluid Mech.,* 2010.

TIME-FREQUENCY ANALYSIS OF TURBULENT JETS USING ORTHOGONALIZED VARIATIONAL MODE DECOMPOSITION

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Mode decomposition techniques like POD, SPOD and DMD have demonstrated their potential in extracting large-scale dynamic phenomena when the underlying dynamics are statistically stationary, but are not well suited to recover non-stationary or transient phenomena in an interpretable manner. There is no technical impediment to their application to flows exhibit these behaviors, but the non-stationary dynamics are artificially smeared out in the resulting modal decomposition, which risks losing key dynamic information.

One approach for the analysis of non-stationary processes is the so-called time–frequency analysis, aiming at the determination of temporally-evolving spectral representations: the temporal coefficient associated with each mode should be allowed to capture amplitude and frequency modulation over time; in consequence, the spectral content of each mode should extend over a finite bandwidth rather than a discrete frequency. This work employs a recently proposed technique named Orthogonalized Variational Mode Decomposition (OVMD) [1, 2], which constructs modes that have finite but compact support in the frequency domain. The method solves a variational optimization problem that aims to minimize the cumulative bandwidth of all the modes while minimizing the quadratic error of the flow representation. Additional orthogonality-promoting constraints are introduced that have a remarkable impact on the robustness of the results, especially under situations in which the spectral content of different modes overlap but their spatial structures are very different.

OVMD is applied here to Large Eddy Simulation data for a turbulent jet with Mach number $M_j = 0.9$ and temperature ratio $T_j/T_\infty = 1$ [3]. Decompositions based on SPOD recover wavepackets which combine spatial amplification by K-H and Orr-mechanism and are in excellent agreement with predictions by resolvent analysis [4]. However computing the radiated noise may require including several modes per frequency, which is attributed to the instrumental role of jet jittering in mixing noise of subsonic jets [5]. This work investigates if the time-frequency modes computed by OVMD properly capture this intermittency, and whether they can effectively recover a low-dimensional model of the noise-generating structures.

Acknowledgments: This work has been carried out under the project MIADDTRANS (PID2024-157642MB-I00) funded by MCIN/AEI/10.13039/501100011033 and European Union's FEDER

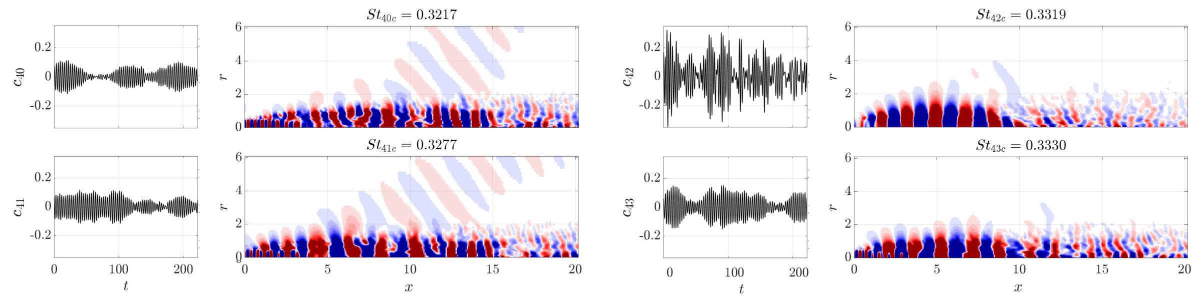

FIGURE 1. *Representative OMVD modes with central frequency $St \approx 0.32 - 0.35$. Left: Amplitude coefficient. Right: Pressure field.*

References

[1] Marbona, H., Rodríguez, D., Martínez-Cava, A., & Valero, E. Orthogonalized Variational Mode Decomposition. *Signal Processing*, **239**, 110251, 2026.

[2] Marbona, H., Rodríguez, D., Martínez-Cava, A., & Valero, E. A time-frequency modal decomposition for the analysis of non-stationary separated flow. *Physics of Fluids*, **37**, 074113, 2025.

[3] Towne, A., Dawson, S. T. M., Brès, G. A., Lozano-Durán, A., Saxton-Fox, T., Parthasarathy, A., Jones A. R., Biler, H., Chi-An Yeh, C.-A., Patel, H. D. & Taira, K. A Database for Reduced-Complexity Modeling of Fluid Flows *AIAA J.*, **61 (7)**, 2867–2892, 2023.

[4] Schmidt, O. T., Towne, A., Rigas, G., Colonius, T. & Brès, G. A. Spectral analysis of jet turbulence *Journal of Fluid Mechanics*, **855**, 953–982, 2018.

[5] Cavalieri, A. V. G., Jordan, P., Agarwal, A. & Gervais, Y. Jittering wave-packet models for subsonic jet noise *Journal of Sound and Vibration*, **330**, 4474–4492, 2011.

REDUCED-ORDER MODELING AND CONTROL OF A SHOCK-LADEN SCRAMJET ISOLATOR

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Scramjet engines may experience flow instabilities and unstart when operating in off-design conditions, primarily due to the unsteady interactions between the shock train and the boundary layers [1]. Actuator-based open-loop control methods have been shown experimentally [2] to mitigate instabilities within the scramjet isolator through modification of the shock train structure. We are interested in determining optimal actuator placement to produce a desired shock train configuration.

Given high-fidelity simulations of an isolator with a stable baseflow – here modeled by an rectangular duct with a shock generating wedge – we develop models to predict the transient response to the system to the step input generated by a plasma discharge actuator. We first develop a linearized model about the unactuated base state and our shock-aware sensitivity formulation [3] to form a linear time-invariant state-space system. Given a desired output state, the optimal actuator location is determined through a least-squares minimization procedure.

Due to the highly nonlinear shock generation and movement brought on by the forcing, the linearized model is not valid for large amplitude actuation. To this end, we also construct reduced-order models (ROMs) using two state-of-the-art data-driven methods: operator inference (OpInf) [4] and the recently-formulated "NiTROM" algorithm [5], both paired with a novel guaranteed-stable parametrization of the latent-space dynamics [6]. Operator inference is used to learn optimal dynamics provided a fixed low-dimensional basis and projected full-order model (FOM) data. NiTROM, on the other hand, learns both the latent-space dynamics and oblique projection operators simultaneously.

When the actuator strength exceeds a threshhold, both OpInf and NiTROM are challenged to create effective low-rank representations of the transient shock dynamics. We therefore explore a shock-aware methodology for generating low-rank dynamical models which handles the shocks separately from the otherwise smooth background flow, and can generally predict shock location and strength as a function of actuator configuration.

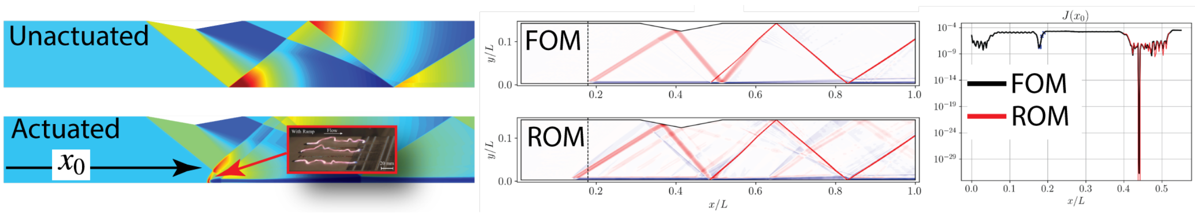

FIGURE 1. *Unactuated (top left) and actuated (bottom left) density fields for the inviscid shock-laden duct with their FOM and NiTROM ROM density perturbation estimates (center) and optimal actuator location x_0 (right).*

References

[1] J. L. Wagner, K. B. Yuceil, A. Valdivia, N. T. Clemens, and D. S. Dolling. Experimental Investigation of Unstart in an Inlet/Isolator Model in Mach 5 Flow. *AIAA Journal*, 47(6):1528–1542, 2009.

[2] S. Elliot, P. Lax, and S. Leonov. Control of Shock Positions in a Supersonic Duct by Plasma Array. *AIAA Scitech 2022 Forum*, 2022.

[3] S. R. Murthy and D. J. Bodony. Resolvent Analysis of Shock-Laden Flows. *Journal of Fluid Mechanics*, 2026.

[4] B. Peherstorfer and K. Willcox. Data-driven operator inference for nonintrusive projection-based model reduction. *Computer Methods in Applied Mechanics and Engineering*, 306:196–215, 2016.

[5] A. Padovan, B. Vollmer, and D. J. Bodony. Data-driven operator inference for nonintrusive projection-based model reduction. *SIAM Journal on Applied Dynamical Systems*, 23(4):3052–3076, 2024.

[6] P. Goyal, I. P. Duff, P. Benner. Guaranteed Stable Quadratic Models and their Applications in SINDy and Operator Inference. *Physica D: Nonlinear Phenomena*, 483:134893, 2025.

Book of Abstracts – Day 2

Session 5 | Chair: Dr. Jeffrey Crouch (The Boeing Company)

"Non-Intrusive control of flow instabilities in a rotor–stator cavity"
Riccardo Maranelli, V. Mons, J.-C. Chassaing, M. Queguineur, T. Sayadi (ONERA)

"From actuation to resonance: wall-impedance strategies for controlling Tollmien-Schlichting waves"
Pierre Champeaux, T. Michelis, M. Kotsonis (TU Delft)

Flash talks | Chair: Prof. Taraneh Sayadi (CNAM)

"Higher-order meshless methods for hydrodynamic stability problems in complex domains"
A. Unnikrishnan, Vinod Narayanan (IIT Gandhinagar)

"Secondary instabilities in nonlinearly distorted pipe-entrance flows"
Bo Yuan, E. Marensi, P. Ricco (U. Sheffield)

"Stabilising effect of a surface hump on crossflow instabilities for varying perturbation wavelength and hump height"
Marco Radaelli, A.F. Rius-Vidales, M. Kotsonis (TU Delft)

"Description of the synchronization of 2nd Mack mode and acoustic waves in highly cooled hypersonic boundary layers by means of AHLNS"
Alberto Franco (DLR)

"Investigation of low-frequency unsteadiness in transonic shock-wave/boundary layer interactions"
Zhen Zhang, J.Hao (Hong Kong Polytechnic University)

"Occurrence of unsteady global instability in hypersonic forward facing step flow"
Zexin Chen, X. Li, X. Liu, J. Hao, C.-Y. Wen (Hong Kong Polytechnic University)

"Linear mechanism underpins superstructures and near-wall scales in turbulent convection"
Xiaojue Zhu, Z. Zhou (Max Planck Inst. for Solar System Research)

Session 6 | Chair: Prof. Julio Soria (Monash University)

"On the flutter feedback loop of a flexible plate in a viscous channel flow"
Roberta Santoriello, S. Cruciani, M. Fournié, F.Auteri, V. Citro (U. Salerno)

"Optimal three-dimensional perturbations in fluttering and non-fluttering bioprosthetic aortic valves"
Mohammad Moniripiri, K.-M Bornemann, D. S. Henningson, D. Obrist, P. J. Schmid, A. Hanifi (KTH)

"Flow instabilities in a recorder's mouthpiece"
M. Fosas de Pando, A. Tassawar, Rodolfo Ostilla (U. Cádiz)

"Local and non-local interactions of phononic subsurfaces with Tollmien–Schlichting waves in air"
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"Vortex breakdown on hydro turbine draft tube"
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"3D Global stability analysis of counter-current jet"
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NON-INTRUSIVE CONTROL OF FLOW INSTABILITIES IN A ROTOR–STATOR CAVITY

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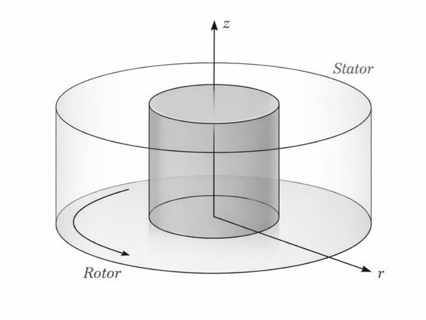
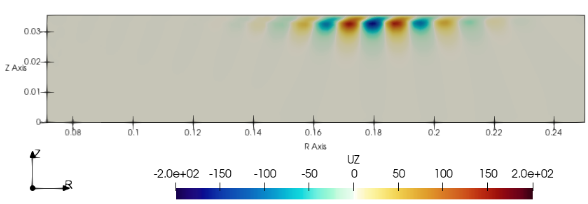
Flows dominated by strong instabilities and nonlinear interactions make the design of control strategies a complex task, typically leading to high-dimensional optimization problems. In such settings, finite-difference, stochastic, and population-based optimization methods quickly become impractical due to their poor scalability, leading to the use of adjoint-based approaches in computational fluid dynamics. Although adjoint methods provide efficient gradient evaluations, their implementation and robustness remain challenging for complex nonlinear systems, limiting their applicability in practice. In particular, the determination of passive control strategies through mean flow-based stability and sensitivity analyses is commonly performed using adjoint-based methods ([1]). However, this requires the treatment of complex adjoint operators, including second-order sensitivity terms. Within a RANS (Reynolds-Averaged Navier-Stokes) formulation, turbulence closures make the derivation and implementation of such operators highly challenging, often rendering this approach impractical for turbulent flows.
In the present work, ensemble-based variational (EnVar) methods ([2; 3]) are used to identify effective steady control strategies for suppressing flow instabilities in a rotor–stator cavity ([4]) (Figure 1a) at a Reynolds number of $Re = 10^5$. The base flow is computed using a RANS approach with the Spalart–Allmaras turbulence model. By estimating cost-function sensitivities from a finite ensemble of perturbed steady forcing configurations, EnVar methods capture nonlinear effects without requiring explicit adjoint formulations. This non-intrusive approach enables optimization in large control spaces and allows one to go beyond the limitations of adjoint-based methods in RANS simulations, leading to the identification of optimal steady forcing strategies that efficiently suppress the onset of instabilities (such as the one in Figure 1b).



(a) Rotor stator configuration.



(b) Instability mode of the axial velocity fluctuations by global stability analysis.

Figure 1: Rotor-stator cavity characterization by configuration 1a, and by one of the unstable modes on the section 1b.

References

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

[2] M. Bocquet and P. Sakov. An iterative ensemble Kalman smoother. *Q. J. R. Meteorol. Soc.*, 140(682):1521–1535, 2013.

[3] V. Mons, Y. Du, and T. Zaki. Ensemble-Variational Assimilation of Statistical Data in Large-Eddy Simulation. *Phys. Rev. Fluids*, 6(10):104607, 2021.

[4] M. Queguineur, T. Bridel-Bertomeu, L. Y. M. Gicquel, and G. Staffelbach. Large eddy simulations and global stability analyses of an annular and cylindrical rotor/stator cavity limit cycles. *Phys. Fluids*, 31(10):104109, 2019.

FROM ACTUATION TO RESONANCE: WALL-IMPEDANCE STRATEGIES FOR CONTROLLING TOLLMIEN–SCHLICHTING WAVES

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While both active wave cancellation and passive wall-impedance strategies have demonstrated significant potential for Tollmien–Schlichting (TS) wave control, a general and unified framework relating the coupled pressure–velocity response at the wall to TS-wave dynamics is still lacking. This response is conveniently expressed through the complex wall admittance $Y = v_w/p_w$. Nonetheless, the role of wall-induced phase ($\angle Y$) and amplitude ($|Y|$) responses, together with the associated physical mechanisms governing instability attenuation or amplification, remains incompletely understood [1]. In parallel, acoustic metamaterials (AMMs) have recently emerged as a promising approach for boundary-layer instability control, as they enable the design of tailored wall-admittance profiles using subwavelength resonant structures [2]. By shaping the effective wall response through local resonance, AMMs extend passive impedance-based strategies by exploiting the wave-like nature of TS instabilities; however, the distinct physics of TS waves with respect to classical waves renders this analogy largely unexplored.

This work investigates impedance-based control of TS waves in a zero-pressure-gradient flat-plate boundary layer, from idealized actuation to passive resonant subsurfaces. Linear analyses are performed using the frequency-domain Delft Harmonic Navier–Stokes Solver (DeHNSSo) [3]. A naturally developing TS wave in a Blasius boundary layer at $f = 450\,\text{Hz}$ is used as the baseline case (subscript B). Control is assessed for three configurations: (i) an idealized wall-normal velocity actuator with prescribed phase and amplitude, (ii) a wall-embedded Helmholtz resonator (HR) modeled via an equivalent impedance, and (iii) a streamwise-periodic array of identical HRs. For the actuator-based configuration, a parametric sweep over amplitude ($|v_w|$) and phase ($\angle v_w$) yields an impedance response map identifying regions of attenuation and amplification (**Figure 1a**). Effective control is achieved when the wall response exhibits sufficiently small amplitude and an opportune phase relation to the incoming TS wave, leading to destructive interference downstream of the actuator. A single HR reproduces this behavior passively when properly tuned to the instability frequency, while periodic arrays of successive HRs induce nearly additive reductions in TS-wave amplitude and enhanced downstream attenuation (**Figure 1b**).

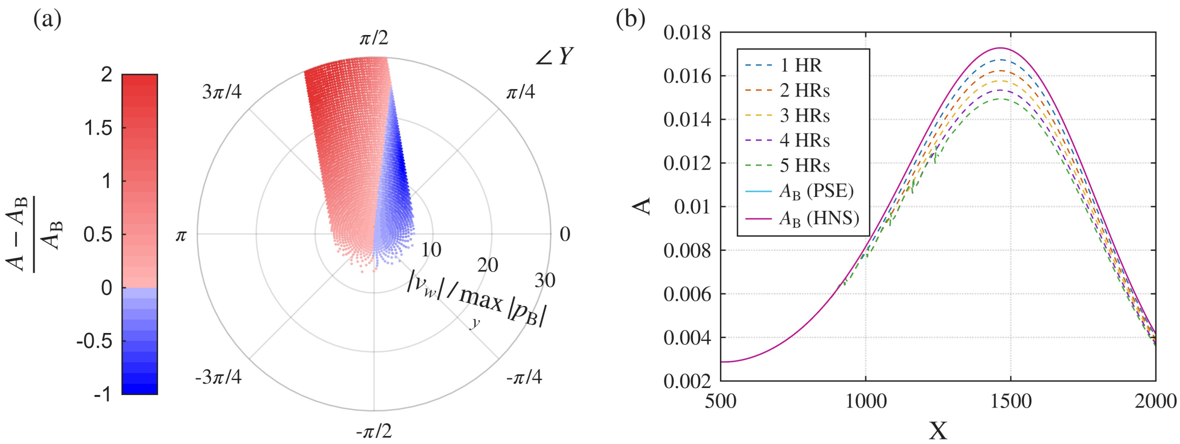

FIGURE 1. *(a) Impedance map obtained from a 1800-simulation sweep over actuation amplitude and phase. Evaluated at the wall and actuator location, the radial coordinate denotes the scaled actuator amplitude, while the azimuthal coordinate represents the phase of the flow's complex impedance (v_w/p_w). TS-wave amplitude (A) is evaluated downstream of the actuator, with red indicating amplification and blue attenuation relative to the baseline case (A_B). (b) Spatial evolution of the TS-wave amplitude for arrays composed of a varying number of HRs.*

References

[1] A. Rouviere, F. Méry, J. Methel, O. Vermeersch, and M. Forte. Experimental and Numerical Study on Wall Impedance Effects on Tollmien–Schlichting Waves *AIAA Journal, 60(1):508-519, 2022.*

[2] T. Michelis, C. de Koning, and M. Kotsonis. On the interaction of Tollmien–Schlichting waves with a wall-embedded Helmholtz resonator *Physics of Fluids, 35(3):034104, March 2023.*

[3] S. H. Westerbeek, S. Hulshoff, H. Schuttelaar, and M. Kotsonis. DeHNSSo: The Delft Harmonic Navier-Stokes Solver for Nonlinear Stability Problems with Complex Geometric Features, *2023.*

HIGHER-ORDER MESHLESS METHODS FOR HYDRODYNAMIC STABILITY PROBLEMS IN COMPLEX DOMAINS

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This study presents a robust biglobal stability analysis framework utilizing a meshless, high-order Radial Basis Function-Generated Finite Difference (RBF-FD) method. Building upon the work of [2], we employ polyharmonic spline (PHS) RBFs with appended polynomials to circumvent the "stagnation errors" and shape-parameter sensitivities common in traditional RBF approaches. This formulation maintains the high-order accuracy typical of spectral methods while operating on scattered node layouts in Cartesian coordinates. This eliminates the need for complex coordinate transformations—such as the bipolar coordinates required for eccentric geometries or the conformal mappings used for aerofoils—thereby avoiding the coordinate singularities often encountered in traditional pipe flow or eccentric cylinder analyses. The 2D laminar baseflows are first computed using the meshless incompressible Navier-Stokes solver detailed in [1]. We apply this framework to the Taylor-Couette system, investigating the transition from standard concentric cylinders to eccentric, elliptical, and square outer boundaries. It is noted that a global instability analysis is performed without assuming any specific waveform in the plane. Consequently, all relevant modes are captured in a single simulation, and the evaluation of algebraic growth across modes is considerably simplified. Our results reveal that breaking the rotational symmetry and introducing geometric singularities (corners) significantly alters the eigenvalue spectrum, leading to the emergence of distinct, multi-modal "corner" modes that are absent in the classical concentric case. The numerical framework is rigorously validated against the benchmarks of [3], [4] and [6] for concentric/eccentric Taylor-Couette flows, and against the canonical pipe flow results of [5], demonstrating excellent agreement and establishing the RBF-FD approach as a versatile alternative for stability analysis in complex-shaped domains.

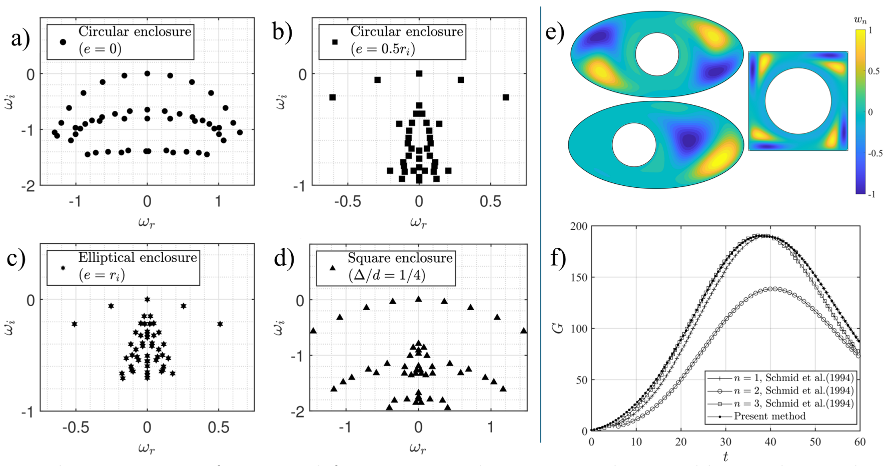

FIGURE 1. *Eigenvalue spectrum of temporal frequency modes at critical Reynolds number and axial wavenumber for: a) concentric placement of circular cylinder, b) eccentric placement of circular cylinder, c) eccentric placement of elliptical cylinder, and d) concentric placement of square cylinder; with inner rotating circular cylinder driving the flow. e) "corner" modes represented with contourmaps of normalised axial velocity from three cases: elliptical enclosure with concentric and eccentric placement of cylinders, and square enclosure with concentric placement. f) Transient energy growth validation of Hagen-Poiseuille flow performed against [5]*

References

[1] Unnikrishnan, A., Shahane, S., Narayanan, V. & Vanka, S. Shear-driven flow in an elliptical enclosure generated by an inner rotating circular cylinder. *Physics Of Fluids.* **34** (2022)
[2] Unnikrishnan, A., Narayanan, V. & Vanka, S. High-order meshless global stability analysis of Taylor–Couette flows in complex domains. *Physics Of Fluids.* **36** (2024)
[3] Oikawa, M., Karasudani, T. & Funakoshi, M. Stability of flow between eccentric rotating cylinders. *Journal Of The Physical Society Of Japan.* **58**, 2355-2364 (1989)
[4] Leclercq, C., Pier, B. & Scott, J. Absolute instabilities in eccentric Taylor–Couette–Poiseuille flow. *Journal Of Fluid Mechanics.* **741** pp. 543-566 (2014)
[5] P. J. Schmid, and D. S. Henningson. *Stability and Transition in Shear Flows.* Springer, Berlin, 2001.
[6] Dandelia, H., Kant, R. & Narayanan, V. Optimal control of growth of instabilities in Taylor–Couette flow. *Physics Of Fluids.* **34** (2022)

SECONDARY INSTABILITIES IN NONLINEARLY DISTORTED PIPE-ENTRANCE FLOWS

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This study investigates secondary instabilities of nonlinearly distorted pipe-entrance flows. The nonlinear distortion is induced by a pair of low-frequency vortical modes entrained into the pipe through its inlet [1]. By accounting for the slow variations in temporal and streamwise scales, we frame the instability analysis as a bi-global instability problem in the azimuthal and radial directions across different time windows and distinct streamwise positions.

First, we calculate the temporal instability modes by solving linear generalised eigenvalue problems. Figure 1 shows the instability characteristics of the distorted flow at 26 radii downstream of the inlet. The maximal growth curve in Figure 1(a) is not dominated by a single continuous mode; instead, it consists of segments from multiple modes. The discontinuities of the frequency in Figure 1(b) further suggest that a multi-family modes coexist alongside the 'mode crossing' phenomenon. Parametric studies show that increasing the Reynolds number and disturbance amplitude both enhances the growth rate and broadens the unstable frequency range. Next, we compute the spatial instability modes by solving nonlinear eigenvalue problems. We use initial guesses derived from the temporal modes via a temporal-spatial transformation [2]. The good agreement between the transformed and calculated results in Figure 2 confirms that the transformation provides instability characteristics of satisfactory accuracy. Finally, the non-parallel effect, stemming from the developing base flow and the streamwise variation of the secondary instability modes, is incorporated into the secondary instability analysis using the non-perturbative approach in [3]. This secondary instability framework can provide accurate initial profiles for subsequent direct numerical simulations (DNS) of disturbed pipe flows.

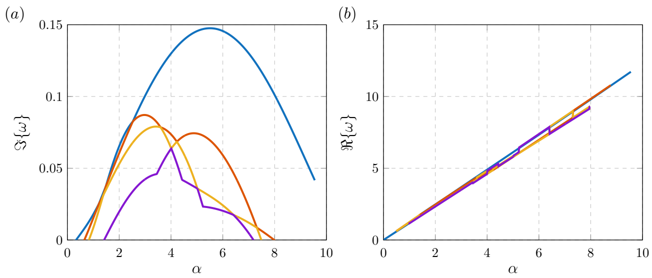

FIGURE 1. *Temporal secondary instability characteristics for an entrained vortical disturbance at $Re = 2000$ (based on the pipe radius) and amplitude $\epsilon = 0.05$. Results are calculated at 26 pipe radii downstream of the inlet.*

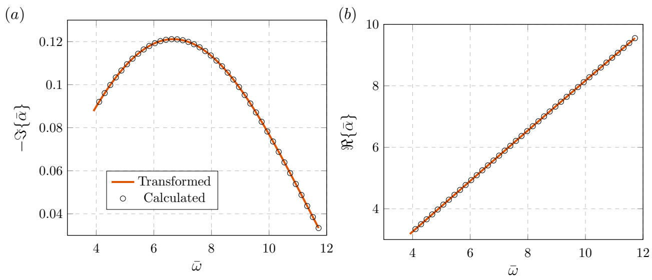

FIGURE 2. *Spatial secondary instability characteristics for the most unstable mode. Parameters adopted are identical to those in Figure 1.*

References

[1] K. Zhu and P. Ricco. Nonlinear evolution of vortical disturbances entrained in the entrance region of a circular pipe. *J. Fluid Mech.*, 998:A19, 2024.

[2] J. Xu, J. Liu, Z. Zhang, and X. Wu. Spatial-temporal transformation for primary and secondary instabilities in weakly non-parallel shear flows. *J. Fluid Mech.*, 959:A21, 2023.

[3] Z. Huang and X. Wu. A non-perturbative approach to spatial instability of weakly non-parallel shear flows. *Phys. Fluids*, 27(5):054104, 2015.

STABILISING EFFECT OF A SURFACE HUMP ON CROSSFLOW INSTABILITIES FOR VARYING PERTURBATION WAVELENGTH AND HUMP HEIGHT

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A passive laminar flow control concept using a smooth, hump-shaped surface modification has been studied to delay transition to turbulence on a swept wing. Previous experiments show that the hump's effect depends on the primary crossflow instability (CFI) amplitude: at high amplitudes the hump causes transition advancement, while at low amplitudes it delays transition [1]. Numerical investigations using a Harmonic Navier-Stokes solver [2] and Direct Numerical Simulations [3] confirm that the hump induces a crossflow reversal region due to pressure-gradient changes, which weakens the lift-up mechanism and reduces linear production. This stabilises the crossflow vortices and delays the onset of secondary instabilities.

From the past research above, it is currently unclear if and how the stabilising effect of the hump is dependent on key parameters such as the incoming CFI wavelength and the hump height. This is investigated in this study by experiments in TU Delft's Low Turbulence Tunnel ($Re_{c_X} = 2.3 \times 10^6$), complemented with numerical data. A cross-sectional schematic of the 45° swept-wing model (M3J) and its features is provided in Figure 1a. Infrared thermography has been used to identify the laminar-to-turbulent transition front, while particle image velocimetry (PIV) has been used to characterise the developing CF vortices. In the experiments, discrete roughness elements (DREs) are used to vary the wavelength, while keeping their height low to ensure a low initial CFI amplitude. Additionally, the effect of distributed roughness patches (DRPs) is investigated, aiming at reproducing conditions closer to what is found over operating aircraft wings (i.e. random background roughness). Furthermore, a variation of hump heights is performed, independent from variations in CFI wavelength. Figure 1b shows spanwise-oriented PIV planes at $x/c = 0.39$, indicating that increasing the hump height leads to greater stabilisation of the CFI downstream of the hump. However, when increasing the height beyond a certain value ([h_h ¿ 3 mm]), transition is significantly advanced, suggesting that there is a point where the destabilising mechanism, as proposed by [2] and [3], is becoming more dominant than the stabilising mechanism.

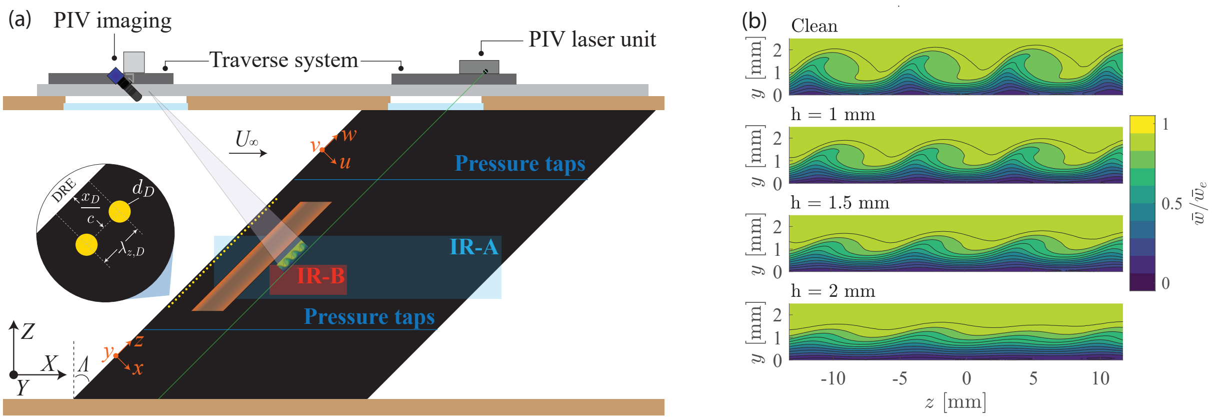

FIGURE 1. *(a) Cross-sectional view of the swept-wing M3J model and its features, with PIV set-up and IR-imaging field of view, and (b) contours of time-averaged spanwise velocity at constant CFI wavelength ($\lambda_z = 7.5$ mm) and different hump heights, taken at the chordwise position $x/c = 0.39$ using PIV.*

References

[1] A.F. Rius-Vidales, L. Morais, S. Westerbeek, J. Casacuberta, M. Soyler, and M. Kotsonis. Delay of swept-wing transition using a surface hump. *J. Fluid Mech.*, 1014:A35, 2025.

[2] S. Westerbeek, J. Casacuberta, and M. Kotsonis. Linear and nonlinear interactions between stationary cross-flow instabilities and a smooth surface hump. *J. Fluid Mech.*, 1026:A43, 2026.

[3] M. Moniripiri, A.F. Rius-Vidales, M. Kotsonis, and A. Hanifi. Direct numerical simulation of the effects of a smooth surface hump on transition in swept-wing boundary layers. *Accepted for publication in J. Fluid Mech.*

DESCRIPTION OF THE SYNCHRONIZATION OF THE 2^{nd} MACK MODE AND ACOUSTIC WAVES IN HIGHLY COOLED HYPERSONIC BOUNDARY LAYERS BY MEANS OF AHLNS

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In high-enthalpy wind tunnels, the wall temperature is significantly smaller than the free-stream temperature. It is well-known that wall cooling promotes the stabilization of the first mode and destabilization of the second mode. Moreover, for sufficiently cooled walls, the unstable modes can travel supersonically with respect to the free-stream. This leads to the synchronization of the second mode with acoustic waves of the continuous spectrum. In the synchronization region, the phase speeds of the discrete unstable mode and the acoustic waves are very similar. This phenomenon is known as *spontaneous radiation of sound* [1].
The linear stability theory (LST) can predict that the second Mack mode radiates acoustic waves on a sufficiently cold plate. However, the results of LST cannot match the direct numerical simulation (DNS) data. This discrepancy has been related with two limitations of the LST approach: to handle non-parallel effects, and to describe the intermodal exchange in the synchronization region [2]. The parabolized stability equations (PSE) exhibit a similar lack of accuracy in the description of the disturbance flow field in the synchronization region [3].
These ideas are reflected in the following example: Figure 1 describes the evolution of a particular 2^{nd} Mack mode in a cooled ($T_w/T_\infty = 0.5$) hypersonic ($Ma = 6$) flat-plate boundary layer flow. The adaptive harmonic linearized Navier-Stokes (AHLNS) approach [4] can reproduce the DNS data. This result is especially remarkable considering that AHLNS requires 30 times less points in streamwise direction than DNS [1]. On the other hand, LST shows notable differences. When the supersonic mode (F^+) reaches the slow acoustic branch (phase-speed $c_s \sim 0.76$), LST is no longer able to trace this supersonic mode, but it follows a new discrete mode (F^-) that originally emerges from the branch point $c_s = 1 - 1/Ma$. Similarly, the marching procedure of PSE is not able to continue at the same location.
The complex interplay of the two supersonic modes, F^+ and F^-, with the acoustic branch will be described during the talk. Moreover, it will be discussed if the elliptic character of the AHLNS and DNS approaches is a key element to take into account for the correct description of the flow instabilities in hypersonic flows, an aspect not covered in the literature.

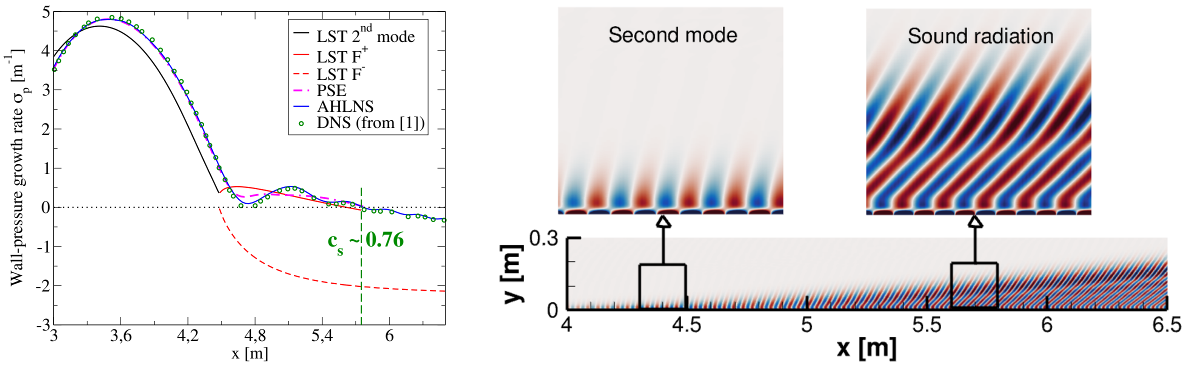

FIGURE 1. *Comparison of growth rates from LST, PSE, AHLNS, and DNS [1] (left), and pressure disturbance contours computed by AHLNS (right). A second Mack mode of frequency $F = 131.24 \times 10^{-6}$ is considered.*

References

[1] P. Chuvakhov, and A. Fedorov. Spontaneous radiation of sound by instability of a highly cooled hypersonic boundary layer. *J. Fluid Mech.*, 905, 188–206, 2016, doi: 10.1017/jfm.2016.560
[2] A. Fedorov, and A. Khokhlov. Prehistory of instability in a hypersonic boundary layer. *Theoret. Comput. Fluid Dynamics*, 14, 359–375, 2001, doi: 10.1007/s001620100038
[3] A. Fedorov. Transition and stability of high-speed boundary layers. *Annu. Rev. Fluid Mech.*, 43, 79–95, 2011, doi: 10.1146/annurev-fluid-122109-160750
[4] J. A. Franco. *The adaptive harmonic linearized Navier-Stokes methodology.* PhD thesis, Universidad Politécnica de Madrid (UPM), 2025, doi: 10.20868/UPM.thesis.90755

INVESTIGATION OF LOW-FREQUENCY UNSTEADINESS IN TRANSONIC SHOCK-WAVE/BOUNDARY LAYER INTERACTIONS

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Low-frequency unsteadiness of transonic flow over a bump is investigated in this study using large-eddy simulation. The freestream parameters are as follows: Mach number $M_\infty = 0.75$, total pressure $P_0 = 14.8$KPa, total temperature $T_0 = 290$K, and a fixed back pressure 0.65 times the total pressure. The instantaneous density gradient magnitude of a unsteady flow is shown in figure 1(a), where the characteristic λ-shock structure can be observe. The wall-pressure spectrum exhibits a low-frequency energy peak at $f = 70$ Hz ($St_L = 0.012$, normalised by the separation length and the freestream velocity) near the mean separation point x_{sep}, as shown in figure 1(b). Spectral proper orthogonal decomposition (SPOD) is employed to extract coherent structures of the unsteady flow. An energy peak around 70 Hz also appears in the leading SPOD modes. Figure 1(c) presents the corresponding SPOD mode, where large streamwise velocity fluctuations u' are primarily concentrated along the normal shock, while relatively weaker fluctuations are observed near the shock foot. The reconstructed separation and reattachment points based on this SPOD mode are compared in figure 1(d). The two points exhibit opposite motions at different instances, which are characteristic features of the breathing motion [1]. Therefore, the SPOD mode at 70 Hz governs the breathing motion of the turbulent separation bubble in transonic flows. Future work will employ global stability analysis and resolvent analysis to examine whether this breathing motion is driven by global instability, similar to observations in supersonic flows [2] and subsonic flows [3].

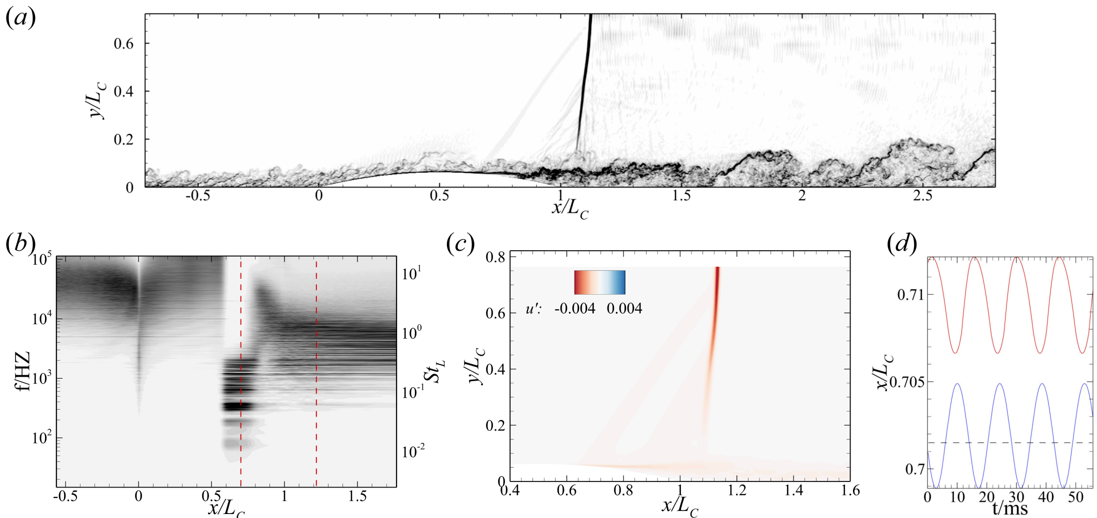

FIGURE 1. *(a) The instantaneous density gradient magnitude of a unsteady flow; (b) wall-pressure spectrum, the two red dashed lines indicate the mean separation x_{sep} and reattachment points x_{rep}; (c) real part of u' of the leading SPOD mode at $f = 70Hz$ ($St_L = 0.012$); (d) reconstructed separation and reattachment points at different instances.*

References

[1] Clemens, Noel T and Narayanaswamy, Venkateswaran. Low-frequency unsteadiness of shock wave/turbulent boundary layer interactions. *Annual Review of Fluid Mechanics*, 1(46):469–492, 2014.
[2] Hao, Jiaao. On the low-frequency unsteadiness in shock wave–turbulent boundary layer interactions. *Journal of Fluid Mechanics*, A28:971, 2023.
[3] Cura, C and Hanifi, Ardeshir and Cavalieri, AVG and Weiss, J. On the low-frequency dynamics of turbulent separation bubbles. *Journal of Fluid Mechanics*, A11:991, 2024.

OCCURRENCE OF UNSTEADY GLOBAL INSTABILITY IN HYPERSONIC FORWARD FACING STEP FLOW

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Hypersonic flow over a forward-facing step (FFS) represents a canonical configuration in high-speed aerodynamics, yet a comprehensive understanding of its stability mechanisms is still lacking. This study investigates the global instability characteristics of a two-dimensional FFS at Mach 6 with a unit Reynolds number of $6.5 \times 10^6 m^{-1}$ through combined global linear stability analysis (GSA) and direct numerical simulation (DNS), with systematic variation of the step height h.

Results show that as h increases, the separated flow region expands and the primary vortex core undergoes splitting (Figure 1 (a)). GSA identifies a critical step height near 3 mm, beyond which the flow becomes linearly unstable (Figure 1 (b) and (c)). Crucially, the dominant global mode is unsteady, distinguishing it from the steady instability modes of compression ramps [1] and backward-facing steps [2]. For $h = 3.5$ mm, the most amplified disturbance occurs at a spanwise wavelength of $\lambda/h = 1.12$, with the corresponding eigenvalue spectrum and spanwise velocity mode presented in Figure 1 (d) and (e), respectively. DNS confirms the exponential growth rate of these perturbations and captures their three-dimensional structure (Figure 1 (f)). Furthermore, the temporal evolution exhibits intensified spanwise velocity oscillations (Figure 1 (g)). A power spectral density analysis of spanwise velocity during saturated stage reveals a dominant frequency matching the unsteady GSA mode (Figure 1(h)), indicating that nonlinear effect does not alter the fundamental frequency. These findings elucidate the prevalence of unsteady global instabilities in FFS flows and provide fundamental insight into their linear and nonlinear development.

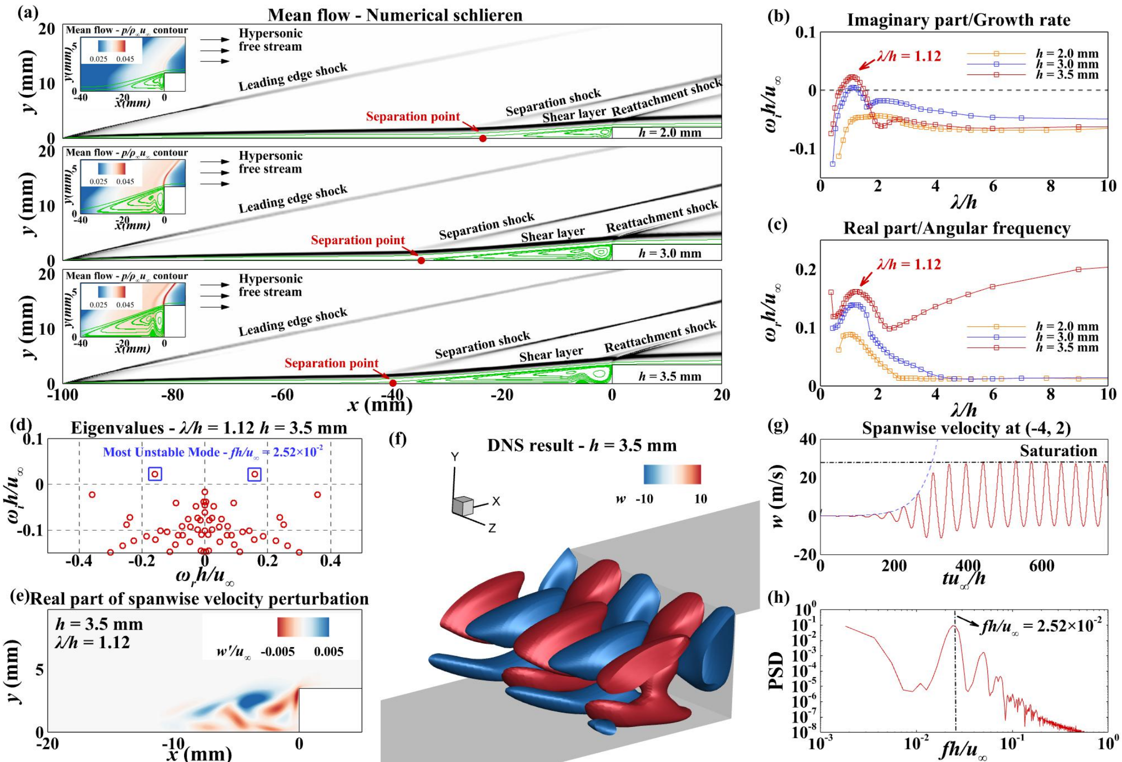

FIGURE 1. *Contours of (a) density gradient magnitude and non-dimensional pressure. Variations of dimensionless (b) growth rates and (c) angular frequencies of the most unstable modes with wavelengths. (d) Eigenvalue spectra and (e) contours of real part of spanwise velocity perturbation at the most unstable wavelength at h = 3.5 mm. (f) 3D spanwise velocity isosurface at the end of the linear growth phase in DNS result of h = 3.5 mm. (g) Temporal evolution of the spanwise velocity at (-4, 2) obtained from DNS result and (h) corresponding power spectral density*

References

[1] Hao J, Cao S, Wen CY, Olivier H. Occurrence of global instability in hypersonic compression corner flow. *Journal of Fluid Mechanics*, 2021 Jul;919:A.

[2] Yu K, Hao J, Wen CY, Xu J. Bi-global stability of supersonic backward-facing step flow. *Journal of Fluid Mechanics*, 2024 Feb;981:A29.

TRANSIENT GROWTH MECHANISM UNDERPINS SUPERSTRUCTURES AND NEAR-WALL SCALES IN TURBULENT CONVECTION

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Turbulent convection is a fundamental transport process that shapes weather and climate, powers flows in planetary interiors and stars, and limits the performance of energy and heat-transfer technologies. Yet how these flows organize simultaneously into large-scale "superstructures" and small-scale near-wall patterns remains unclear. Here, using Rayleigh–Bénard (RB) convection with large domain size as a test bed, we show that both structures can be described by optimal linear modes that maximize transient energy amplification, identified via linear analysis based on turbulent mean profiles. Two amplification regimes emerge with clear scale separation: large-scale modes spanning the full vertical domain with horizontal wavelengths ~ 6 times the plate separations, and small-scale modes confined near the walls at ~ 11 times the thermal boundary layer thickness. These results identify linear energy amplification as the organizing mechanism of multiscale turbulent convection and establish a unifying link to analogous non-modal processes in wall-bounded shear turbulence.

We adopt a linear energy amplification framework tailored to turbulent RB convection. By computing linear energy amplification under background conditions defined by turbulent mean temperature profiles and turbulent thermal diffusivity, we relate optimal linear modes to observed superstructures and small-scale structures in RB convection. We consider the dynamics of small-amplitude perturbations (denoted with primes) to the mean temperature profile $\Theta(y)$, which are governed by the non-dimensional linearized N-S equations within the Boussinesq approximation, written as

$$\partial_t \boldsymbol{u'} = -\nabla p' + \sqrt{\frac{Pr}{Ra}} \nabla^2 \boldsymbol{u'} + \theta' \boldsymbol{e}_j, \tag{1}$$

$$\partial_t \theta' = -\frac{d\Theta(y)}{dy} v' + \frac{1}{\sqrt{PrRa}} \nabla \cdot \left[\left(1 + \widetilde{\kappa_\theta}(y)\right) \nabla \theta' \right], \tag{2}$$

$$\nabla \cdot \boldsymbol{u'} = 0, \tag{3}$$

where, $\boldsymbol{u} = [u, v, w]^T$ denotes the velocity field, with y the wall-normal direction and x, z the horizontal directions. Temperature, pressure, and time are denoted by θ, p, and t, respectively. All quantities are non-dimensionalized using the temperature difference Δ, the layer height H, the free-fall velocity U_f, and corresponding free-fall time unit t_f. $\widetilde{\kappa_\theta}(y)$ is the turbulent thermal diffusivity, defined by

$$\langle v'\theta' \rangle = -\frac{\widetilde{\kappa_\theta}(y)}{\sqrt{PrRa}} \frac{d\Theta(y)}{dy} \tag{4}$$

where $\langle \varphi \rangle$ denotes the statistical averaging of an arbitrary variable φ in horizontal and time directions.
In this talk, we will show that both superstructures and near-wall small-scale structures in turbulent RB con- vection are captured by linear transient growth modes that undergo the largest energy amplification under the turbulent mean profile.

ON THE FLUTTER FEEDBACK LOOP OF A FLEXIBLE PLATE IN A VISCOUS CHANNEL FLOW

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A cantilever flexible plate in a viscous channel flow represents a canonical fluid-structure interaction problem [1], with applications ranging from cooling enhancement in heated channels [2] to the biomechanics of the human upper airway [3]. Despite its apparent simplicity, this coupled system exhibits complex self-sustained oscillations, and the underlying feedback loop that triggers and sustains the global instability still defies complete characterization.

In this work, we adopt the classical tools of linear stability analysis (LSA) [4], to study the flutter instability of a clamped-free flexible plate in a two-dimensional viscous channel flow at Re=100 (based on the bulk velocity and channel height), in the mass ratio–reduced velocity parameter space. The problem is governed by the incompressible Navier–Stokes equations coupled with a linear elasticity model for the structure, and it is spatially discretized via the finite element method using the open-source GetFEM library [5], within a monolithic Arbitrary-Lagrangian-Eulerian framework [7].

Leveraging LSA results, we perform an energetic analysis to provide a deeper understanding of the instability mechanism. Figure 1a shows the spatio-temporal distribution of the instantaneous local power, which quantifies the net energy exchange between the fluid and the structural global modes over two oscillation cycles. This map identifies regions where the flexible structure receives energy from the fluid perturbations (red) and regions where the compliant plate transfers energy back feeding the fluid disturbances (blue). This energetic analysis reveals that the instability is sustained by a feedback loop between a downstream-traveling kinematic wave (Fig. 1b) and a reverse dynamic wave of pressure disturbances traveling upstream (Fig. 1c) [8].

Finally, we propose a gradient-based optimization procedure that suppresses the unstable mode by redistributing the structural mass. This procedure is shown to successfully stabilize the system by attenuating the local energy transfer at the fluid-structure interface, while preserving the mass of the structure.

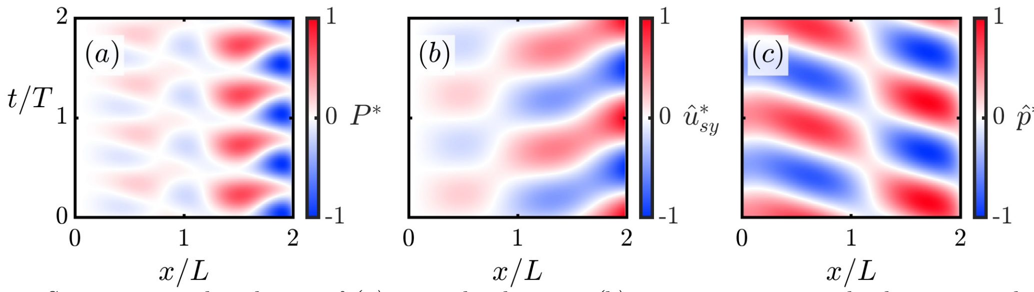

FIGURE 1. *Spatio-temporal evolution of (a) normalized power, (b) transverse structural velocity perturbation, and (c) interface pressure fluctuations. All quantities are normalized by their respective absolute maximum values. Here, L denotes the plate length, while T represents the oscillation period. Simulation parameters, defined as in [6]: Re=100, cantilever-length-to-channel-height ratio L/H=2, mass ratio M=2, reduced velocity U=6.98.*

References

[1] M. P. Païdoussis. Fluid-Structure Interactions, Volume 2: Slender Structures and Axial Flow. *Elsevier*, 2003.
[2] P. Hidalgo and A. Glezer. Direct actuation of small-scale motions for enhanced heat transfer in heated channels. *Proc. Semi-Therm*, 17–23, 2014.
[3] T. S. Balint and A. D. Lucey. Instability of a cantilevered flexible plate in viscous channel flow. *J. Fluids Struct.*, 20(7):893–912, 2005.
[4] V. Theofilis. Global linear instability. *Annu. Rev. Fluid Mech.*, 43:319–352, 2011.
[5] Y. Renard and K. Poulios. GetFEM: Automated FE modeling of multiphysics problems based on a generic weak form language. *ACM Trans. Math. Softw.*, 47(1):1–31, 2020.
[6] J. Cisonni, A. D. Lucey, N. S. J. Elliott, and M. Heil. The stability of a flexible cantilever in viscous channel flow. *J. Sound Vib.*, 396:186–202, 2017.
[7] J.-L. Pfister, O. Marquet, and M. Carini. Linear stability analysis of strongly coupled fluid–structure problems with the Arbitrary-Lagrangian–Eulerian method. *Comput. Methods Appl. Mech. Eng.*, 355:663–689, 2019.
[8] S. Michelin, S. G. Llewellyn Smith, and B. J. Glover. Vortex shedding model of a flapping flag. *J. Fluid Mech.*, 617:1–10, 2008.

OPTIMAL THREE-DIMENSIONAL PERTURBATIONS IN FLUTTERING AND NON-FLUTTERING BIOPROSTHETIC AORTIC VALVES

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This study examines the transition to turbulence downstream of fluttering and non-fluttering bioprosthetic aortic valves using global linear stability theory. During systole, increasing inflow velocities result in temporally evolving flow profiles downstream of the valve which are highly influenced by the leaflet kinematics (figure 1a). These profiles are time-averaged at the sinotubular junction over successive windows and used as boundary conditions to obtain base flows for stability analysis. Three-dimensional global modes are computed for one design of each valve type across multiple time windows, revealing several unstable modes whose frequencies and growth rates increase over time. Notably, the non-fluttering valve exhibits higher growth rates than the fluttering valve. The resulting eigenspectra show that, for each case, the most unstable eigenvalues align along two distinct parabolic branches in the complex plane. For each valve case, the modes within each branch are found to have similar group velocities, suggesting that the unstable modes along a branch constitute a coherent structure. Motivated by this, a transient growth analysis is conducted to identify the optimal initial perturbations that maximize energy gain for a given time horizon. When superimposed onto the base flow, these perturbations generate vortical structures that closely resemble those observed in fully coupled nonlinear fluid–structure interaction (FSI) simulations for a similar time-scale as the one used to obtain the optimal perturbations (figures 1b-c). These results suggest that the optimal perturbations may initiate the shear-layer instabilities responsible for transition to turbulence, providing valuable insight into the underlying mechanisms in the flow fields downstream of bioprosthetic valve designs.

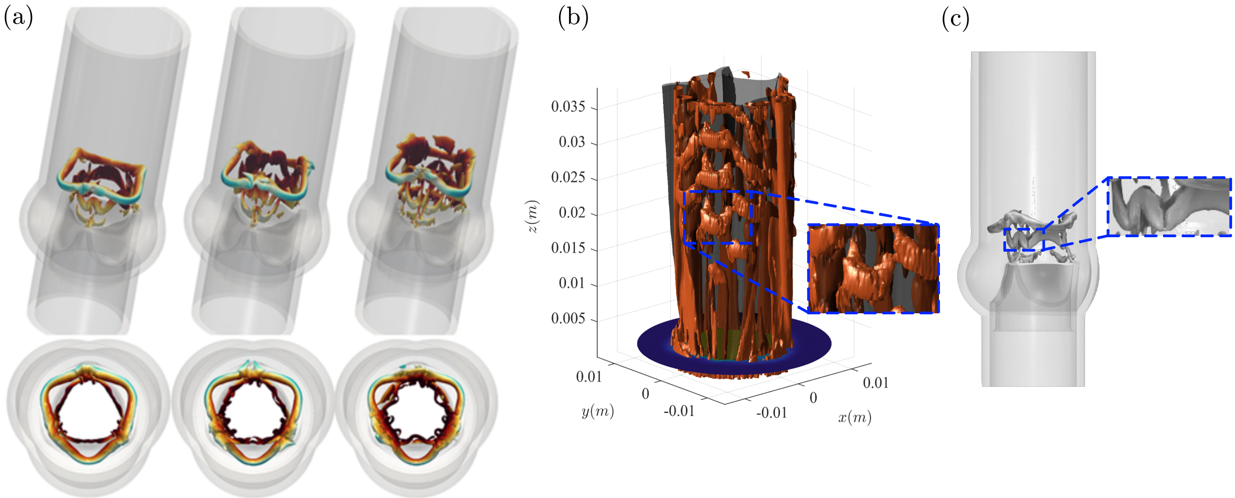

Figure 1. *(a) Volume-filtered, moving-averaged λ_2-criterion iso-surfaces for the non-fluttering valve over time in FSI simulations. (b) λ_2 visualisation of the base flow with optimal perturbations for the non-fluttering case. (c) Volume-filtered, moving-averaged λ_2 visualisation for the non-fluttering case in FSI simulations.*

FLOW INSTABILITIES IN A RECORDER'S MOUTHPIECE

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The recorder is one of the simplest woodwind instruments, yet despite its 700-year history, a comprehensive understanding of the interplay between hydrodynamic processes and sound generation at the mouthpiece remains incomplete. This study investigates these mechanisms using simplified simulations and hydrodynamic stability theory. We develop a computational model of the recorder, parameterized by key geometric features of the mouthpiece, specifically focusing on the transverse offset between the mouth channel and the labium. Linear stability analysis is performed to identify the onset of hydrodynamic instabilities, with results validated against fully unsteady flow simulations. Notably, our analysis reveals distinct flow regimes dictated by the labium geometry: we identify parameters that produce stable, steady oscillations, as well as regimes characterized by intermittent behavior. Finally, we discuss how these regime transitions influence instrument design and playability, providing a theoretical framework for optimizing the recorder's acoustic response.

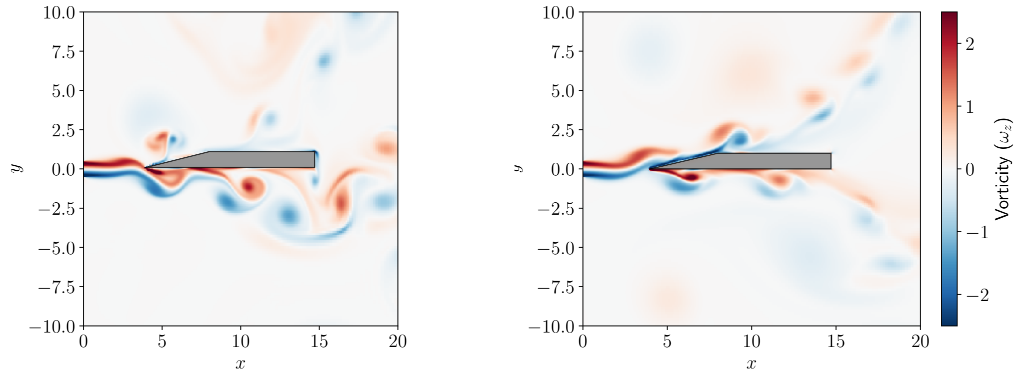

FIGURE 1. *Vorticity for two different offset settings. Left: if the labium is alligned with the top of the channel, the flow is predominantly deflected downwards, generating a force which gives rise to large-scale vortices which cause intermittency. Right: if the labium is slightly shifted, the jet now breaks symmetrically, and no net downforce is generated on the labium.*

LOCAL AND NON-LOCAL INTERACTIONS OF PHONONIC SUBSURFACES WITH TOLLMIEN-SCHLICHTING WAVES IN AIR

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Extensive research [1] has demonstrated the efficacy of compliant surfaces in the passive control of convective instabilities, such as Tollmien–Schlichting waves (TSW), to delay transition in low disturbance environments. However, the fluid-structure coupling required by these systems facilitates the emergence of flow induced surface instabilities [2]. To suppress these additional modes, a range of structural modifications has been proposed, and recently, the research has moved towards the use of phononic metamaterials [3]-[4]. Michelis et al.(2023)[5] showed how a phononic subsurface (PSub) (whose length is only a fraction of the TSW wavelength) can effectively interact with TSW in air, offering an alternative to the utilization of extended compliant walls, whose limitations in air flows have been exhaustively described[1].
The proposed work analyses the performance of phononic crystal interacting with TSW at frequencies both above and below the truncation frequency of the structure, in a Blasius' boundary layer in air. The coupling within the system is established through a linearization of the ALE formulation [6]. At frequencies below the truncation one, as previously documented, a local increase in velocity perturbation energy is observed[3]-[5]. However, a consistent down-stream reduction is also obtained, due to the development of a phase shifted TSW after the interaction with the PSub (Fig.1c). The resulting flow can, in fact, be decomposed into a TS-like component, that develops downstream coherently with the undisturbed wave (Fig.1e) and a local disturbance around the PSub interface (Fig.1f). This configuration is thus able, for specific frequency ranges to offer effective and persistent reductions in perturbation energy with one single PSub.

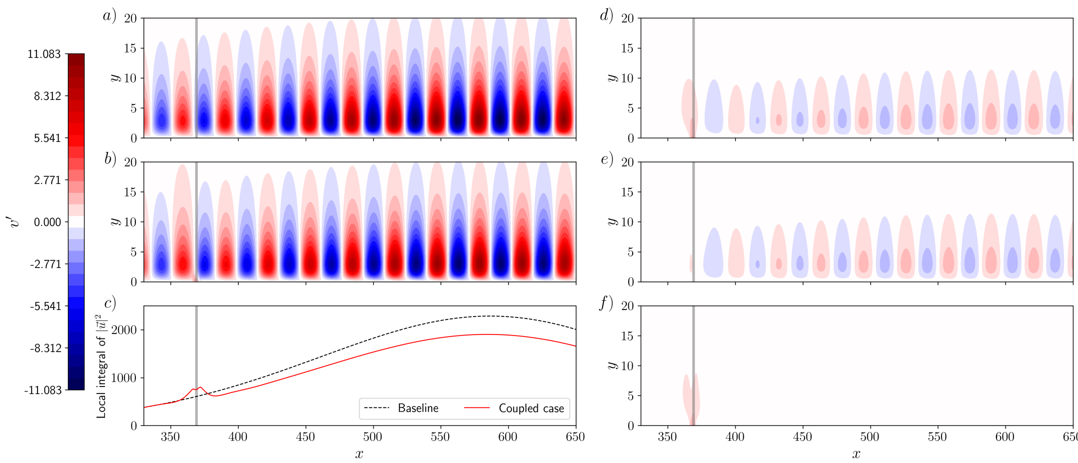

FIGURE 1. *For a TSW frequency $\omega_{TS} = 0.069$ and a truncation frequency $\omega_{TR} = 0.06905$: wall-normal perturbation velocity field for the rigid-wall case without PSub (a), for coupled case with a PSub (b), difference between the coupled case and rigid-wall case (d), component of the difference field coherent with the rigid-wall case TSW (e), residual of the difference field non-coherent with the rigid-wall case TSW (f). Local integral of the perturbation velocity $|\vec{u}'|^2$ (c). The gray bands indicate the position of the PSub.*

References

[1] P.W. Carpenter, A. D. Lucey. Progress on the Use of Compliant Walls for Laminar-Flow Control. *Journal of Aircraft*, Vol 38(3), 2001.
[2] T.B. Benjamin. The Threefold Classification of Unstable Disturbances in Flexible Surfaces Bounding Inviscid Flows. *Journal of Fluid Mechanics*, Vol 16(3):436-450, 1963.
[3] M. I. Hussein, S. Biringen, O. R. Bilal, A. Kucala. Flow stabilization by subsurface phonons. *Proceedings of the Royal Society A*, Vol 471:20140928, 2015.
[4] N. Fabbiane, O. Marquet, L. Pierpaoli, R. Cottereau, M. Couliou. Phononic compliant surfaces for the suppression of travelling wave flutter instabilities in boundary-layer flows. *Journal of Fluid Mechanics*, Vol 1020:A47, 2025.
[5] T. Michelis, A. B. Putranto, M. Kotsonis. Attenuation of Tollmien–Schlichting waves using resonating surface-embedded phononic crystals. *Physics of Fluids*, Vol 35:044101, 2023.
[6] J. Pfister. Instabilities and optimization of elastic structures interacting with laminar flows. *Univ. Paris Saclay* , 2019.

VORTEX BREAKDOWN ON HYDRO TURBINE DRAFT TUBE

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Hydraulic turbines operated away from their design point often exhibit reduced efficiency and increased pressure pulsations caused by unsteady swirling flow phenomena developing downstream of the runner. In this work, we numerically investigate the outlet swirling jet of a Francis turbine using experimentally validated mean flow and turbulence profiles from Resiga et al. [1, 2] at operating conditions below, at, and above the best efficiency point (BEP) discharge. We focus on the role of turbulence closure, and the associated eddy viscosity field, in determining instability onset, dominant azimuthal content, and sensitivity mechanisms. Unsteady RANS simulations are performed in a simplified draft tube configuration with OpenFOAM using several closures (Spalart–Allmaras, $k-\varepsilon$ variants, and $k-\omega$ models). The results show strong model dependence: some closures relax to a steady, nearly axisymmetric state, whereas others sustain self-excited oscillations consistent with a precessing helical vortex structure. To rationalize these differences, we complement the uRANS computations with linear analyses, including a rapid local (parallel) stability (shown in figure 1) and adjoint sensitivity study of the turbine outlet swirling jet, as well as global stability/resolvent analyses of selected RANS baseflows using a frozen eddy viscosity formulation. Across operating points, increased eddy viscosity substantially attenuates inviscid growth rates and confines unstable azimuthal modes to a limited range, with partial load conditions emerging as the most susceptible. Adjoint sensitivities indicate that perturbations to the axial velocity profile primarily regulate growth, azimuthal velocity modifications mainly shift the oscillation frequency, and spatial variations of turbulent viscosity are critical for predicting the unstable mode band.

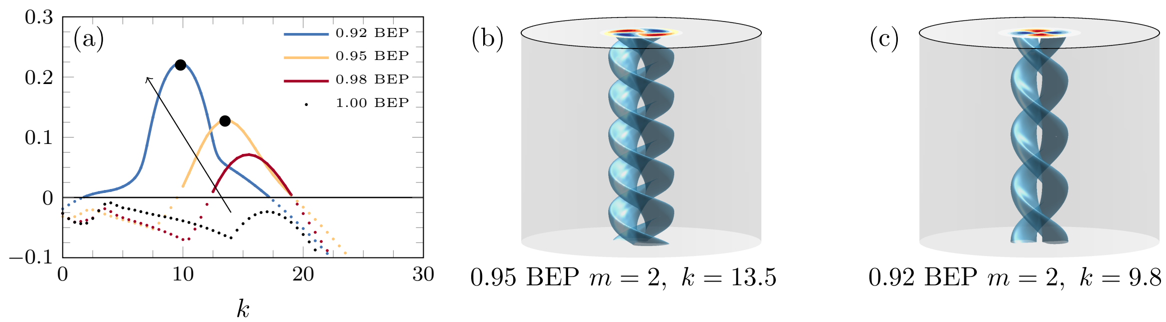

FIGURE 1. *(a) Growth rate λ curves of the $m = 2$ mode under different flow rate conditions using the experimentally measured $k-\varepsilon$ viscosity model as a function of the axial wavenumber k. Solid lines indicate positive growth rates, while dotted markers indicate negative growth rates. Three-dimensional expansion of the most unstable modes in vorticity (b) 0.95 BEP and (c) 0.92 BEP.*

References

[1] Susan-Resiga, R. and Ciocan, D. and Anton, I. and Avellan, F., *Analysis of the swirling flow downstream a Francis turbine runner*, J. Fluids Eng. **128**, 1 (2006).

[2] Susan-Resiga, R. and Muntean, S. and Hasmatuchi, V. and Anton, I. and Avellan, F., *Analysis and Prevention of Vortex Breakdown in the Simplified Discharge Cone of a Francis Turbine*, J. Fluids Eng. **32**, 5, 051102 (2010).

3D GLOBAL STABILITY ANALYSIS OF COUNTER-CURRENT JET

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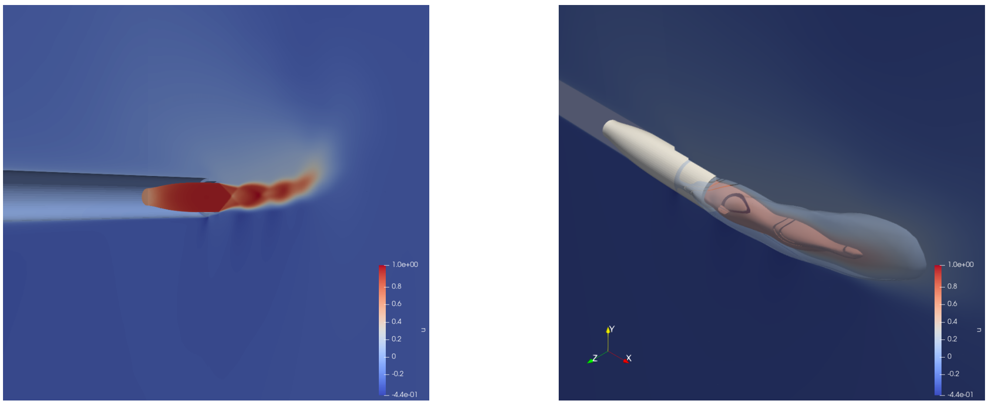
To minimize environmental impact and operational costs, the aerospace sector is moving towards low-impact solutions and sustainable application. Among the various innovations, the possibility of using reusable rockets is of great interest. Building upon experiments and numerical simulations carried out by CNES and the Pprime institute, this study performs a global stability analysis of a 3D jet with a counterflow ($M_\infty = 0.8$) at a angle of attack $\theta = 10°$. Capture the oscillation frequency and their underlying physical mechanisms is crucial for ensure a safe landing.
Given the complexity of the phenomenon under consideration and the high Reynolds number ($Re_{jet} = 2 \times 10^6$), the isentropic profile of the nozzle is implemented, so as not to resolve the boundary layer. Furthermore perfect gas is considered. These simplifications do not affect the fundamental physics of the problem maintaining computational feasibility.
Figure 1 shows the time-averaged streamwise velocity component field after the impact of the jet with the countercurrent flow inclined at 10°. Due to the presence of the latter, despite the nozzle being initially adapted, there is an increase in pressure in the outlet section, leading to the formation of oblique shocks. The 3-D Unsteady Reynolds-Averaged Navier-Stokes (URANS) is linearized around the base flow, thereby also perturbing the turbulent viscosity. To take into account the high speed of the outgoing jet ($M_{jet} = 2.79$), the system is closed with the k-log(ω) SST model with compressibility correction [1]. For these computationally expensive cases, it is not possible to extract the Jacobian matrix directly, therefore the eigenvalue problem is solved using time stepper methods such as Krylov-Schur [2].
The global stability results are presented via the resulting eigenspectrum, accompanied by a physical analysis of the captured modes and frequencies.



(a) Contours of U on the $x-y$ plane (b) 3D isosurfaces of U

Figure 1: Mean streamwise velocity U of the jet at Mach $M = 2.79$ with an angle of attack $\theta = 10$

References

[1] D. C. Wilcox Dilatation-dissipation corrections for advanced turbulence models, *AIAA journal*, 30(11):2639–2646, 1992.
[2] J.-C. Loiseau, M. A. Bucci, S. Cherubini, and J.-C. Robinet Time-stepping and krylov methods for large-scale instability problems, *Computational modelling of bifurcations and instabilities in fluid dynamics* Springer, 2019,

Book of Abstracts – Day 3

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"Learning with memory: non-Markovian bilinear models for adaptive predictive control of non-autonomous systems"
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"Inference of stable reduced-order models with memory history"
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LEARNING WITH MEMORY: NON-MARKOVIAN BILINEAR MODELS FOR ADAPTIVE PREDICTIVE CONTROL OF NON-AUTONOMOUS SYSTEMS

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Data-driven reduced-order modelling of nonlinear, non-autonomous dynamical systems is a key enabler for real-time flow control. Recent approaches based on Koopman operator theory seek finite-dimensional linear or bilinear representations in latent spaces, enabling tractable prediction and control. However, such representations rely on truncations of an inherently infinite-dimensional operator, introducing modelling errors that can degrade control performance, particularly in non-autonomous and strongly nonlinear regimes.
In this work, we extend Mori–Zwanzig (MZ) based closure framework for non-autonomous, control-affine systems. By systematically accounting for the influence of unresolved observables through memory terms, the resulting reduced-order model retains essential non-Markovian dynamics that are neglected in standard Koopman approximations. This provides a principled route to augment finite-dimensional models with data-driven memory effects.
We integrate the resulting memory-enhanced model within an adaptive Model Predictive Control (MPC) framework. The memory kernel is estimated online, enabling the controller to adapt to time-varying dynamics and unmodelled effects. This leads to a data-driven control architecture that improves robustness and predictive accuracy compared to conventional Markovian Koopman-MPC approaches.

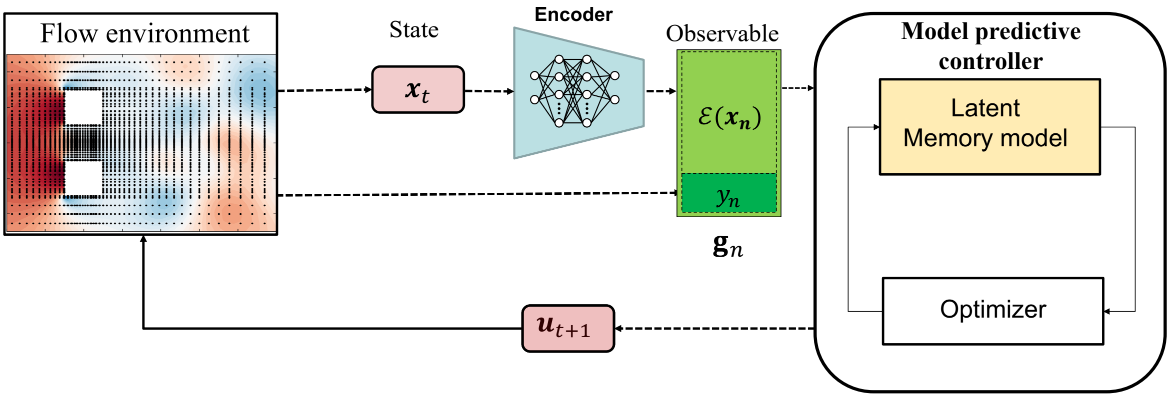

FIGURE 1. *Schematic of the proposed memory-augmented control framework. The flow environment provides high-dimensional states x_t, which are mapped via an encoder to a latent observable space. A Mori–Zwanzig-inspired latent memory model is embedded within a model predictive control loop, enabling non-Markovian predictions and adaptive optimisation of control inputs u_{t+1}.*

The proposed methodology is demonstrated on nonlinear and chaotic dynamical systems, where it achieves optimal regulation performance and faster convergence compared to Markovian model-based control and model-free reinforcement-learning approaches, respectively. These results highlight the importance of non-Markovian effects in data-driven control and open new directions for combining operator-theoretic modelling with adaptive, learning-based control strategies.

References

[1] P. Gupta, P. J. Schmid, D. Sipp, T. Sayadi, and G. Rigas. Mori–Zwanzig latent space Koopman closure for nonlinear autoencoder. *Proc. R. Soc. A*, 481(2313):20240259, 2025. doi:10.1098/rspa.2024.0259.
[2] Y. T. Lin, Y. Tian, D. Livescu, and M. Anghel. Data-driven learning for the Mori–Zwanzig formalism: A generalization of the Koopman learning framework. *SIAM J. Appl. Dyn. Syst.*, 20(4):2558–2601, 2021.

INFERENCE OF STABLE REDUCED-ORDER MODELS WITH MEMORY HISTORY

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We develop a data-driven framework for constructing *stable reduced-order models* (ROMs) equipped with *memory term* for long-time forcast. The reduced dynamics is inferred from time-series data via the quadratic recurrence

$$v^{n+1} = A\, v^n + \text{Memory} + \mathbf{Q}\big(v^n \otimes v^n\big), \qquad n \geq 0,$$

where the linear operator A and the quadratic contribution $\mathbf{Q}$ jointly describe the evolution. Such models naturally arise in systems governed by the Navier–Stokes equations, where the nonlinear quadratic interactions represent the convective contribution.

To ensure long-time robustness, we incorporate structural constraints motivated by stability and energy conservation. Specifically, we impose spectral-norm bounds on the linear operator and enforce skew-symmetry conditions on the quadratic operator. To numerically approximate the operators of the model, we adopt the strategy introduced in [1]. The resulting optimality problem is solved using a Hessian-free Newton-Raphson method combined with an adapted conjugate-gradient algorithm. This approach is computationally efficient, as it requires only the evaluation of Hessian–vector products rather than the explicit construction of the underlying high-dimensional Hessian operator. Finally, through a series of numerical experiments, we assess the ability of the proposed framework to produce stable models that accurately capture the system dynamics within the training time window while exhibiting strong generalization performance beyond it.

References

[1] R. Ayoub, M. Oulghelou, P.J. Schmid *Improved Greedy Identification of latent dynamics with application to fluid flows.* Computer Methods in Applied Mechanics and Engineering Volume 437, 15 March 2025

PASSIVE ATTENUATION OF TOLLMIEN–SCHLICHTING WAVES IN AIR BY OPTIMISED STRUCTURED COMPLIANT SURFACES

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Compliant surfaces have been largely investigated, with mixed results, as a means of delaying the laminar-to-turbulent transition in boundary-layer flows by attenuating flow instabilities, such as the Tollmien–Schlichting (TS) waves, via fluid-structure-interaction (FSI) [1]. However, the recent introduction of metamaterials—composite media whose static and dynamic behaviour can be engineered through their internal micro-structure—has revived interest in compliant surfaces for passive flow control [2].
One of the challenges is to transpose the promising results obtained in water [3, 4] to boundary-layer flows in air, where the solid-to-fluid density ratio is several orders of magnitude larger—$\rho_{solid}/\rho_{water} \sim 1$ vs. $\rho_{solid}/\rho_{air} \sim 10^3$. A solution explored in the literature is the use of resonant metamaterials [5], but the single-frequency nature of resonance can be at odds with the broadband spectrum of TS waves.
Rather than exploiting the internal structure of the metamaterial to suppress FSI instabilities as in previous studies [4], the present work explores a metamaterial design that promotes compliance. The optimisation-based design builds on the experience gained from the aeroelastic optimisation of composite structures [6] using efficient global optimisation [7]. A periodic arrangement is considered based on a unit cell (Figure 1, top-left) that considers a thin elastomer-based structure. This parametrisation permits to tune the effective stiffness of the surface so that (i) the incoming TS wave is attenuated and (ii) no additional instabilities appear, as verified by resolvent and global-stability analyses of the FSI system [3].
Preliminary optimisation results are displayed in Figure 1. The optimal compliant surface (top-right) yields a substantial reduction of the perturbation energy in the fluid with respect to the baseline rigid-wall scenario over a wide frequency range (bottom-left). Moreover, the streamwise distribution of the kinetic perturbation energy at a representative frequency (bottom-right) shows that the TS wave is progressively attenuated within the extent of the compliant surface and exhibits a lower amplitude downstream of it.

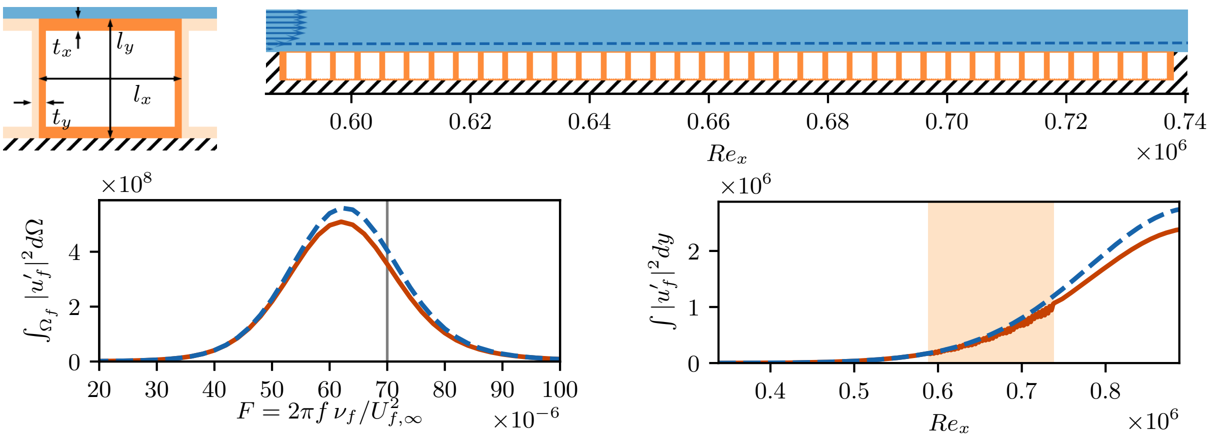

FIGURE 1. *Prelimianry results. (top-left) Geometrical parametrisation of the unit cell: fluid (air) in blue and solid (elastomer) in orange. (top-right) Optimised geometry of the compliant surface. (bottom-left) Kinetic perturbation energy in the fluid domain obtained from a resolvent analysis: the dashed line corresponds to the baseline rigid-wall case, the solid line to the compliant surface. (bottom-right) Streamwise distribution of the kinetic perturbation energy for a forcing frequency $F = 70 \times 10^{-6}$: the shaded area indicates the extension of the compliant surface.*

References

[1] P.W. Carpenter, A.D. Lucey. Progress on the use of compliant walls for laminar-flow control. *J. Aircr.*, Vol 38(3), 2001.
[2] F. Avallone, . . . , and A. Krushynska. Metamaterials and fluid flows. *Nat. Commun.*, in press. (arXiv:2509.05371)
[3] J.-L. Pfister, N. Fabbiane, and O. Marquet. Global stability and resolvent analyses of laminar boundary-layer flow interacting with visco-elastic patches. *J. Fluid Mech.* Vol 937:A1, 2022.
[4] N. Fabbiane, O. Marquet, L. Pierpaoli, R. Cottereau, and M. Couliou. Phononic compliant surfaces for the suppression of travelling wave flutter instabilities in boundary-layer flows. *J. Fluid Mech.*, Vol 1020:A47, 2025.
[5] T. Michelis, A.B. Putranto, M. Kotsonis. Attenuation of Tollmien–Schlichting waves using resonating surface-embedded phononic crystals. *Phys. Fluids*, Vol 35:044101, 2023.
[6] R. Ballester Claret, L. Coelho, C. Fagiano, C. Julien, D. Lucor, and N. Fabbiane. Reliability based optimisation of composite plates under aeroelastic constraints via adapted surrogate modelling and genetic algorithms. *Compos. Struct.*, Vol 347:118461, 2024. *Composite Structure*, Vol 347:118461, 2024.
[7] R. Lafage. egobox, a Rust toolbox for efficient global optimization. *J. Open Source Softw.*, Vol 7(78):4737, 2022.

DEVELOPMENT OF MODAL AND NON-MODAL INSTABILITIES IN HYPERSONIC BOUNDARY LAYER OVER BLUNTED CONES

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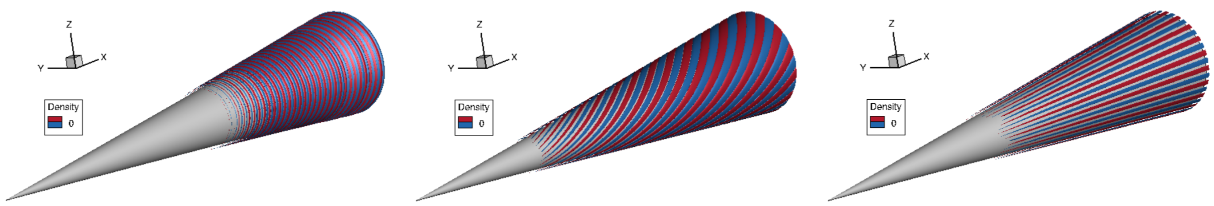
With applications spanning from space exploration to high-speed commercial transportation or defence, hypersonic flight and its "heat barrier" [1] is a critical frontier in aerospace engineering. Indeed, the thermal loads experienced by such vehicles in atmospheric flight or re-entry make aero-heating a major concern for their design. To mitigate these loads most hypersonic vehicles are designed with a blunt forebody, but this bluntness also impacts the boundary-layer properties. As turbulent boundary layers generate significantly larger wall heat fluxes and viscous drag than laminar ones, the position of transition to turbulence is crucial to optimize hypersonic vehicles. The boundary-layer state may also influence the efficiency of eventual control surfaces, air intakes or engines.

Considering absolutely stable flows, the transition is due to small environmental perturbations triggering convective instabilities. In low perturbation environments such as in flight, this process is characterized by modes which experience linear growth up to saturation when non-linearities appear and the breakdown to turbulence occurs [2]. For bi-dimensional geometries with no Angle of Attack and sharp leading-edges, transition is dominated by the 1st and 2nd Mack modes below and above Mach 5 respectively [5]. Increasing nose bluntness on blunt plates and cones with no AoA has been found to delay transition up to a critical nose radius, beyond which the onset of transition actually moves upstream [3, 4]. This phenomenon is called Transition-Reversal and is not fully understood yet. Though some numerical studies suggest that in this high bluntness range, non-modal streaks lead to transition through secondary instabilities [6, 7].

In this study the boundary-layer stability over 5° blunted cones with nose radii ranging from 0.1 to 15 mm is assessed experimentally at Mach 6 in the ONERA R2Ch blowdown wind tunnel. The chosen freestream Reynolds numbers allow for the exploration of both small bluntness and Transition Reversal regimes. Some small bluntness cases are also investigated numerically by means of Resolvent (Input/Output) analysis thanks to the BROADCAST toolbox [8] taking advantage of Algorithmic Differentiation. The goal of this study is to better understand how bluntness effects can either delay or promote transition to turbulence.



(a) (b) (c)

Figure 1: Optimal response fields corresponding to the 2^{nd} (**a**) and 1^{st} (**b**) Mack modes as well as the streaks (**c**), on a sharp cone (0.1mm) at Mach 6.

References

[1] T. Heppenheimer. *Facing the heat barrier: a history of hypersonics.* NASA History Division, Washington, 2007.

[2] M. Morkovin, E. Reshotko, and T. Herbert. Transition in open flow systems : a reassessment. *American Physical Society*, 39(9), 1994.

[3] K. F. Stetson, and G. H. Rushton. Shock Tunnel Investigation of Boundary-Layer Transition at M = 5.5. *AIAA Journal*, 5(5), 1967.

[4] E. J. Softley. Transition of the hypersonic boundary layer on a cone Part II: Experiments at Mach 10 and more on blunt cone transition. *GE Space Science Lab Technical Report*, 1968.

[5] L. M. Mack. Boundary-Layer Linear Stability Theory. *AGARD Technical Report, 709, Jet Propulsion Laboratory*, 1984.

[6] P. Paredes, M. M. Choudhari, and F. Li. Mechanism for frustum transition over blunt cones at hypersonic speeds. *Journal of Fluid Mechanics*, 894(22), 2020.

[7] P. Guo, J. Hao, and C. Y. Wen. Transition Reversal over a blunt plate at Mach 5. *Journal of Fluid Mechanics*, 1005(5), 2025.

[8] A. Poulain, C. Content, D. Sipp, G. Rigas, and E. Garnier. BROADCAST: A high-order compressible CFD toolbox for stability and sensitivity using Algorithmic Differentiation. *Computer Physics Communications*, 283(108557), 2023.

EFFECTS OF CATALYTIC WALLS ON THE STABILITY OF HYPERSONIC BOUNDARY LAYERS

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Hypersonic flows often exhibit strong thermochemical nonequilibrium, involving a complex interplay between thermodynamics, chemistry, and fluid mechanics. In this regime, gas–surface interactions (GSI), and in particular catalytic reactions at solid walls, can strongly affect heat transfer and the overall boundary-layer composition. The stability of hypersonic boundary layers has been extensively studied in the literature, with most early investigations neglecting chemical effects. More recently, direct numerical simulations of chemically reactive boundary layers subjected to harmonic wall forcing [1, 2] have assessed the influence of finite-rate chemistry on flow stability at high temperatures. Both studies have shown that, although chemical reactions may have a negligible impact on the mean-flow topology, they can produce order-one changes in the amplification of instability waves. All existing studies, nevertheless, have considered chemically inert solid walls, thereby neglecting the role of surface chemistry in boundary-layer stability. In the present work, we aim to investigate the influence of surface chemistry on hypersonic boundary-layer stability, with a particular focus on heterogeneous catalysis. The proposed configuration is a Mach 5.75 boundary layer developing over a flat plate with a non-catalytic baseline wall and a fully catalytic patch located in the middle of the domain. Simulations are performed using the in-house Multispecies hyperSonic Solver (MS^2) [2], which consists of a direct numerical flow solver able to account for real-gas nonequilibrium effects at high enthalpies. The solver has been extended to include wall catalytic reactions through surface mass and energy balance models [3]. The effect of catalysis on the steady-state flow for a five-species air mixture is illustrated in Fig. 1, which presents the steady-state streamwise velocity field u (top) and the species mass fractions $Y_s = \rho_s/\rho$ at the wall (bottom) as functions of the non-dimensional streamwise coordinate x. With the catalytic patch promoting the recombination of radical species, a considerable reduction in free nitrogen (N) and oxygen (O) can be observed at the solid wall, while having a negligible effect on the shape of the velocity field. The effect of catalysis on the growth of instabilities will be assessed by unsteady simulations of the forced boundary layer.

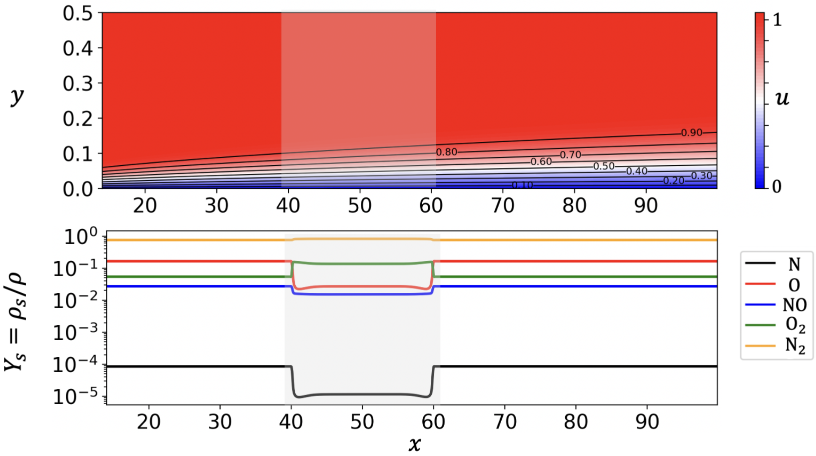

FIGURE 1. *Contours of the steady-state non-dimensional streamwise velocity field u (top) and species mass fractions $Y_s = \rho_s/\rho$, $s \in [\mathrm{N}, \mathrm{O}, \mathrm{NO}, \mathrm{O_2}, \mathrm{N_2}]$ at the solid wall ($y = 0$) versus the nondimensional streamwise distance x (bottom). The extent of the catalytic patch is indicated by the shaded gray region.*

References

[1] O. Marxen, G. Iaccarino, and T. E. Magin, Direct numerical simulations of hypersonic boundary-layer transition with finite-rate chemistry, *J. Fluid Mech.* **755**, 35–49 (2014).

[2] A. T. Margaritis, C. Scherding, O. Marxen, P. J. Schmid, and T. Sayadi, Chemical-nonequilibrium effects in a range of hypersonic applications, *European Journal of Mechanics – B/Fluids* **114**, 204273 (2025).

[3] A. O. Başkaya, M. Capriati, A. Turchi, T. Magin, and S. Hickel, Assessment of immersed boundary methods for hypersonic flows with gas–surface interactions, *Computers & Fluids*, 2024.

BAYESIAN OPTIMAL DESIGN OF THERMACOUSTIC INSTABILITY EXPERIMENTS

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Predicting how the thermoacoustic instability of an industrial combustor changes across operating conditions is a long-standing challenge because small uncertainties in the flame response lead to large uncertainties in the thermoacoustic response. In this paper, we address this challenge for a 1 MegaWatt industrial test rig using a combination of Bayesian inference, Gaussian process regression, and information-theoretic experiment design. Starting from a physics-based model whose parameters are inferred at several operating conditions using Bayesian inference, we use Gaussian process regression to learn how the five parameters of a flame model vary with six operating condition parameters. The resulting Gaussian process model predicts the flame response at unseen conditions with quantified uncertainty, and, when coupled into the acoustic network, produces operating maps of the full thermoacoustic response. We then use metrics from information theory to identify the small number of forcing frequencies that are most informative about the flame parameters. For this industrial test rig, three optimally chosen frequencies recover the flame behaviour to the same fidelity as the full dataset of around 20 frequencies forced from both upstream and downstream, reducing the data required by up to 90%.

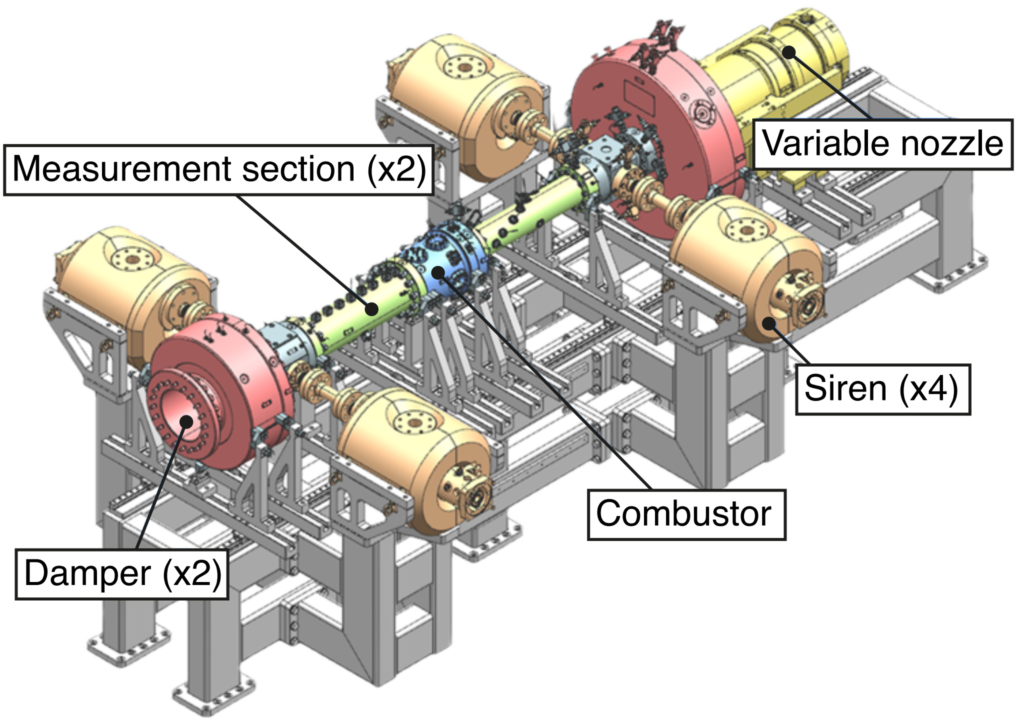

FIGURE 1. *One MegaWatt industrial rig for the study of thermoacoustic instability*

OPTIMAL RECONSTRUCTION OF EXPERIMENTAL SPOD MODES FROM RESOLVENT RESPONSES: APPLICATION TO HYPERSONIC BLUNT CONES BOUNDARY-LAYERS

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We perform optimal reconstruction of experimental SPOD modes from schlieren visualisations using resolvent analysis responses to further understand transition-to-turbulence of hypersonic boundary layers on blunt cones. Due to the bluntness of the geometry, a curved detached shock appears upstream the nose creating an entropy layer above the boundary layer and has for consequence the dampening of the 1^{st} and 2^{nd} Mack modes which are usually responsible for the transition on the sharp cone canonical case, making the path to turbulence unclear. To better understand the mechanisms of transition, an experimental campaign lead by A. Cerruzi [1] has experimentally identified coherent structures using SPOD of high-speed schlieren visualisations of the boundary and entropy layers in the transition region, see Figure 1.

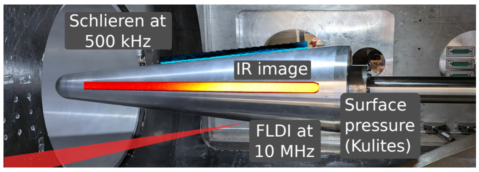
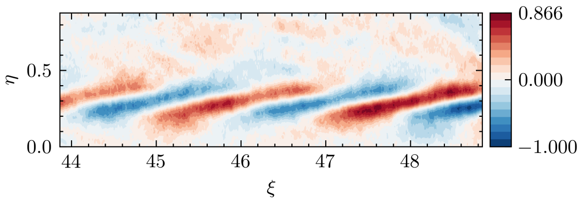


Figure 1: Experimental setup

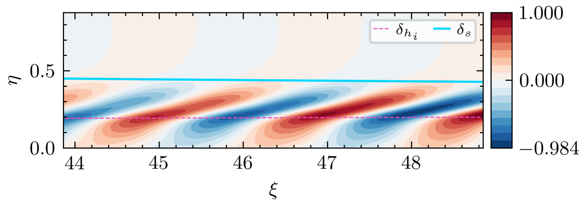
At $M = 6, R_n = 9$ mm, $Re_{R_n} = 104000$, the experimental data reveals a broadband amplification between 30 to 100 kHz corresponding to modes with a strong signature in the entropy layer, see Figure 2(a). Linearising the Navier-Stokes equations in the frequency domain gives the resolvent operator $\boldsymbol{\mathcal{R}}$: $\hat{\boldsymbol{q}} = \boldsymbol{\mathcal{R}}\hat{\boldsymbol{f}}$. Enabling finding optimal linear amplification mechanisms that give the biggest response $\hat{\boldsymbol{q}}$ for a forcing $\hat{\boldsymbol{f}}$. Resolvent analysis also shows a broadband amplification in the same frequency range corresponding to entropy-layer modes [2]. These findings are what motivated a rigorous comparison between experimental and numerical modes. In this study, resolvent analysis was performed on a baseflow matching the experimental test case and numerical schlieren modes are reconstructed on the experimental measurements points from the resolvent ansatz following equation 1,

$$(1) \quad \boldsymbol{\sigma}_{\text{num}}\left(\boldsymbol{g},\boldsymbol{\varphi}\right) = \sum_{m=0}^{N-1} g_m \mu_{0,m}^2 \int_{z=-z_{\max}}^{z_{\max}} \frac{\partial \widehat{\boldsymbol{\rho}}_m}{\partial y} e^{i(m\theta+\varphi_m)} dz, \qquad (2) \quad \underset{(\boldsymbol{g},\boldsymbol{\varphi})}{\text{argmin}} \left(\beta = \frac{|<\boldsymbol{\sigma}_{\text{num}}, \boldsymbol{\sigma}_{\text{exp}}>|}{||\boldsymbol{\sigma}_{\text{num}}|| \, ||\boldsymbol{\sigma}_{\text{exp}}||}\right).$$

Where m is the azimuthal wavenumber, $\widehat{\boldsymbol{\rho}}_m$ the corresponding resolvent mode at a given frequency with gain $\mu_{0,m}^2$, θ the azimuthal angle. $(\boldsymbol{g},\boldsymbol{\varphi})$ are vectors of parameters to optimise for, see Figure 2(b). To evaluate the agreement between experimental and numerical modes the alignment coefficient β is used which is equal to 1 if the modes are identical and 0 if they are orthogonal. Using this framework, we can optimise the selection of optimal modes and their respective amplitude and phase $(\boldsymbol{g},\boldsymbol{\varphi})$ of the numerical reconstruction for the best possible match following equation 2. Thus giving us information on the receptivity coefficient $c(m) = \mu_{0,m}^2 < \hat{\boldsymbol{f}}_m, \hat{\boldsymbol{f}}_{Oxford} >$ as function of the azimuthal wavenumber for the forcing environment present at Oxford's windtunnel. Preliminary work shows good agreement between experimental and numerical modes. In the future more frequencies will be analysed to construct a better picture of the physical mechanisms at play. This work is a first step into creating a methodology to numerically reconstruct the forcing environment from experimental optical data.



2(a) Experimental SPOD mode at $f = 47$ kHz [1]



2(b) Numerical reconstruction of schlieren mode using only the optimal resolvent mode at $(f, m) = (47\text{kHz}, 18)$

References

[1] A. Ceruzzi, L. M. Le Page, P. Kerth, B. A. Williams, and M. McGilvray. Observations of Boundary Layer Transition Reversal on a Blunt Cone in Hypersonic Flow *AIAA*, 2025.

[2] N. d'Eprémesnil, C. Caillaud, G. Lehnasch, M. Olazabal, and P. Jordan. Receptivity and instability of the hypersonic flow over moderately blunt cones. *arXiv:2601.02341*, 2026.

ON A PATHOLOGICAL LAMINAR SEPARATION BUBBLE ON A BUFFETING AEROFOIL

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It is a well-established fact that at a fixed angle of attack, with increasing Reynolds number, Re, a laminar separation bubble (LSB) will shrink and eventually cease to exist, due to increase in the growth rate of hydrodynamic instability modes. However, during this wind tunnel test campaign, we observed that paradoxically the laminar separation bubble increased in length from $Re = 2 \times 10^5$ to $Re = 2.5 \times 10^5$. Further diagnostics showed that this was due to a modification of the background forcing environment, through excitation of structural modes, duct modes and during a scenario potentially similar to buffeting, often neglected in the literature. The perturbation generated from this aero-vibro-acoustic interaction unexpectedly boosted Tollmien-Schlichting (TS) modes and their faster amplification even upstream of the LSB drove the rapid secondary growth and breakdown at $Re = 2 \times 10^5$. At $Re = 2.5 \times 10^5$, when the lock-in was not significant a well-behaved LSB was observed with spatially amplifying Kelvin-Helmhotz (KH) modes as reported in the literature in the absence of strong background perturbation. This finding raises important questions on the mechanisms entailing the dynamics and instability of LSBs proposed from not only experiments in similar facilities in the literature, but also in other scenarios where vibration and confinement are non-negligible.

This switch in instability mode can be confirmed from the hot-wire measurements shown in figure 1. Further results from microphone and accelerometer will be presented to show the acoustic field of the tunnel and the vibration of the model, together with pressure and flow visualisation to confirm the reduction in the length of the bubble.

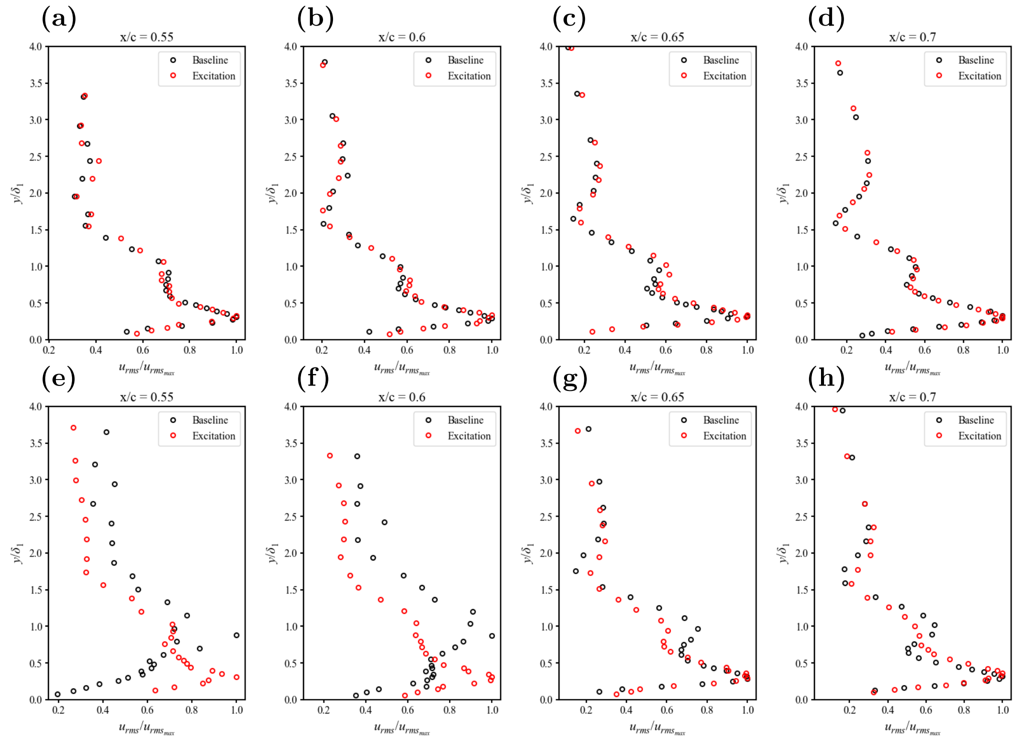

FIGURE 1. *RMS of the fluctuating velocity signal, u_{rms}, normalised by the local $u_{rms_{max}}$ at $x/c = 0.55$, $x/c = 0.6$, $x/c = 0.65$ and $x/c = 0.7$. Where (a) to (d) and (e) to (h) correspond to $Re = 2.0 \times 10^5$ and $Re = 2.5 \times 10^5$ respectively. The excited case is obtained by driving the disc-exciter with a frequency band of 1 to 500Hz.*

EXPERIMENTAL EVALUATION OF A SELF-SIMILAR TURBULENT BOUNDARY LAYER ON THE VERGE OF SEPARATION DEVELOPING ON D-TYPE ROUGHNESS

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The present study investigates the influence of surface roughness on an adverse pressure gradient turbulent boundary layer (APG-TBL). Although results on zero pressure gradient turbulent boundary layers (ZPG-TBLs) are present in the literature [1, 2, 3], fewer analyses address the APG-TBL case. To avoid dependence on the pressure-gradient history during the development of the APG-TBL, a self-similar adverse pressure gradient turbulent boundary layer (SS-APG-TBL) is considered. One approach to establishing and maintaining self-similarity across the entire boundary layer is to reach the verge of separation [4]. To this end, experiments are carried out at the Laboratory for Turbulence Research in Aerospace & Combustion (LTRAC) APG-TBL wind tunnel, which is capable of generating the conditions of the verge of separation, with a low and stable value of the skin-friction coefficient C_f, thereby establishing a SS-APG-TBL. The Reynolds number based on the boundary-layer thickness δ is $Re_\delta = 7.9 \times 10^4$, while the Clauser pressure-gradient parameter is kept constant at $\beta \approx 20.3$.

A d-type roughness is investigated, corresponding to a regime in which skin friction is the dominant contributor to the total drag [2]. Namely, the d-type roughness used for this study consists of squared elements with spacing s, width w, and height k equal to 5 mm ($k/\delta \approx 0.033$).

High-spatial-resolution (HSR) two-dimensional, two-component particle image velocimetry (2D-2C PIV) is employed. Two single-shutter Emergent HZ-100-GM cameras are used. These high-resolution cameras feature a 103.7-megapixel CMOS sensor (11,276 × 9,200 pixels) with a pixel size of 3.2 μm × 3.2 μm. The cameras are optically coupled via a beam splitter, enabling the two single-exposure acquisitions to share an identical field of view [5]. The flow is seeded using water-glycerol droplets, which scatter the light of an InnoLas Compact 400 lamp-pumped Nd:YAG PIV laser. In addition, a 1:1 optical relay is used to compensate for the light loss resulting from the introduction of the beam splitter camera coupler. This optical system, composed of two 2-inch achromatic doublets with a focal length of f = 150 mm, transmits the intermediate image formed by a 100 mm photographic lens at its nominal focal plane and then refocuses it onto the sensor plane. The resulting field of view spans 1δ in the vertical direction and approximately 1.22δ in the horizontal direction, with a spatial resolution of 16.9 μm/px. The image acquisitions and laser pulses are synchronized by a BeagleBone Black signal generator [6].

The two cameras are aligned on a common reference frame via holographic pixel-to-pixel registration [5]. Velocity fields are computed from 10,000 single-exposure image pairs using a multi-grid multi-pass cross-correlation PIV (MCCDPIV) algorithm [7] and then corrected for lens distortions with a third-order polynomial model [8].

References

[1] S Leonardi, RJ Smalley, L Djenidi, and RA Antonia. Direct numerical simulations of turbulent channel flow with transverse square bars on one wall. *Journal of Fluid Mechanics*, 491:229–238, 2003.

[2] Stefano Leonardi, Paolo Orlandi, and Robert A Antonia. Properties of d-and k-type roughness in a turbulent channel flow. *Physics of fluids*, 19(12), 2007.

[3] Anthony Edward Perry, William H Schofield, and Peter N Joubert. Rough wall turbulent boundary layers. *Journal of Fluid Mechanics*, 37(2):383–413, 1969.

[4] Vassili Kitsios, Callum Atkinson, Juan A Sillero, Guillem Borrell, AG Gungor, J Jiménez, and Julio Soria. Direct numerical simulation of a self-similar adverse pressure gradient turbulent boundary layer. *International Journal of Heat and Fluid Flow*, 61:129–136, 2016.

[5] Bihai Sun, Callum Atkinson, and Julio Soria. 2C-2D PIV/PTV measurements of high Reynolds number turbulent channel flow with sub-viscous-length wall-normal resolution. *Experimental Thermal and Fluid Science*, 166:111481, 2025.

[6] Marcus Fedrizzi and Julio Soria. Application of a single-board computer as a low-cost pulse generator. *Measurement Science and Technology*, 26(9):095302, 2015.

[7] Julio Soria. An investigation of the near wake of a circular cylinder using a video-based digital cross-correlation particle image velocimetry technique. *Experimental Thermal and Fluid Science*, 12(2):221–233, 1996.

[8] Bihai Sun, Muhammad Shehzad, Daniel Jovic, Christophe Cuvier, Christian Willert, Yasar Ostovan, Jean-Marc Foucaut, Callum Atkinson, and Julio Soria. Distortion correction of two-component two-dimensional piv using a large imaging sensor with application to measurements of a turbulent boundary layer flow at Re_τ= 2386. *Experiments in Fluids*, 62(9):183, 2021.

TRI-GLOBAL STABILITY ANALYSIS OF LOW-FREQUENCY DYNAMICS IN A TURBULENT SEPARATION BUBBLE

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Turbulent separation bubbles (TSBs) exhibit complex dynamics with significant implications for engineering applications, inducing structural vibrations, noise, and mechanical fatigue. Despite extensive experimental [1] and numerical [2, 3] research, the low-frequency "breathing" motion (i.e., the contraction and expansion of the bubble) remains a subject of ongoing investigations. In our previous study [4], we reported on experimental investigations in a half-diffuser configuration, providing empirical evidence of large-scale spanwise standing wave patterns governing the breathing motion. In the study, we proposed a low-dimensional model based on linear stability (LSA) and resolvent analysis (RA) of a 2D mean flow. By superposing left- and right-traveling RA modes to satisfy sidewall boundary conditions, we constructed a standing wave model that accurately reproduced the spatial structure of data-driven modes obtained via spectral proper orthogonal decomposition (SPOD). We demonstrated that the breathing motion is driven by a stationary eigenmode associated with a centrifugal instability, consistent with findings for laminar and transitional separation bubbles [5, 6, 7, 8]. Furthermore, we revealed that this mode is subsequently amplified downstream through a non-modal lift-up process.
However, this model relies on the assumption of a 2D mean flow, whereas the actual experimental mean flow exhibits significant three-dimensionality, including a characteristic U-shaped separation line and large sidewall vortices. In this presentation, we address this limitation by conducting a tri-global stability analysis on full 3D RANS mean fields. This approach allows us to assess the validity of the standing wave theory in a fully 3D framework. We specifically investigate the effect of realistic no-slip versus simplified slip boundary conditions on the resulting mode shapes and growth rates. By comparing these tri-global modes with our previous standing wave model, we aim to clarify the role of sidewall effects and mean flow three-dimensionality in the selection of dominant low-frequency mechanisms.

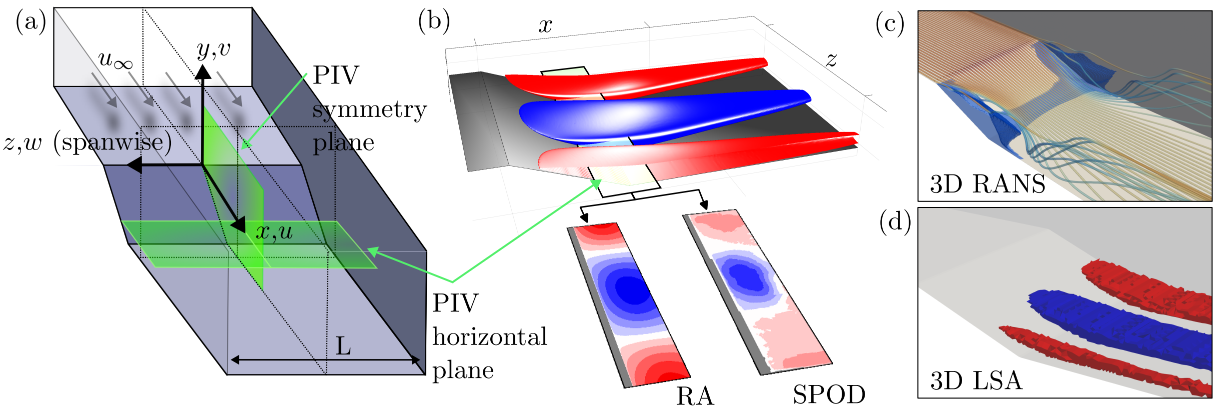

FIGURE 1. *Geometric setup and of position PIV planes (a). Standing wave model, RA mode and leading SPOD mode in the horizontal plane (b). Preliminary 3D RANS of slip sidewall setup (isosurface shows recirculation region) (c). Eigenmode from preliminary tri-global LSA of a spanwise homogenious 3D mean field (d).*

References

[1] A. Mohammed-Taifour, and J. Weiss. Unsteadiness in a large turbulent separation bubble. *Journal of Fluid Mechanics*, 799, 2016.
[2] W. Wu, et al. Spatio-Temporal dynamics of turbulent separation bubbles. *Journal of Fluid Mechanics*, 883, 2019.
[3] C. Cura, et al. Linear modeling of a family of turbulent separation bubbles. *Physical Review Fluids*, 10, 2025.
[4] L.M. Fuchs, et al. Standing-Wave Dynamics in Low-Frequency Breathing of a Turbulent Separation Bubble. *arXiv* preprint, 2026. accepted in *Journal of Fluid Mechanics* on 13-Jan-2026.
[5] D. Barkley, et al. Three-dimensional instability in flow over a backward-facing step. *Journal of Fluid Mechanics*, 473, 2002.
[6] D. Rodríguez, et al. The two classes of primary modal instability in laminar separation bubbles. *Journal of Fluid Mechanics*, 734, 2013.
[7] F. Gallaire, et al. Three-dimensional transverse instabilities in detached boundary layers. *Journal of Fluid Mechanics*, 571, 2007.
[8] F. Savarino, et al. Optimal transitional mechanisms of incompressible separated shear layers subject to external disturbances. *Journal of Fluid Mechanics*, 1016, 2025.

TANGENT SPACE PRECURSORS OF EXTREME EVENTS AND CRITICAL TRANSITIONS

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We propose a theory based on dynamical systems to explain and predict the occurrence of extreme events, of which critical transitions form a subset. In fast–slow nonlinear systems, we identify a cascade of events preceding extreme events: (i) a *slow regime*, in which the fast covariant Lyapunov vectors (CLVs) are both tangent to the fast eigenvectors and remain transversal to the slow subspace; (ii) a *transition regime*, in which the fast eigenvalues become neutrally stable while the fast CLVs are no longer tangent to the fast eigenvectors; and (iii) a *critical regime*, in which a strong spectral gap in the eigenvalues causes both fast and slow CLVs to become tangent along the dominant fast direction, breaking the transversality between fast and slow subspaces. Building on this cascade, we propose two precursors to forewarn the occurrence of extreme events. We numerically test the theory and precursors on low- and higher-dimensional systems. The proposed precursors predict extreme events and critical transitions with 100% precision and recall. This work opens opportunities for time-forecasting extreme events using theoretically grounded precursors.

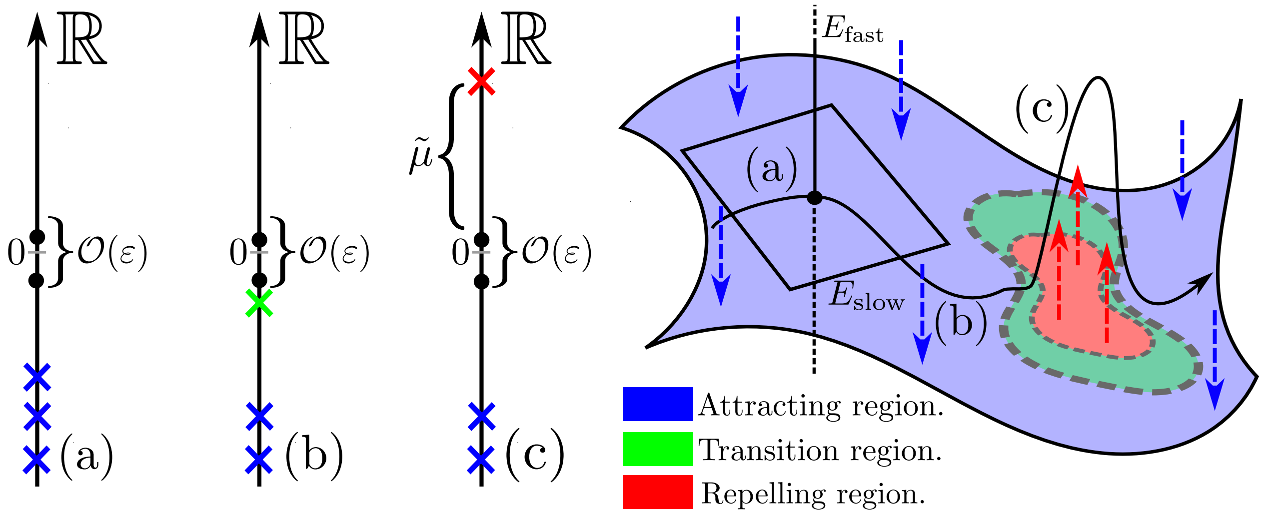

FIGURE 1. *Schematic of an extreme event in a fast–slow system.*

UNDERSTANDING PERTURBATION GROWTH IN WALL TURBULENCE BEYOND THE LYAPUNOV TIME

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We study the evolution of small perturbations applied to a fully developed turbulent field in the context of turbulent Couette flow over the full time horizon. Our main objective is to characterise the growth of small perturbations in the (highly anisotropic) setting of near-wall turbulence, specifically, identifying and evaluating the roles played by the coherent structures present in the flow in said growth process. To this end, we consider the minimal flow unit to study the dynamics of the coherent structures in the framework of the well-understood self-sustaining process [1]. Predictably, in the short term, once transient effects have passed, the perturbation is found to grow exponentially according to the well-know leading Lyapunov exponent. Further, we show, in agreement with previous findings [2, 3], the streamwise-dependent flow, which is primarily related to the dissipation events in the self-sustaining process, to be the main driver of the perturbation growth during this initial phase. Once the exponential response saturates, we find the perturbation to grow algebraically for a very long period - spanning tens of integral time scales - before the two fields completely decorrelate. Despite the resemblance of this behaviour to previous theoretical predictions and observations in other turbulent flows (HIT, in particular) [4, 5, 6, 7], we discover a fundamentally different physical process and formulate an alternative theoretical framework. In contrast with the exponential response phase, the growth during this period is dominated by the streamwise-independent streaky flow, and we observe the energy of the latter to grow linearly in time. This can be clearly observed in figure 1. We show that this regime appears once the length scale of the perturbation field (in particular the wall-normal streak length scale) saturates at the largest dimension posed by the flow geometry (i.e., the channel height). Finally, we evaluate the dominant production term and reveal that the dominant physical mechanism driving the perturbation growth is the well-known lift-up effect.

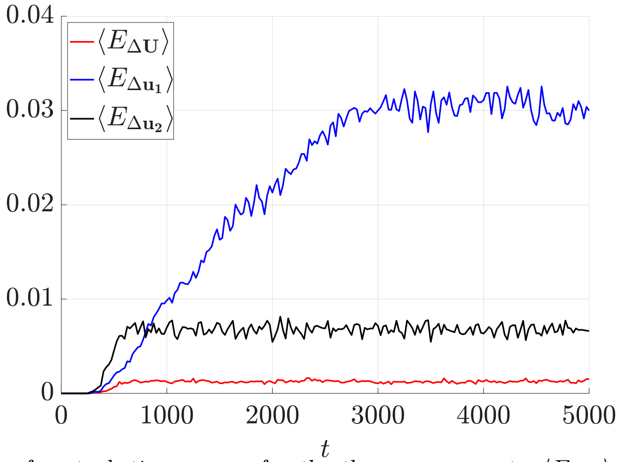

FIGURE 1. *Time evolution of perturbation energy for the three components,* $\langle E_{\Delta \mathbf{U}} \rangle$, $\langle E_{\Delta \mathbf{u}_1} \rangle$ *and* $\langle E_{\Delta \mathbf{u}_2} \rangle$*; where* $\Delta\mathbf{U}$, $\Delta\mathbf{u}_1$ *and* $\Delta\mathbf{u}_2$ *represent the perturbation field mean velocity, streamwise-averaged fluctuating velocity and remaining fluctuating velocity components respectively. Further,* $\langle \cdot \rangle \equiv 1/V \int_\Omega (\cdot) dV$ *where* Ω *is the given flow domain and* V *is its volume.*

References

[1] J. M. Hamilton, J. Kim, and F. Waleffe. Regeneration mechanisms of near-wall turbulence structures. *J. Fluid Mech.*, 287:317–348, 1995. DOI: 10.1017/S0022112095000978.
[2] M. Inubushi, S.-I. Takehiro, and M. Yamada. Regeneration cycle and the covariant Lyapunov vectors in a minimal wall turbulence. *Phys. Rev. E*, 92(2):023022, 2015. DOI: 10.1103/PhysRevE.92.023022.
[3] N. Nikitin. Characteristics of the leading Lyapunov vector in a turbulent channel flow. *J. Fluid Mech.*, 849:942–967, 2018. DOI: 10.1017/jfm.2018.418.
[4] E. N. Lorenz. The predictability of a flow which possesses many scales of motion. *Tellus*, 21, 1969. DOI: 10.3402/tellusa.v21i3.10086.
[5] C. E. Leith and R. H. Kraichnan. Predictability of turbulent flows. *J. Atmos. Sci.*, 15–17, 1972. DOI: 10.1175/1520-0469(1972)029¡1041:POTF¿2.0.CO;2.
[6] G. Boffetta and S. Musacchio. Chaos and predictability of homogeneous-isotropic turbulence. *Phys. Rev. Lett.*, 119(5):1–5, 2017. DOI: 10.1103/PhysRevLett.119.054102.
[7] A. Berera and R. D. J. G. Ho. Chaotic properties of a turbulent isotropic fluid. *Phys. Rev. Lett.*, 120:024101, 2018. DOI: 10.1103/PhysRevLett.120.024101.

IMAGE-BASED QUANTITATIVE ANALYSIS OF LARGE-SCALE STRUCTURES IN TWO-DIMENSIONAL CHANNEL TURBULENCE

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In two-dimensional turbulent channel flow, large-scale structures extend over several tens of the channel width in the streamwise direction. Monty et al. [1] reported meandering streamwise structures at a very high Reynolds number ($Re = U_b d/\nu = 144{,}000$) using rake hot-wire measurements. Where d denotes the channel width, U_b the mean velocity and ν the kinematic viscosity. Using two-point correlations of the streamwise velocity, Takai et al. [2] demonstrated the existence of two distinct large-scale structures and an abrupt change in spanwise scale around $Re = 3500$. Yimprasert et al. [3] observed, using flow visualisation techniques, that at $Re = 2{,}700$, clusters of densely packed, long, meandering filaments exist within the peripheral region filled with wall-attached structures, and that these regions result in the flow becoming batch-like. In this study, to investigate the distinction and generation processes of these large-scale structures, quantitative investigations of their advection characteristics are conducted using flow visualisation image analysis. The flow visualisation was performed using pearlescent pigment in the channel experimental apparatus employed by Yimprasert et al. [3] with a test section length of 4650 mm, a width in the spanwise direction of 580 mm, and a channel width d of 7 mm. Figure 1 illustrates the two-point correlation distribution of brightness in images captured at different times. The horizontal axis represents the nondimensional streamwise interval, $\Delta x^* = \Delta x/d$, while the vertical axis represents the nondimensional time interval, $\Delta t^* = \Delta t U_b/d$. At $Re = 3000$, three distinct proportional relationships with differing slopes are observed between x^* and t^* ($\Delta t^* \leq 4$, $4.5 \leq \Delta t^* \leq 8$, $9 \leq \Delta t^* \leq 12$). The lines in the figure are linear approximations of these proportional relationships, with each line's slope representing the advection velocity. As Δt^* increases, the slope decreases, indicating a reduction of the advection velocity. This variation is observed across all analysed Reynolds numbers, demonstrating the existence of at least three distinct structures with different advection velocities within the flow. At $Re = 4200$, $\Delta t^* \gtrsim 13$, a fourth slope with a steeper gradient than the third slope appears. The fourth slope is observed at $Re \gtrsim 3800$, suggesting the presence of four distinct structures within the flow. The existence of structures corresponding to different advection velocities indicates that the two-dimensional turbulent channel flow involves the coexistence of three or more structures, each possessing a specific advection velocity.

Since advection velocities of large-scale structures are expected to manifest at large Δt^*, structures corresponding to small Δt^* are probably the well-known wall-attached structures. The structure at large Δt^* is expected to be a large-scale structure, though it is inferred that at least one structure with a distinct, constant advection velocity exists, and at $Re \gtrsim 3800$, two such structures are present. By identifying these structures corresponding to advection velocities in visualisation images individually, it is expected that the relationship between these complex turbulent structures in the two-dimensional channel can be elucidated.

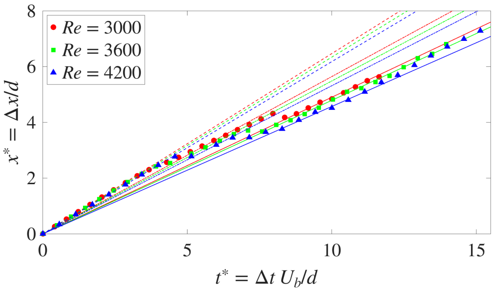

FIGURE 1. *Peak position of the streamwise and time-shift correlation distribution.*

References

[1] J. P. Monty, J. A. Stewart, R. C. Williams, and M. S. Chong. Large-scale features in turbulent pipe and channel flows. *Journal of Fluid Mechanics*, 589:147–156, 2007.

[2] R. Takai, S. Rin, S. Yimprasert, K. Kato, and M. Matsubara. Sudden alternation of very large structures in the post-transition state of two-dimensional channel flow. In *IUTAM Symposium on Laminar-Turbulent Transition*, 2024.

[3] S. Yimprasert, M. Kvick, P. H. Alfredsson, and M. Matsubara. Flow visualization and skin friction determination in transitional channel flow. *Experiments in Fluids*, 62:34, 2021.

INTERSCALE ENERGY TRANSFER IN ADVERSE PRESSURE GRADIENT TRANSITION UNDER INCREASING INFLOW COMPLEXITY

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We propose a comparative investigation of boundary layer transition in an adverse pressure-gradient (APG) configuration with three progressively more complex inflow conditions: (i) laminar inflow, (ii) turbulent inflow, and (iii) inflow forced by incoming unsteady wakes. The first two cases are representative of external-aerodynamics environments, whereas the wake-forced case targets turbomachinery-relevant interactions promoted by incoming periodic disturbances and APG-induced separation.
The analysis focuses on how transition is initiated and develops through nonlinear energy pathways. Using a multiscale/POD-based decomposition applied to a full-scale DNS (about $400M$ elements) via a dedicated parallel GPU framework, we track how energy is extracted from the mean flow and redistributed as the boundary layer undergoes transition. We focus on the interscale transfer (triadic interactions across scales) [1]. Figure 1 shows the transfer term for laminar and turbulent inflow cases; in both, the dominant transfer is directed towards near-wall scales, consistent with the emergence of near-wall turbulence during APG transition.
To connect transfer to reduced-order descriptions, we use the POD expansion $u_i(x,\tau) = \sum_{l=1}^{N} \phi_i^{(l)}(x)\,\chi^{(l)}(\tau)$ and write the triadic contribution as

$$\mathcal{T}^{(\ell,m,n)} = -\,\phi_i^{(\ell)}\,\phi_j^{(m)}\,\frac{\partial \phi_i^{(n)}}{\partial x_j}\,\frac{1}{N}\sum_{\tau=1}^{N}\chi^{(\ell)}(\tau)\chi^{(m)}(\tau)\chi^{(n)}(\tau), \tag{1}$$

which separates a spatial interaction kernel from a temporal triple product. The right panel of Fig. 1 reports the same information in POD space through a triadic interaction cube.
Finally, we relate the triadic transfer term above to the nonlinear term in Galerkin dynamics. In the POD/Galerkin framework of Rempfer & Fasel [2],

$$\dot{c}_i = \sum_{j,k} N_{ijk}\,c_j c_k + \nu \sum_j D_{ij}\,c_j, \tag{2}$$

where N_{ijk} is the quadratic interaction tensor. The present work uses this analogy to compare transition pathways across the three inflow scenarios and to identify which nonlinear interactions are most associated with near-wall energy transfer during transition in APG boundary layers.

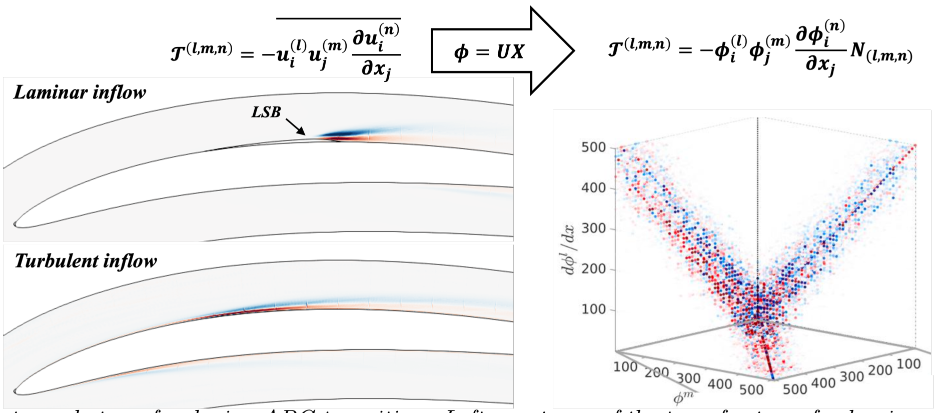

FIGURE 1. *Interscale transfer during APG transition. Left: contours of the transfer term for laminar and turbulent inflow cases, showing transfer directed towards near-wall scales. Right: triadic interaction map in POD space.*

References

[1] P. Baj and O. R. H. Buxton, "Interscale energy transfer in the merger of wakes of a multiscale array of rectangular cylinders," *Physical Review Fluids*, vol. 2, no. 11, art. 114607, 2017. doi:10.1103/PhysRevFluids.2.114607.
[2] D. Rempfer and H. F. Fasel, "Dynamics of three-dimensional coherent structures in a flat-plate boundary layer," *Journal of Fluid Mechanics*, vol. 275, pp. 257–283, 1994. doi:10.1017/S0022112094002351.