EUROPEAN MECHANICS SOCIETY

EUROMECH COLLOQUIUM 658

Coherent structures and instabilities in transitional and turbulent wall-bounded flows

Bari, Italy / 15-17 September 2025

SCHEDULE
BOOK OF ABSTRACT

ARTS ET MÉTIERS ParisTech Paris

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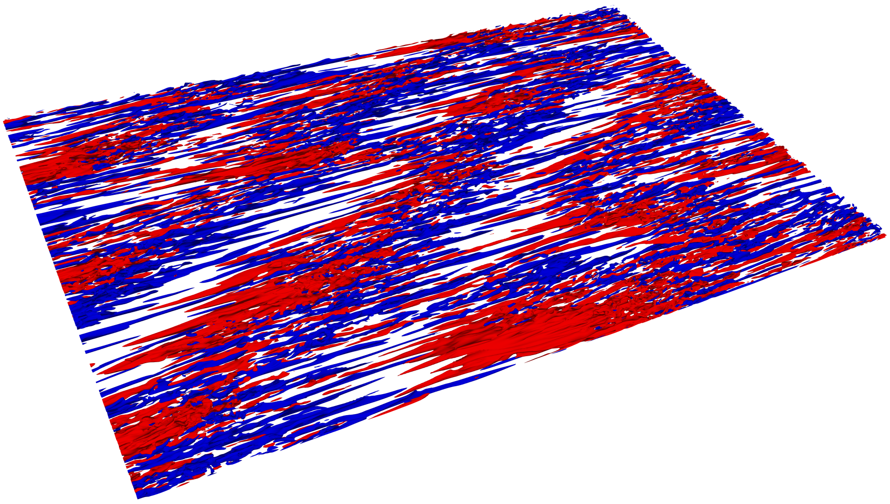
Euromech Colloquium 658

Coherent structures and instabilities in transitional and turbulent wall-bounded flows

Politecnico di Bari - Dipartimento di Meccanica, Matematica e Management - September 15-17, 2025

Schedule



DNS of turbulent channel flow
PhD thesis of N. Ciola
DynFluid - Arts & Métiers ParisTech / Politecnico di Bari

We gratefully acknowledge the Sponsors of the EUROMECH Colloquium 658:

- Politecnico Di Bari,
- EUROMECH (the European Mechanics Society),

Practical Information

Room location & Registration The EUROMECH-Colloquium 658 will be held at the Polytechnical University of Bari (Via Orabona 4, Bari, you'll find a map here https://maps.app.goo.gl/fDM5NxrLuyUpSyeX6), about 20 minutes of walk from the Railway Station. The Colloquium will be held in the "Aula Magna Orabona" room. The route to the "Aula Magna Orabona" will be signaled with arrows. The registration desk will be found at the entrance of the "Aula Magna Orabona" on the first floor. Registration of the participants to the Colloquium will be active in the morning of 15th September between 08:00 and 08:45.

Social Events Lunches and coffee breaks are planned during the conference according to the time plan. Lunches will be served in the hall at the entrance of the "Aula Magna Orabona", on the first floor. Furthermore, two social events are planned:

- Monday, the 15th of September from 18:00: The Conference participants are invited to a welcoming tour cocktail in the Old Town of "Bari Vecchia". After a guided tour of the Old Town, drinks and snacks will be served.
- Tuesday, the 16th of September from 20:00: The social dinner will be held in the characteristic town of Alberobello, which has been declared World Heritage of UNESCO for the "Trulli" (fig. 2) , prehistoric drywall buildings characteristics of this region. The bus to Alberobello will move at 17:30 from the entrance of the Politecnico di Bari (Via Orabona, 4).

Figure 1: The dock in the Old Town of Bari.

Figure 2: View of Alberobello by night.

How to get to the conference?
By plane: via the Bari-Palese Airport
Be aware that there are direct flights to Bari from many European cities (from Paris Beauvais, London Stansted and so on). Don't forget to check the available flights on low-cost airlines which provide many of those direct (and very cheap) flights. From the Airport take the train to Bari Centrale Station, whose timetable and price can be found at this link:
https://www.ferrotramviaria.it/en/from-airport.
By train Get off at Bari Centrale Station and enjoy a 20 minutes walk towards the Politecnico of Bari or take bus 21 in Via Melo 230 (right in front of the railway station) to Caduti di via Fani, and get off at the stop Re David (PoliBa) (you'll find further information at the link: https://www.amtab.it/en/move-with-us/routes-and-timetables).

Wi-Fi All the campus is covered by the Wi-Fi network, where the access points are located mostly in the conference rooms and public places. The account associated to the conference will be given during the registration process. The participants can also use the Wi-Fi network Eduroam which is active in the whole Campus.

Public transport Below, a map of the metro lines covering the city and its suburbs (fig. 3) as well as a map of the city with the bus lines (fig. 4).

Figure 3: Bari subway map.

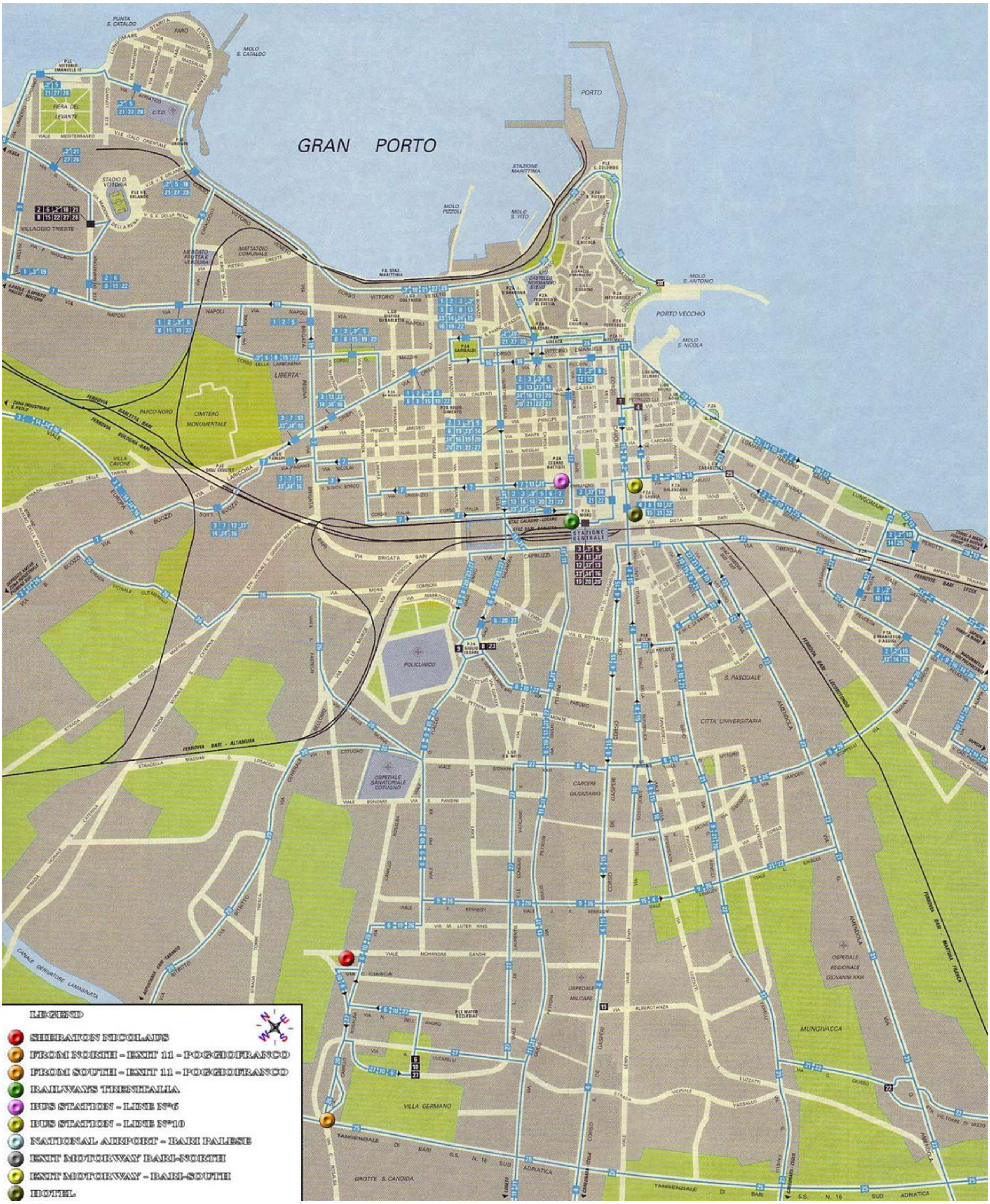


Figure 4: City map of Bari.

Schedule

September 15, 08:00 - 16:20			
08:00 - 08:45	**Registration**		
08:45 - 09:00	**Welcome and opening remarks. S. Cherubini**		
Keynote lecture - Chair: Y. Duguet			
09:00 - 09:50	E. Marensi	Transition to and from turbulence in a vertical heated pipe	Univ. of Sheffield UK
Session: Invariant coherent structures - Chair: Y. Duguet			
09:50 - 10:10	S. P. Gepner	Geometric Homotopy in Pipe Flow: Tracing Invariant Solutions from Discrete to Continuous Symmetries	Warsaw Univ. of Technology, Poland
10:10 - 10:30	O. Ashtari	Variational methods for computing unstable invariant solutions in wall-bounded fluid flows	EPFL, Switzerland
10:30 - 10:50	N. Ciola	Modelling laminar-turbulent patterns in transitional channel flow	DynFluid/ENSAM Politecnico di Bari
10:50 - 11:10	A. Kozluk	Exploring order at the edge of chaos: global streamwise-localised simple invariant solutions in square duct flow	Univ. of Osaka Japan
11:10 - 11:30: **Coffee break**			
Session: Periodic flows - Chair: A. Bottaro			
11:30 - 11:50	F. Alizard	Wavepacket dynamics in compliant pulsatile plane channel flows	Univ Lyon 1 / LMFA France
11:50 - 12:10	R. Bertoncello	Secondary stability of Tollmien-Schlichting waves in a Blasius boundary layer	Politenico di Milano Italy
12:10 - 12:30	J.-C. Loiseau	LightKrylov + neklab : a modern Fortran framework for bifurcation analysis of large-scale systems	DynFLuid/ENSAM France
12:30 - 12:50	S. Kern	Stability of large-amplitude pulsatile flow in a torus	DynFluid/ENSAM France
12:50 - 13:10	P;-Y. Passaggia	Instabilities of pulsating Poiseuille flows heated from above	Univ. of Orleans, PRISME, France
13:10 - 14:20: **Lunch**			
Session: Flow unsteadiness and low-order modeling - Chair: J. Jimenez			
14:20 - 14:40	B. Semin	Second oscillatory bifurcation past a sphere: experiments	ESPCI, PMMH France
14:40 - 15:00	C. Mimeau	Second oscillatory bifurcation past a sphere and route to chaos: numerical analysis	M2N/CNAM France
15:00 - 15:20	J. V. N. Neiva	Low order model for unsteady state of laminar separation bubble using experimental data	Pontifícia Univ. Catolica do Rio de Janeiro, Bresil
15:20 - 15:40	O. Semeraro	Mean flow data assimilation using physics-constrained Graph Neural Network	LISN-CNRS France
15:40 - 16:00	K. Volokh	Transition to Turbulence via Material Instabilities	Israel Inst. of Technology Israel
16:00 - 16:20	S. Vellala	Effect of periodic velocity modulation on stability of the 1D Kuramoto-Sivashinsky system	Delft Univ. of Tech. The Netherlands
18:00 - 19:00 **Old Town tour**			
19:00 - 20:00: **Welcoming cocktail**			

September 16, 08:40 - 16:40			
Keynote lecture - Chair: J.-C. Loiseau			
08:40 - 09:30	K. Oberleithner	Too Large to See: Spectral Insights into Very Low Frequency Coherent Structures	Technische Universität Berlin Germany
Session: Transitional flows - Chair: J.-C. Loiseau			
09:30 - 09:50	A. Palumbo	Transition to turbulence in planar synthetic jets: numerical simulations and coherent structures eduction	Sapienza Univ. di Roma, Italy
09:50 - 10:10	A. Bottaro	Instability and transition of the rotating disk boundary layer over homogenized textured surfaces	Univ. of Genova Italy
10:10 - 10:30	C. Leclercq	Closed-loop control robust to finite-amplitude perturbations: application to reduced-order models of subcritical transition	ONERA DAAA France
10:30 - 10:50	H. Fasel	Investigations of the interaction of boundary-layer transition and separation for swept wings: DNS, wind- and flight experiments	Univ. of Arizona Tucson USA
10:50 - 11:10: **Coffee break**			
Session: Coherent structures in turbulent flows - Chair: H. Fasel			
11:10 - 11:30	J. Jimenez	Regeneration of long streaks in wall-bounded flows	Politecnica Madrid Spain
11:30 - 11:50	Z. Hao	Linearized Processes Preceding Orr Bursts in Turbulence in Minimal Channels	Politecnica Madrid Spain
11:50 - 12:10	J. Soria	Energy transfer of energy-containing motions in zero-pressure gradient turbulent boundary layer	Monash Univ. Australia
12:10 - 12:30	G. Porpora	Stability analysis of large-scale structures in highly confined turbulent wakes	Sapienza Univ. di Roma, Italy
12:30 - 12:50	U. Rist	Lagrangian Areas of Minimal Stretching in a TBL	Univ. of Stuttgart IAG, Germany
12:50 - 13:10	E. Wesfreid	Transition and self-sustained process in Couette-Poiseuille flow	ESPCI/PMMH France
13:10 - 14:20: **Lunch**			
Session: Resolvent and receptivity analyses - Chair: U. Rist			
14:20 - 14:40	A. Bongarzone	Mean resolvent analysis of periodic flows	ONERA/DAAA France
14:40 - 15:00	T. Burton	Variational Framework for Approximating Chaotic Statistics and Sensitivities using Resolvent Analysis	Univ. of Southampton UK
15:00 - 15:20	Y. Duguet	Linear and nonlinear receptivity of axisymmetric rotor-stator flow	LISN, CNRS France
15:20 - 15:40	P. Penet	Perturbed eddy-viscosity approach in resolvent analysis of a turbulent boundary layer	ONERA/DAAA France
15:40 - 16:00	T. Roemer	Experiments on roughness-induced laminar-turbulent transition with free-stream turbulence	Univ. of Stuttgart IAG, Germany
16:00 - 16:20	A. Ravaioli	Experimental study of receptivity and transition to turbulence in consecutive asymmetrical bifurcating ducts	Univ. di Bologna Italy
16:20 - 16:40	N. Alferez	An automatic code generation framework applied to GSA of 3D screeching jets.	DynFluid-CNAM France
17:30: **Departure by bus for Alberobello**			
20:00 - 24:00: **Conference Dinner at Alberobello**			

September 17, 08:40 - 14:45			
Keynote lecture - Chair: J.-C. Robinet			
08:40 - 09:30	F. Gallaire	Noise-induced transitions after a steady symmetry-breaking bifurcation: the case of the sudden expansion	EPFL LMFI Switzerland
Session: Compressible flows - Chair: J.-C. Robinet			
09:30 - 09:50	J. Cohen	Coherent Structures in Axisymmetric Hypersonic Cavities	Technion Israel
09:50 - 10:10	L. Larcheveque	Broadband quadratic couplings in a transitional shock wave-boundary layer interaction	IUSTI France
10:10 - 10:30	T. Bergeon	Global linear stability analyse of over-expanded nozzle	ONERA/DynFluid France
10:30 - 10:50	J. W. Nichols	Large-Scale Input/Output Analysis of High-Speed Boundary-Layer Instability and Receptivity	Univ. of Minnesota Twin Cities, USA
10:50 - 11:10	D. Variale	Resolvent analysis of overexpanded nozzle	DynFluid/ENSAM Politecnico di Bari
11:10 - 11:30: **Coffee break**			
Session: Coherent structures and instabilities in complex flows- Chair: S. Cherubini			
11:30 - 11:50	A. Giannotta	Thermoacoustic Instability Analysis of Hydrogen-Enriched Premixed Methane-Air Flames Using FGM	Politecnico di Bari Italy
11:50 - 12:10	J. Sablon	Novel transient growth mechanism in variable-density q-vortices	ISAE/DAEP France
12:10 - 12:30	L. Klotz	Influence of porous material on the flow behind a backward-facing step: experimental study	Warsaw Univ. of Technology Poland
12:30 - 12:50	G. Innocenti	Effect of a regularly micro-structured inner wall on the onset of the Taylor-Couette instability	Univ. of Genova Italy
12:50 - 13:10	F. Manganelli	Coherent structures in the wake of a wind-turbine with Coriolis force	Politecnico di Bari Italy
13:10 - 13:20	**Closing remarks. S. Cherubini**		
13:20 - 14:25: **Lunch**			

Book of Abstract

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Transition to and from turbulence in a vertical heated pipe

Elena Marensi
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Flows through pipes or channels play a vital role in energy systems by enabling heat transfer between components to facilitate power generation, heating or cooling, and chemical production. In a vertical configuration, buoyancy forces can assist the flow, but they may also suppress turbulence and dramatically degrade heat transfer (figure 1). Despite the relatively simple geometry, buoyancy complicates the prediction and control of both the flow state and thermal performance, leading to rich dynamics that are not yet fully understood. In this talk, I will discuss our recent efforts to model and understand transitional and turbulent flows in a vertical heated pipe, focusing on the competition between shear- and buoyancy-driven instabilities and the resulting suppression or enhancement of coherent structures. Using tools from dynamical systems theory, stability analysis, and optimisation methods, I will show how we can gain insight into the mechanisms driving transitions between flow regimes and inform strategies to suppress or promote turbulence under varying thermal conditions. Drawing parallels with isothermal pipe flow, I will highlight common and distinct features in the mechanisms that trigger and sustain turbulence in both systems, with a view to controlling turbulence for drag reduction and/or heat transfer enhancement.

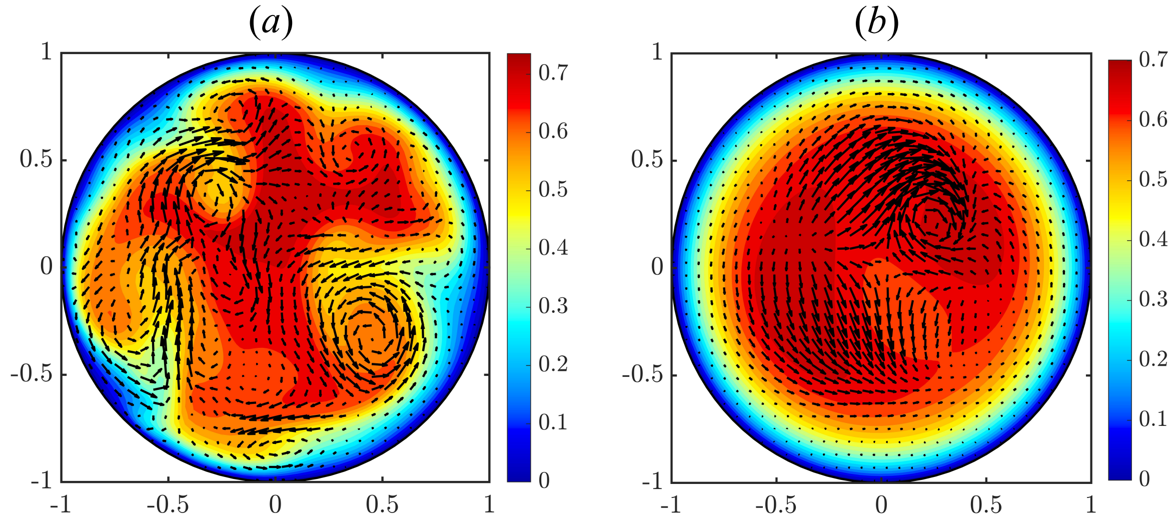

Figure 1: Flow structures in (a) shear turbulence and (b) convective state. Contours show the total streamwise velocity, and the arrows represent cross-stream components [1].

References

[1] S. Chu, A.P. Willis, and E. Marensi. The minimal seed for transition to convective turbulence in heated pipe flow. *J. Fluid Mech.*, 997:A46, 2024.

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Geometric Homotopy in Pipe Flow: Tracing Invariant Solutions from Discrete to Continuous Symmetries

S.W. Gepner[1] **A. Koźluk**[2] **S. Motoki**[2] **G. Kawahara**[2]
[1] *Warsaw University of Technology,* [2] *Osaka University*
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Invariant solutions offer a foundational geometric framework for transitional turbulence, capturing the complex dynamics of turbulent flows as trajectories that transiently visit unstable exact coherent structures (ECS) [1]. While many such solutions have been identified in canonical shear flows, spatially localised ECS remain scarce, despite their relevance to the formation, persistence, and decay of turbulent spots and puffs. Only few streamwise-localised solutions are known in circular pipe flow, often discovered under strong symmetry restrictions [2, 3]. Square duct flow fares no better, with only two such travelling wave solutions identified to date—forming a classic lower- and upper-branch pair [4, 5]. Despite their physical relevance as intermediaries between circular and square cross-sections, Elliptic pipe geometries remain entirely unexplored in this regard.

We introduce a geometric homotopy approach for discovering new invariant solutions in pipe flow systems. Unlike prior homotopy techniques, our method systematically transitions from geometries with discrete symmetries (square or elliptical ducts) to those with continuous symmetries (circular pipe). This controlled deformation allows us to regularise the symmetry group, making otherwise elusive localised ECS accessible in the discrete regime. We then continuously trace their evolution into the continuous-symmetry limit.

This approach leverages the stabilising effects of discrete symmetry, typically lowering the dimensionality of the unstable manifold, to reveal localised ECS that can then be continued into fully symmetric configurations. Applying this method, we uncover previously unknown localised structures in elliptic and circular pipe geometries, expanding the known solution space and providing new insight into transitional turbulence.

Our findings establish geometric homotopy as a powerful tool for exploring ECS in high-dimensional fluid systems and highlight the intricate interplay between geometry, symmetry, and turbulence. This work opens a novel pathway for systematic ECS discovery across a continuum of flow configurations.

References

[1] G. Kawahara, M. Uhlmann, and L. Van Veen. The significance of simple invariant solutions in turbulent flows. *Annual Review of Fluid Mechanics*, 44:203–225, 2012.

[2] M. Avila, F. Mellibovsky, N. Roland, and B. Hof. Streamwise-localized solutions at the onset of turbulence in pipe flow. *Physical Review Letters*, 110(22):224502, 2013.

[3] M. Chantry, A. P Willis, and R. Kerswell. Genesis of streamwise-localized solutions from globally periodic traveling waves in pipe flow. *Physical Review Letters*, 112(16):164501, 2014.

[4] S. Okino. Spatially localized solutions in rectangular duct flow. In *Prodeedings of JSME FED Meeting 2014*, page 0802. JSME, 2014.

[5] S. Gepner, S. Okino, and G. Kawahara. Chaotic and time-periodic edge states in square duct flow. *To appear in J. Fluid Mech.*, 2025.

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Variational methods for computing unstable invariant solutions in wall-bounded fluid flows

Omid Ashtari[1] and Tobias M. Schneider[1]

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The dynamics of a chaotic flow is supported by unstable invariant solutions embedded within the chaotic attractor of the system. These include non-chaotic but dynamically unstable solutions to the governing equations, such as equilibria and periodic orbits. Common methods for computing these solutions rely on time-marching the flow and updating the initial conditions. As a result of the exponential separation of trajectories due to chaos, these methods exhibit poor convergence properties, and the identification of unstable invariant solutions remains a computational challenge. We introduce an alternative family of methods that bypass time-marching of chaotic dynamics, resulting in robust convergence properties.

We recast the computation of an invariant solution as a minimization problem in the space of all sets of the same topological structure as the objective solution. For instance, this space includes all loops when searching for a periodic orbit. The deviation of a trial set from satisfying the definition of the target solution is penalized by a non-negative cost function. Minimizing this cost function evolves a guess until at a global minimum, where the cost is zero, an invariant solution is found (Fig. 1). This approach has demonstrated success in identifying equilibria, periodic orbits, and connecting orbits in model systems [1] as well as 2D Kolmogorov flow [2]. We demonstrate the successes of this method in wall-bounded flows [3] and discuss the challenges in computing more complex invariant sets, such as invariant tori.

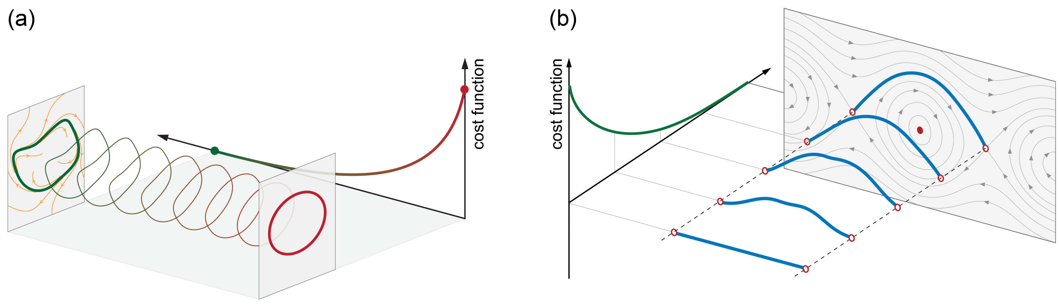

Figure 1: Variational approach to computing an unstable periodic orbit (a) and a heteroclinic orbit (b).

References

[1] S. Azimi, O. Ashtari, and T. M. Schneider. Constructing periodic orbits of high-dimensional chaotic systems by an adjoint-based variational method. *Phys. Rev. E*, 105:014217, 2022.

[2] J. P. Parker and T. M. Schneider. Variational methods for finding periodic orbits in the incompressible Navier–Stokes equations. *J. Fluid Mech.*, 941:A17, 2022.

[3] O. Ashtari and T. M. Schneider. Identifying invariant solutions of wall-bounded three-dimensional shear flows using robust adjoint-based variational techniques. *J. Fluid Mech.*, 977:A7, 2023.

EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Modelling laminar-turbulent patterns in transitional channel flow

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[3] *DynFluid, Arts et Métiers Paris /CNAM, 151 Bd de l'Hôpital, 75013 Paris, France*
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Turbulence in the channel flow becomes spatially modulated as the Reynolds number is lowered below a critical threshold. The result is an alternation of turbulent and quasi-laminar flow in the form of an oblique pattern (figure 1). This phenomenology calls for a mean field model where small scale motions are implicitly taken into account through a closure. Similar modelling efforts have been pursued by Barkley [1] in transitional pipe flow and, more recently, by Benavides and Barkley [2] and Kashyap et al. [3] for planar shear flows. Interestingly, the models of planar shear flows suggest the presence of a pattern-forming linear instability consistently with the findings of a recent DNS study of channel flow [4]. The objective of this work is to elaborate a modelling strategy that can bridge the complexity of the full Navier-Stokes system and the simple dynamics of the reduced models mentioned above. Such model may unveil important information about the development and the role of the large-scale flow that co-exists with the pattern.

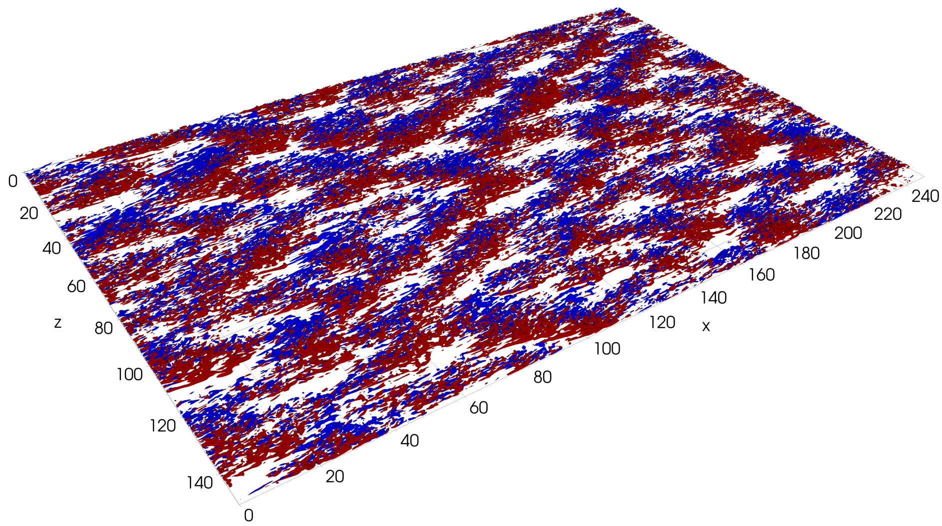

Figure 1: Isocontours of the spanwise velocity component (red positive, blue negative) from a direct numerical simulation (DNS) of channel flow at $Re_\tau \approx 71.4$ ($Re = 1000$ based on the bulk velocity). The flow is in the x direction from left to right. Lengths are in units of channel half-height.

References

[1] D. Barkley. Simplifying the complexity of pipe flow. *Physical Review E—Statistical, Nonlinear, and Soft Matter Physics*, 84(1):016309, 2011.

[2] S. J. Benavides and D. Barkley. Model for transitional turbulence in a planar shear flow. *arXiv preprint arXiv:2309.12879*, 2023.

[3] P. V. Kashyap, J. F. Marìn, Y. Duguet, and O. Dauchot. Laminar-turbulent patterns in shear flows: evasion of tipping, saddle-loop bifurcation and log scaling of the turbulent fraction. *arXiv preprint arXiv:2407.04993*, 2024.

[4] P. V. Kashyap, Y. Duguet, and O. Dauchot. Linear instability of turbulent channel flow. *Physical Review Letters*, 129(24):244501, 2022.

EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Exploring order at the edge of chaos: global streamwise-localised simple invariant solutions in square duct flow

Adrian Koźluk[1], **Stanisław W. Gepner**[2], **Shingo Motoki**[1] **and Genta Kawahara**[1]

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Spatially-localised invariant solutions are vital in understanding the dynamics of transitional turbulence, as they often serve as organising centres for the onset and decay of turbulent structures [1]. Despite their significance, the number of known localised solutions remains very limited. In circular pipe flow, for instance, only a handful of localised solutions have been identified, notably the lower-upper branch pairs by Avila *et al.* [2] and Chantry *et al.* [3], all of which were obtained with symmetry restrictions. Similarly, regarding the square duct geometry, highly relevant for industrial applications, only a single localised solution has been found so far, under simplifying symmetry constraints [4].

This work presents the first full-space localised invariant solution for square duct flow, substantially distinct from the symmetry-constrained solutions obtained previously in similar studies. We use the spectral element method to perform numerical calculations in an extended spatial domain. Employing an edge-tracking approach, we identify a steady travelling-wave invariant solution. It turns out to be particularly noteworthy since its lower branch is an edge state, meaning that in the full space its stable manifold is a subspace of codimension one. We then follow with parametric continuation to obtain the bifurcation point and the corresponding upper-branch solution. Stability analysis reveals that while the lower branch remains an edge state, the upper branch solution gains an additional unstable direction, in contrast to the symmetric-subspace pipe-flow solution [2].

Moreover, by examining the unstable directions of both solutions near the bifurcation point, we find that, in fact, the upper-branch solution lies as well on the laminar-turbulent edge, within the stable manifold of its lower-branch counterpart. This aligns with the solution framework established in a recent study [5] and suggests that the bifurcation point and the solution pair reside on the edge of chaos. Our results thus constitute a novel class of localised invariant solutions and emphasise the critical role of full-space edge states in understanding the mechanism of transitional turbulence in square duct flow.

Our findings not only expand the catalogue of known invariant solutions, shedding light on the problem of subcritical transition in square duct flow, but also illustrate that in systems with discrete symmetries, identifying full-space localised edge states is within reach.

References

[1] G. Kawahara, M. Uhlmann, and L. Van Veen. The significance of simple invariant solutions in turbulent flows. *Annual Review of Fluid Mechanics*, 44:203–225, 2012.

[2] M. Avila, F. Mellibovsky, N. Roland, and B. Hof. Streamwise-localized solutions at the onset of turbulence in pipe flow. *Physical Review Letters*, 110(22):224502, 2013.

[3] M. Chantry, A. P Willis, and R. Kerswell. Genesis of streamwise-localized solutions from globally periodic traveling waves in pipe flow. *Physical Review Letters*, 112(16):164501, 2014.

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[5] S. Gepner, S. Okino, and G. Kawahara. Chaotic and time-periodic edge states in square duct flow. *To appear in J. Fluid Mech.*, 2025.

EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Wavepacket dynamics in compliant pulsatile plane channel flows

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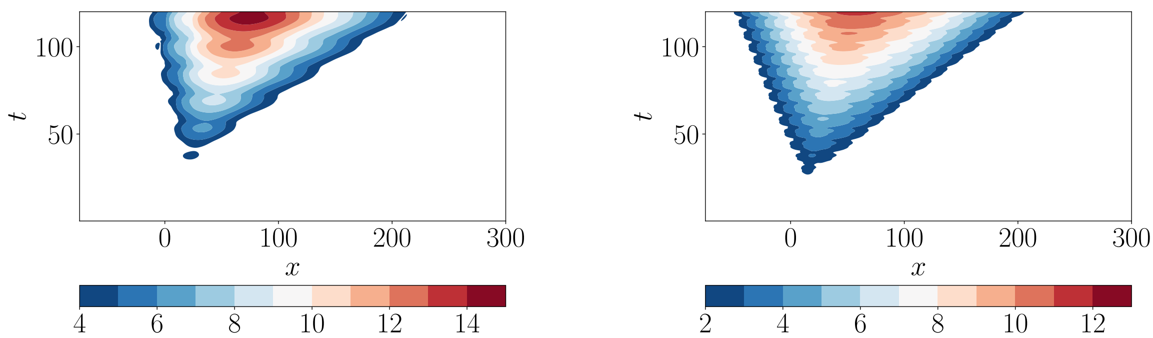
The absolute/convective transition of the steady and pulsatile channel flow interacting with compliant walls is investigated using local stability theory and linearized direct numerical simulations. For the steady flow case [1], an absolute instability mode is found due to the coalescence of the evanescent and traveling-wave flutter branch of modes.

For the pulsatile flow case, the space-time wavepacket dynamics will be explored using linearized DNS by injecting Gaussian-type, spatially localized flow disturbances as initial conditions (see [2]) for Womersley numbers W_O varying from 10 to 25 and base-flow modulation amplitudes ranging from $\widetilde{Q} = 0$ to 1 (see figure 1).



(a) Womersley number $W_O = 10$

(b) Womersley number $W_O = 15$

Figure 1: Spatio-temporal dynamics for a wavepacket developing in a pulsatile compliant channel flow for the Reynolds number $Re = 1000$, an amplitude of modulation $\widetilde{Q} = 0.8$ and the wall compliance corresponds to a reduced velocity $V_R = 0.8$. Iso-contours of the envelope of the wavepacket are shown in a logarithmic scale.

References

[1] W.A.A. Ali. Onset of global instabilities in the plane channel flow between compliant walls. Phd. Cardiff University, 2016.

[2] I. Delbende, J.M. Chomaz, and P. Huerre. Absolute/convective instabilities in the Batchelor vortex: a numerical study of the linear impulse response. J. Fluid Mech., 355:229–254, 1998.

EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Secondary stability of Tollmien-Schlichting waves in a Blasius boundary layer

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The first instability of a Blasius Boundary Layer (BL) is characterized by the appearance and growth of the Tollmien-Schlichting (TS) waves (see figure 1 left). As their amplitude grows, they become prone to secondary instabilities, which lead the BL to natural transition. The secondary instability of the TS waves was first investigated by Herbert [1] who stated that they grow in the BL until they saturate, leading to a new quasi-steady state. In his inspiring work, Herbert introduced some assumptions in order to make the problem more tractable. Indeed, he studied a parallel BL in which the amplitude of the TS waves was considered locally constant and their evolution was assumed unaffected by the nonlinear distorsion present in the Navier-Stokes (NS) equations. Further authors studied the secondary stability of BL flows and they followed at least in part Herbert's approach [2, 3]. In our work we intend to relax these assumptions and quantify their impact on the results of the secondary stability of the TS waves. Our approach to the problem involves a sequence of steps. First, we study the stability of a non-parallel Blasius BL and we characterize the TS waves in presence of a non-zero vertical velocity. Then, we let them evolve in the BL within a nonlinear framework and we observe the modulation of their amplitude along the streamwise direction. The nonlinearity implies that the growth of the waves is influenced by their intensity at the inlet section (see figure 1 right) with respect to the Blasius base flow. After an initial transient, the TS waves settle in the BL, leading to a new periodic reference state whose stability properties are studied by means of the Floquet analysis. By comparing our results with Herbert's ones we intend to investigate the importance of the non-parallel and nonlinear assumptions.

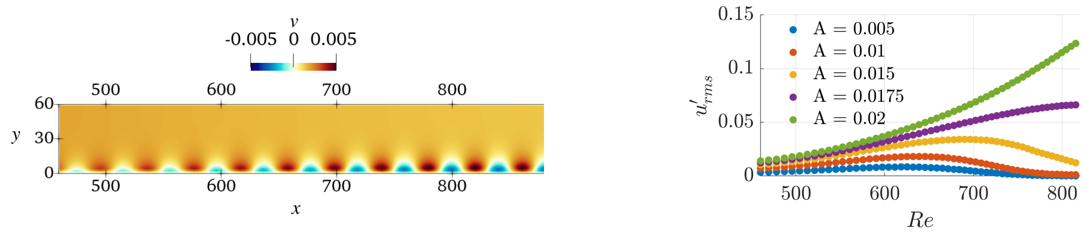

Figure 1: Left: superposition of the Blasius BL vertical velocity v with the TS velocity profile. Right: nonlinear streamwise evolution of the amplitude of the TS waves.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

`LightKrylov + neklab` : A modern Fortran framework for bifurcation analysis of large-scale systems

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Owing to the continuous distribution of open-source yet high-performance Navier-Stokes solvers over the past two decades, an increasing number of studies have been conducted to elucidate the linear stability properties of fully three-dimensional flows, see Ref. [1] for an extensive review of the recent literature. While extending the capabilities of an existing CFD solver to perform linear stability analysis is greatly simplified using a *time-stepper* approach, it might still require a non-negligible number of additions to the code base in order to cover both modal and non-modal analyses.

In this contribution, we'll present `neklab`, our latest toolbox enabling the computation and linear analyses (both modal and non-modal) of fixed points and periodic orbits using the `Nek5000` solver as well as *optimal time-dependent mode analysis* and a low-rank approximation of the differential Lyapunov and Riccati equations ubiquituous in optimal control. Under the hood, this toolbox relies on `LightKrylov`, a modern Fortran package developed by the present authors. It is a Fortran 2018-compliant library with minimal dependencies providing `scipy`-inspired interfaces to a collection of Krylov-based techniques (e.g. Arnoldi, Lanczos, Golub-Kahan, GMRES, etc). Krylov methods can be implemented without making explicit reference to the particular data structure used to represent a vector or a linear operator, nor to how the actual matrix-vector product is being computed. Leveraging this high level of abstraction, `LightKrylov` makes extensive use of modern Fortran `abstract type` features enabling the implementation of the different algorithms to be agnostic both to the data structure (serial or parallel) as well as (to some extent) to the hardware used (e.g. CPU or GPU) to perform the matrix-vector product. From a user perspective, only a limited amount of boiler plate code is needed to extend the `abstract type` in order to define the basic `blas`-like operations needed for their particular data structure.

During the presentation, we will illustrate how to use both `LightKrylov` and `neklab` on a number of standard flow configurations with an emphasis on its versatility. In all our test cases, no performance degradation has been observed despite the use of object-oriented programming in Fortran.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Stability of large-amplitude pulsatile flow in a torus

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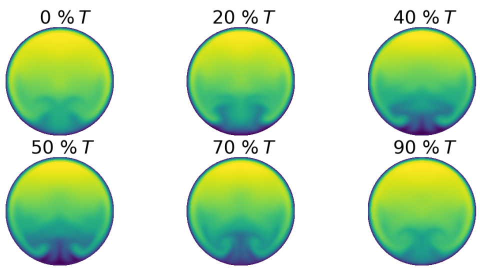
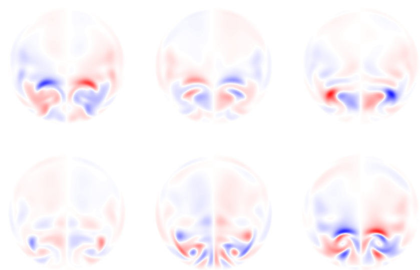
Pipe flows are ubiquitous in nature and technology, from the cardiovascular system to heat exchangers and hydraulic piping. Recent efforts by a number of research teams have conducted steady stability analysis on toroidal and helical pipes, showing that even small amounts of curvature and torsion lead to a linear instability at finite Reynolds numbers (e.g., [1], among others). However, many practical applications involving pipe flows in curved geometries are not subject to steady flow. Linear stability analyses of pulsatile channel flow have shown that time-periodic variations of the baseflow can lead to both stabilisation and destabilisation of the flow [2], results that have recently been shown to qualitatively hold also for toroidal pipes [3].

In the present work, we revisit the case of pulsatile flow in the torus considered in [3] but using a fully three-dimensional matrix-free time-stepper approach, thus eliminating the main restrictions of the previous analysis. The new implementation unlocks not only a considerably larger parameter range for the harmonically forced case, in particular to larger pulsation amplitudes in the highly nonlinear regime, but also opens up the perspective to include more complex geometries or pressure variations at modest extra development cost. The results are two-fold: We confirm the results from the reference and, by extending the computations at a frequency that is initially stabilised by pulsations (Wo = 40) to larger pulsation amplitudes, discover the destabilisation of the pulsed case for high pulsation amplitudes ($Q \approx 0.2$) via a different instability. The analysis is performed using `neklab`, a combination of the spectral element solver `Nek5000` with the novel open-source toolbox `LightKrylov` for linear algebra and stability calculations using Krylov-based methods written in modern Fortran.



(a) Streamwise velocity of the (unstable) nonlinear periodic orbit over the period T for $\delta = 0.3$, Wo $= 40$, $Q = 0.2$.



(b) Streamwise velocity of the corresponding leading unstable eigenvector over the period T.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Instabilities of pulsating Poiseuille flows heated from above

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The onset of instabilities of a pulsating Poiseuille flow are analysed combining laboratory experiments and stability analyses. An experimental flume with dimensions $[L \times W \times H] = [5 \times 0.2 \times 0.016]$ m^3 which allows to reach Reynolds numbers up 10^4 based on the half height of the channel $H/2$ was designed using a variable velocity pump which can pulse the flow at frequencies up to 2 Hz and relative flow rates $\tilde{Q} = 2$ (see [1] for the definitions). The experiment is also fully insulated and equipped together with heat pads on the upper wall which outputs up to 6 kW/m^2. Further, time-resolved temperature measurements are also available at each side of the wall providing simultaneous measurements of heat fluxes and temperatures fluctuations in the fluid. Experiments show that the onset of instabilities is observed for $Re \approx 550$, Womersley numbers $Wo \approx 5$ and relative pulsation flow rates $\tilde{Q} \approx 0.5$ where a temporal instability grows and decays during the pulsation cycle. The origin of the instability is shown to be associated with the inflexion point in the flow [2] and is compared with the prediction from the stability analysis which is of Floquet type. In particular, we show the importance of sub-harmonic periodic orbits in driving the transition process and how it controls the instantaneous growth rate during the pulsation phase. In the second part of the talk, we analyse the effect of these instabilities on the heat transfer and show how pulsating flows can used to improve the Nusselt number for cooling applications in confined environments.

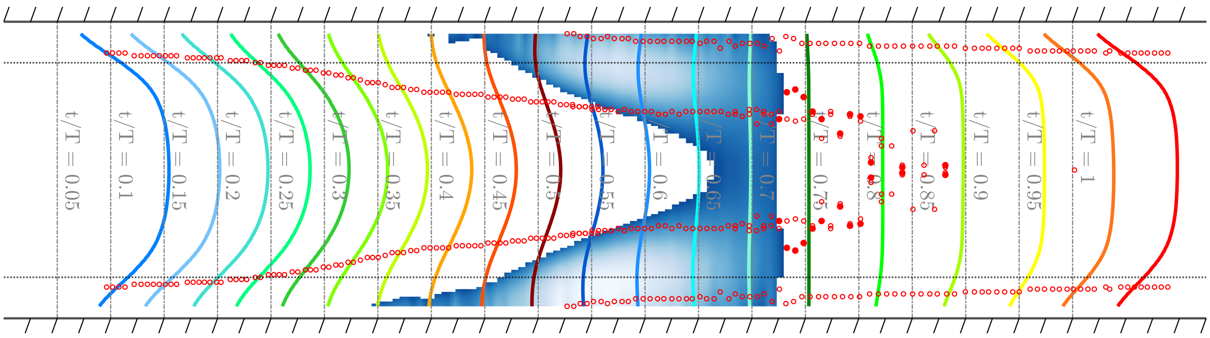

Figure 1: Pulsation cycle for $Re \approx 550$, $Wo \approx 5$ and $\tilde{Q} \approx 1.292$ including regions of reverse flow (blue), Stokes' layer height (dotted black lines) and local baseflow profiles. Red points indicate the location of inflexion points in the profile and their stability (filled) or instability (empty) based on the local Fjørtøft criterion, estimated using PIV measurements.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Second oscillatory bifurcation past a sphere: experiments

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Transition to turbulence past 3D objects like spheres occurs through a succession of bifurcations when the Reynolds number increases. We investigate experimentally the second oscillatory instability.

We consider a sphere of diameter $D = 14$ mm, placed in a water channel of height and width $h = 100$ mm (see figure a). The velocity U is uniform upstream, except at the boundary layers of the channel. The upstream flow is independent of time. The Reynolds number is defined as $\mathrm{Re} = DU/\nu$, where ν is the kinematic viscosity.

It is known that at a Reynolds number of about 210 a stationary instability appears with two counter-propagating vortices. A first oscillatory instability is observed above a Reynolds number of about 270, with a frequency f_1 [1].We have studied the second oscillatory instability, which is characterized by a frequency f_2 lower than f_1 and not commensurable with f_1. This low frequency has been mentioned in several articles, but a numerical systematic study has only been performed recently [2]. We characterize this instability experimentally.

We measure the velocity field using PIV in yz planes for different distances x from the center of the sphere. We compute the barycenter of the absolute value of the vorticity field, and then we use a periodogram to obtain the low frequency and the associated power (see figure c). We also project the vorticity field on azimuthal modes.

The Strouhal number $\mathrm{St}_2 = f_2 U/\nu$ is displayed as a function of the Reynolds number in figure b. The value of this Strouhal number is finite at the threshold (0.04). We have shown that the power varies linearly with the distance to the threshold (see figure c). The secondary bifurcation associated to the low frequency is thus a secondary supercritical Hopf bifurcation (also called Neimark-Sacker).

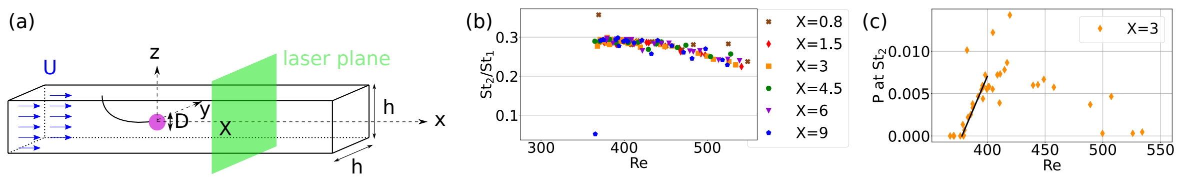

Figure 1: (a): schematic of the experimental set-up. (b) : Ratio $\mathrm{St}_2/\mathrm{St}_1$ as a function of the Reynolds number. (c) : orange diamonds : power associated to the low frequency St_2, as a function of the Reynolds number, straight line: linear fit.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Second oscillatory bifurcation past a sphere and route to chaos: numerical analysis

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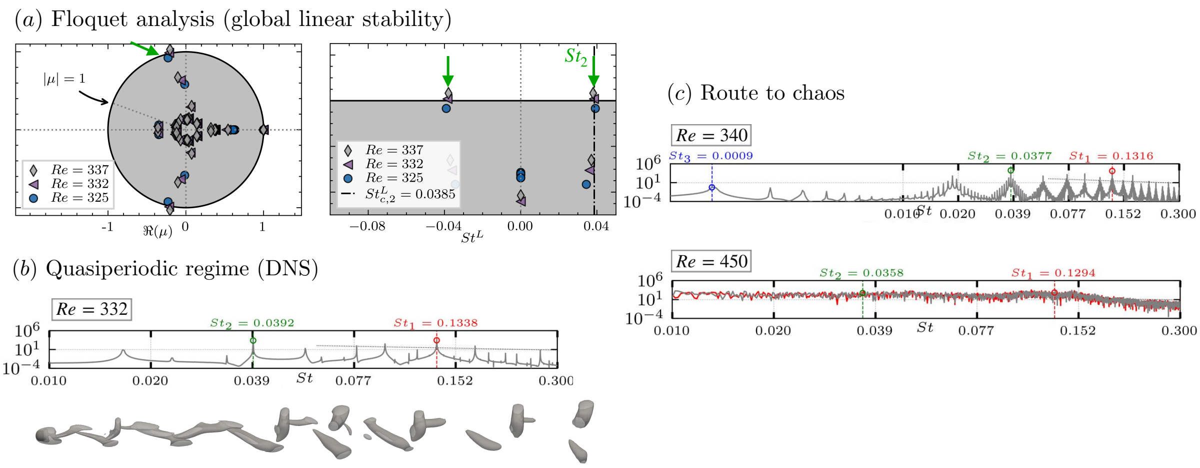
It is well known that, when increasing the Reynolds number, the flow past a solid sphere first bifurcates from a steady/axisymmetric regime (I) to a steady/planar-symmetric regime (II) via a regular pitchfork bifurcation. Then, regime II is followed by a periodic/planar-symmetric regime (III) through a Hopf bifurcation. After the onset of the Hopf bifurcation, experimental studies (e.g. [1]) have reported a fourth regime characterized by an irregular shedding presumably related to the measurement of two frequencies in the wake, namely St_1 (the vortex shedding frequency) and a lower frequency St_2. However, despite the large number of existing studies of flow past a sphere, to our knowledge, there is no explicit characterization of the instabilities arising after the pitchfork and Hopf bifurcations. In the present work we perform a Floquet stability analysis [2] of a periodic flow past a sphere (regime III). This linear stability analysis allows us to identify the tertiary bifurcation: a secondary supercritical Hopf bifurcation (or Neimark-Sacker) (cf Fig. (a)), responsible for the onset of a quasi-periodic regime (IV) driven by two incommensurate frequencies St_1 and St_2 (cf Fig. (b)), forming what is called a T^2-torus. We also propose a spatial description of the flow dynamics in the quasiperiodic regime, where the low frequency St_2 is found to impose a phase oscillation of the fundamental hairpin shedding occuring with frequency St_1, while preserving planar-symmetry (cf Fig. (b)). Finally, from DNS-based temporal analyses and starting from the quasi-periodic regime, we present the scenario of the route to chaos of flow past a sphere. It appears that this scenario follows the so called Ruelle-Takens-Newhouse's route, characterized by the apparition of a third and very low incommensurate frequency St_3 leading to the formation of a T^3-torus (cf Fig. (c), $Re = 340$) before the onset of chaos (cf Fig. (c), $Re = 450$).



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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Low order model for unsteady state of laminar separation bubble using experimental data

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Laminar separation bubbles (LSBs) have a significant role in the aerodynamic performance of airfoils operating at low Reynolds numbers. In many applications, they are subject to a time-varying level of environmental disturbances, such as in turbine cascades and unmanned aerial vehicles. This time–varying regime is not yet fully described. In this scenario, reduced order models (ROMs) emerge as useful tool to help describing and modelling the phenomenon. In this work, a three-dimensional Galerkin model and a non-linear model using Sparse Identification of Dynamical System (SINDy) [1] are tested for modeling the formation of a LSB. The models are built using experimental data from time-resolved Particle Image Velocimetry (PIV) measurements on a flat plate in a water tunnel [2]. To this end, the three most energetic modes, according to Proper Orthogonal Decomposition (POD) and Orthogonal Variational Mode Decomposition (OVMD) were employed, namely shift mode (u_3), and two oscillatory modes (u_1 and u_2) [3]. The time dynamics of the first two modes indicate an oscillating permanent regime reached after a transient and a Hopf bifurcation is conjectured as one possible route. The Hilbert-Huang Transform is used to identify the growth rate and frequency of the oscillatory modes for the model. For comparison, the same modes were then used with PySINDy to identify the non-linear dynamics. The resulting three-dimensional Galerkin model predicts correctly the transient growth and frequency of both oscillatory modes. The prediction of PySINDy model display larger deviations during the bubble formation. Results suggests that an interaction of additional modes might be necessary to improve the model predictions.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Mean flow data assimilation using physics-constrained Graph Neural Networks

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We present *PhyCo-GNN*, a physics-constrained data assimilation framework that combines Graph Neural Networks (GNNs) with an adjoint-based optimization process to reconstruct mean flow fields in two-dimensional incompressible fluid dynamics scenarios. Unlike architectures such as convolutional neural networks, the GNN formulation is naturally compatible with unstructured CFD meshes: each node in the graph corresponds to a mesh vertex, and message-passing operations directly leverage mesh connectivity to propagate flow information. This hybrid approach is enabled by a dedicated interface that synchronizes vector fields between the finite element (FEM) solver and the neural model, inspired by recent work [1]. The process consists of two steps: first, a prior stress closure is computed (see [2] and Fig.1); then, the model is employed within a direct-adjoint optimization process based on the Reynolds-Averaged Navier–Stokes (RANS) equations. We demonstrate the effectiveness of PhyCo-GNN for mean flow reconstruction across a series of canonical test cases, including flow past bluff bodies, sparse sensor reconstructions, denoising under Gaussian perturbations (Fig.1), and inpainting of masked flow regions.

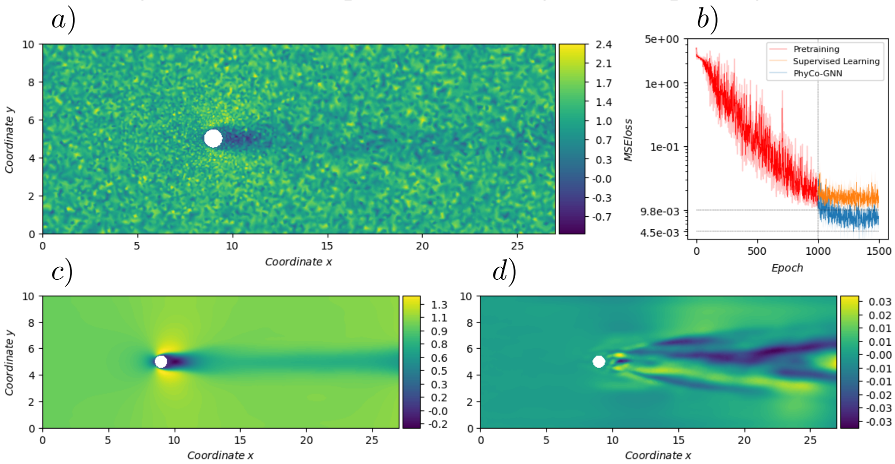

Figure 1: Denoising – training dataset: 3 mean flow-forcing pairs at $Re = [90, 110, 130]$, perturbed with Gaussian noise; (a) mean flow at $Re = 130$; (b) Loss curves for the pure supervised approach (orange line), the proposed PhyCo-GNN method (blue line), and the pre-training phase (red line). (c) Reconstructed mean flow obtained with the PhyCo-GNN approach. (d) Contour plot of the absolute reconstruction error across the entire flow field.

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Transition to Turbulence via Material Instabilities

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We present the Navier-Stokes (N-S) model enhanced with the viscous strength, which introduces material instabilities in addition to the kinematic ones.

We use the new model to simulate the pipe flow. In simulations we observe the spontaneous transition to turbulence around the critical Reynolds number of 2000. Such observation corresponds to the experimental data, while the classical N-S theory fails to predict any instability in the pipe flow [1] – Fig. 1. We argue that the transitional flow is a result of developing material instabilities.

We also use the enhanced N-S model to explain the drag reduction in the pipe flow via addition of a polymer solute. Simulations show that such an addition helps to suppress the chaotic flow yet does not allow making it fully laminar [2].

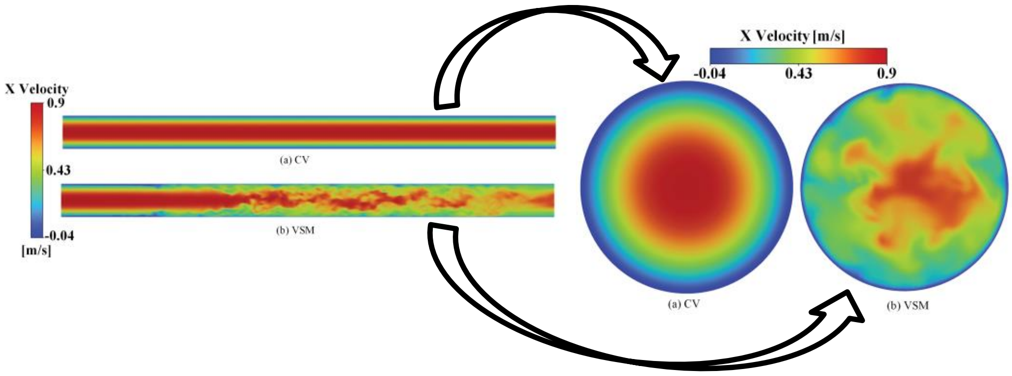

Figure 1: Left – longitudinal velocity profile for: (a) the classical Navier-Stokes model (CV) and (b) the modified Navier-Stokes model with viscous strength; Right – longitudinal velocity profile across the cross-section of the pipe at $L=10D$ from the inlet

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Effect of periodic velocity modulation on stability of the 1D Kuramoto-Sivashinsky system

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Flow over an aircraft wing at cruise condition often consists of wave-like instabilities namely Tollmien-Schlichting (TS) and stationary Cross Flow (CFI) instabilities inside the boundary layer. These wave-like instabilities act as precursors to the transition process, further growing in amplitude which leads to a sequence of events such as formation of three-dimensional waves, vortex structures and their decay, turbulent spots and thereby culminating into a fully turbulent flow. Both TS and CFI exhibit dispersive, wave-like characteristics, making them analogous to classical acoustic and elastic waves while propagating at different wave speeds.

In the field of solid-state physics, periodic structures, namely Acoustic Metamaterials (AM) [1] and Phononic Crystals (PC) [2], have created a lasting impact on wave manipulation and control by achieving band gaps. A wave propagating in a medium can be suppressed completely within a certain frequency range (i.e. the band gap) determined by a periodic arrangement of materials of different properties. In the present work, the concepts of phononic crystals are applied to a one-dimensional fluid flow system described by the Kuramoto-Sivashinsky (KS)/Euler equations where waves propagate in a moving medium.

The governing equation for the one-dimensional flow system is linearised to gain physical insights into the dynamics of perturbations. The linearised governing equation is further solved using a simple yet robust numerical method which minimises dispersive, dissipative and diffusive errors. Neumann boundary condition is implemented at the right boundary (outflow) and the left boundary (inflow) is described with a Dirchilet condition which consists of a periodic sinosidal inflow that represents an incoming instability entering the flow system. A grid independent solution is obtained and the flow field is further manipulated to understand the effects of velocity modulation.

The stability properties of the linearised system with and without spatial mean-velocity modulation are also analyzed theoretically assuming a wave-like ansatz and obtaining the analytical dispersion relation. A stepwise modulation of the velocity profile which is a function of $\tanh(\sin(x))$ is assumed. A parameterization study is conducted by varying the (i) Amplitude and (ii) Wavenumber of the modulated velocity field and the (iii) Inflow frequency of the wave. The results are analysed using the amplification factor (ratio of the perturbation after and before the modulation) and the changes to the wavenumber across the domain.

The objective of the present study is to gain fundamental understanding into whether a modulated step-wise velocity profile in a flow system can manipulate an incoming wave or not.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Too large to see: spectral insights into very low frequency coherent structures in turbulent shear flows

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Very large-scale coherent structures in turbulent shear flows, though energetically dominant and technically critical, often remain elusive due to their exceedingly low characteristic frequencies. These dynamics occur at temporal and spatial scales that challenge conventional experimental and numerical techniques. Yet, they are key drivers of phenomena such as fluid structure interaction, flutter and trailing edge noise in aerodynamics, or flashback in hydrogen combustion systems. In this keynote, we present a physics-based modelling framework that leverages linearized mean field analysis to uncover and interpret these structures. We emphasize how this approach provides spectral access to low frequency modes that are otherwise difficult to resolve. Beginning with a general introduction to coherent structure modelling, we highlight the essential methodological building blocks, from data assimilation and closure modelling to adjoint-based shape optimization enabling a systematic transition from data to design. Through selected case studies, we demonstrate how this framework reveals critical low frequency dynamics: the emergence of low frequency breathing in turbulent separated flows; the generation of broadband trailing edge noise; and the role of large-scale flow structures in flame flow interaction and flashback dynamics in hydrogen combustion. Our approach demonstrates how embedding physics into data driven strategies can extend the spectral vision of engineers and researchers, revealing structures too large to see otherwise.

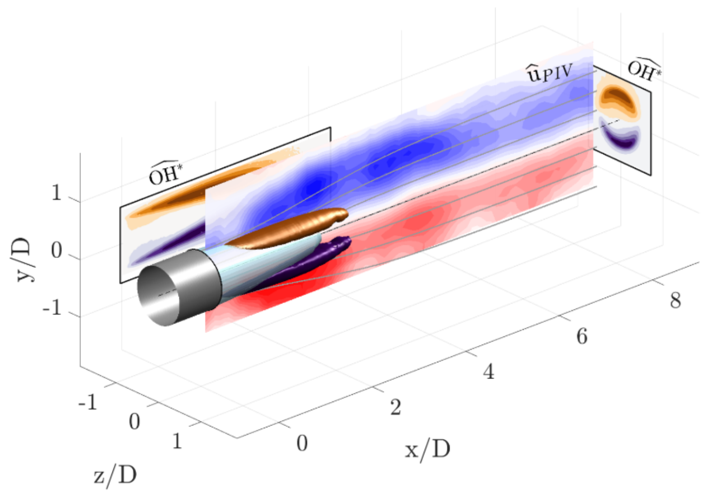

Figure 1: 3D reconstruction of a low-frequency streaky structure in a hydrogen jet flame [1]

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Transition to turbulence in planar synthetic jets: numerical simulations and coherent structures eduction

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Synthetic Jet (SJ) actuators have emerged as efficient flow control tools for thermal and aerodynamic applications. The alternation of fluid ejection and suction from a circular or rectangular orifice produces a train of discrete vortical structures, which break down to form a zero-net-mass-flux jet stream. In most applications, SJs operate in the turbulent regime to maximize fluid mixing and heat/momentum transfers. For high-aspect-ratio rectangular jets, previous studies observed that the flow transition is initiated by three-dimensional instabilities [1], leading to the formation of spanwise-regular, rib-like structures around the core of the primary vortices at the beginning of the suction phase (as shown in figure 1, left). These distorted structures undergo cellular breakdown and generate small-scale turbulence.

In this work, we aim to provide insights into the physical mechanisms leading to SJ formation using direct numerical simulations. A large spanwise-periodic domain, similar to the one used in [2] (fig. 1, right), is used to identify three-dimensional structures while eliminating spanwise end effects. Information on those coherent structures is obtained by data-driven modal analyses. It is shown that, during the suction phase, flow detachment in the slot and the cavity results in the formation of turbulent structures over a wide range of spanwise wavelengths. These vortices fill the whole actuator and are advected outside of it during the subsequent expulsion phase, thereby triggering primary vortex break-up. The analysis emphasizes the prominent role of velocity fluctuations in the cavity on the SJ transition, in conjunction with detached shear layer instabilities within the actuator during the suction phase.

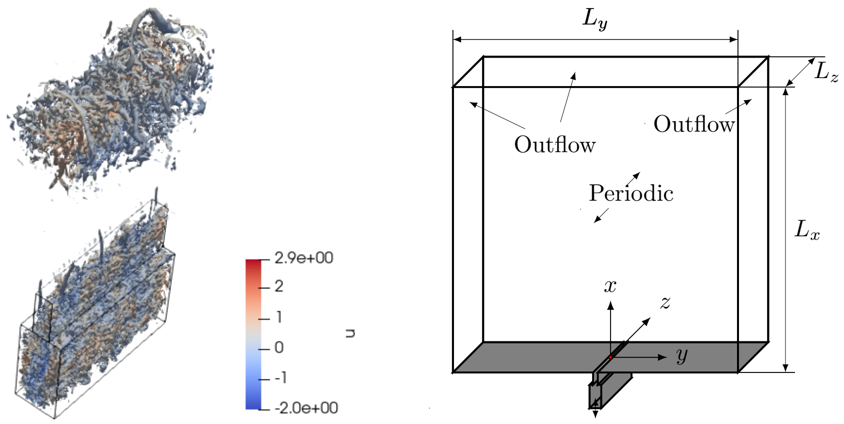

Figure 1: Left panel: view of the primary vortex break-up in the external region via λ_2 criterion (end of suction phase). Right panel: computational domain and boundary conditions used in the present study.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Instability and transition of the rotating disk boundary layer over homogenized textured surfaces.

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Textured and complex surfaces are ubiquitous in nature. In engineering applications, textured surfaces are of interest for their potential drag reduction properties. These surfaces are often characterized by a length scale much smaller than the flow coherent structures. Homogenization theory [1] exploits this scale separation to model the textures as smooth boundary conditions. In this way, turbulent and transitional flows over these surfaces are efficiently simulated. In this work, this approach is employed to study the effect of wall roughness on the stability and transition of the flow over a rotating disk [2]. The boundary conditions for several textures (circular ribs, inline cones and staggered cones) are derived applying homogenization theory on the disk geometry. The theory gives Navier slip conditions with the corresponding slip lengths for the wall-parallel velocities plus a transpiration condition for the wall-normal velocity. The influence of the textures on the modal stability of the flow is assessed using the local spatial analysis both with and without transpiration. Finally, the nonlinear development of the unstable modes is studied by means of direct numerical simulations of a disk annulus (figure 1).

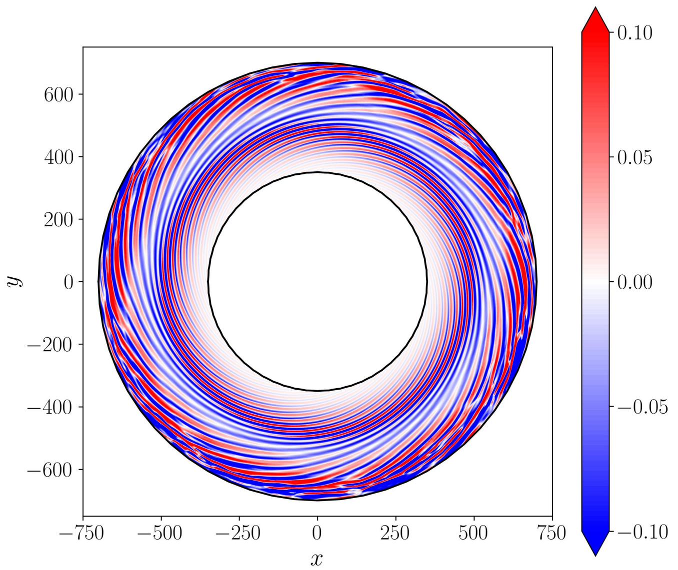

Figure 1: Direct numerical simulation of the boundary layer over a rotating disk with textured wall (inline cones). Contours of the azimuthal velocity component (perturbation of the von Kármán similarity solution) at wall distance $z\sqrt{\Omega/\nu} \approx 0.5$. The unstable mode with reduced azimuthal wavenumber $\overline{\beta} = 0.08$ is forced at the inlet.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Closed-loop control robust to finite-amplitude perturbations: application to reduced-order models of subcritical transition

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We investigate new methods to design static feedback gain matrices intended to optimally stretch the basin of attraction of a fixed-point. The methodology is applied to two reduced-order models of subcritical transition to turbulence, i.e. Dauchot–Manneville's 2-dofs [1] and Waleffe's 4-dofs models [2, 3], with the aim to increase the robustness of the 'laminar' fixed point to finite-amplitude perturbations. The minimal seed (MS) and the edge state (ES) methods respectively maximize the minimal seed and the edge state energies for a given controller gain $G = \frac{1}{2}\|\mathbf{K}\|_F^2$. The resulting controllers are compared with two alternative controllers solely based on the linear dynamics: the classical infinite-horizon linear quadratic regulator (LQR), and the controller minimizing the worst-case linear transient growth (LTG). Except for LQR, all approaches successfully extend the basin of attraction. In Waleffe's model, the minimal seed energy can be multiplied by a factor of 6 in the range of G considered (see figure 1a). The threshold of secondary perturbations w inducing turbulent breakdown of a streaky flow is increased for all streak amplitudes u (see figure 1b). Surprisingly, the LTG approach yields nearly optimal results despite being fully linear, a result which is not guaranteed to hold for greater values of G.

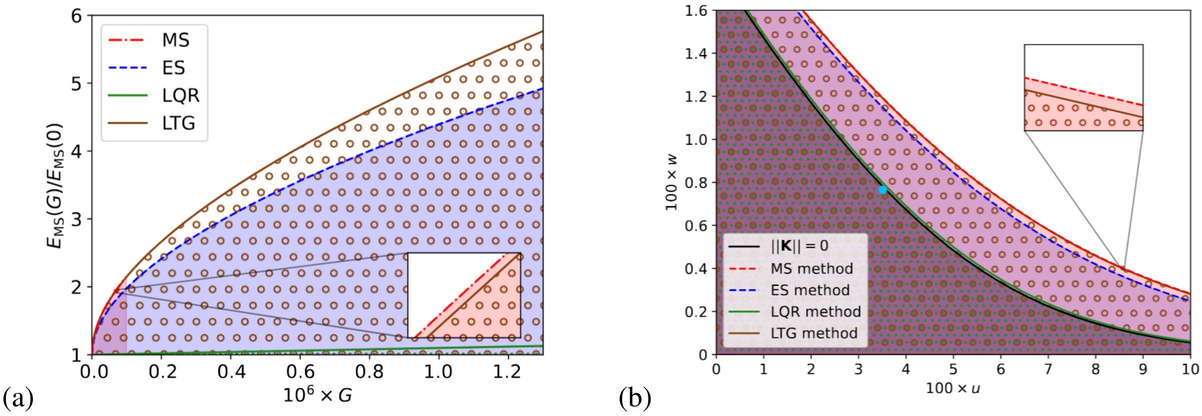

Figure 1: (a) Evolution with the controller gain of the minimal seed energy for Waleffe's model [3], with various synthesis methods. (b) Slice of the basin of attraction in the longitudinal velocity/transverse velocity (u, w) plane containing the uncontrolled edge state (blue dot), with and without control, for a gain $G = 9.9 \times 10^{-8}$.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Investigations of the interaction of boundary-layer transition and separation for swept wings: Direct numerical simulations, wind- and flight experiments

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The complex physics of the interaction of transition and separation for boundary layers that develop on a “laminar” airfoil (NACA 643-618) is investigated in a synergistic manner using wind-tunnel and freeflight experiments, direct numerical simulations (DNS) and linear stability theory. This airfoil tends to develop a so-called laminar separation bubble (LSB), for which the boundary layer is still laminar at the separation location and transitions in the separated shear layer with subsequent turbulent reattachment. The dominant transition mechanisms in two-dimensional LSB are due to traveling wave (Kelvin-Helmholtz) instabilities, for which a significant body of research was carried out including ours. However, for LSBs in three-dimensional boundary layers that develop on swept wings, the understanding of the relevant physical mechanisms of transition in the separated region and subsequent turbulent reattachment is still amiss. This is particularly true when the sweep angle of the wing is sufficient large so that the boundary layer upstream of the separation location is unstable with respect to crossflow modes, that lead to crossflow vortices (stationary or travelling), which can then affect the separation and transition in the bubble. The research to be presented and discussed in our presentation will be exactly for this scenario. From previous investigations (DNS, wind-tunnel and free-flight experiments) with a wing sweep angle of 35 degrees, we have found that the cross-flow instability was not yet strong enough to develop strong crossflow vortices that affect the physics of the LSB for the chord Reynolds numbers that were achievable with the 1/3 scale modified X56A flight model(see Fig. 1). Therefore, in a subsequent investigative campaign, we have increased the sweep angle to 45 degrees, for which LST and PSE analyses indicated that the crossflow instability would be strong enough to produce crossflow vortices that can interact with the separation. This was confirmed in wind-tunnel experiments (see Fig. 2). For flight experiments, a new UAV has been designed and built that allows for varying the sweep angle from 0 to 60 degrees (see Fig. 3). In the final presentation, results will be presented and discussed from wind-tunnel and flight experiments, as well from high fidelity DNS, for 45-degree wing sweep, and for a range of chord Reynolds numbers that are achievable with the new flight model. Emphasis of the presentation will be on the nonlinear transition stages and on the resulting large coherent structures that result from the various nonlinear instability mechanism. In addition, to conventional data, infrared imaging will be carried out for both wind-tunnel and fight experiments (see Fig.4) to allow for comparison with the DNS results.

Fig 1: Modified 1/3 scale X56A with 35deg swept wing.

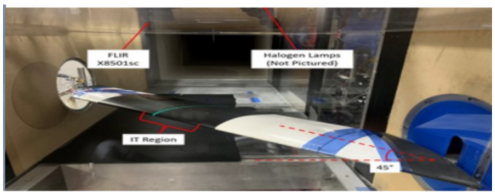

Fig 2: Wind-tunnel experiments with 45 deg sweep.

Fig 3: New flight test model allowing variable wing sweep.

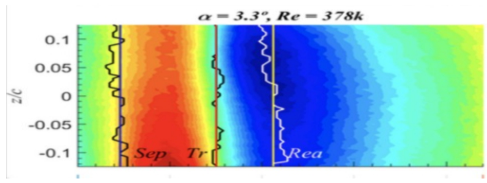

Fig 4: Infrared image from flight experiment showing separation, transition and reattachment.

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Regeneration of long streaks in wall-bounded flows

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Long streaky structures of the streamwise velocity, u, are well-known features of wall-bounded flows. They contain a substantial fraction of the kinetic energy, and are often proposed as required components of the turbulence regeneration cycle, but [1] showed that turbulence survives when they are artificially shortened. All that is needed are perturbations of u with lengths of the order of the flow thickness h, comparable to those of the 'quadrant' structures of the tangential Reynolds stress. In this view, long streaks are not part of the cycle, but one of its by-products, leaving open the question of how they become so long in natural flows. Here, we present experiments in which the shortening torque is suddenly removed from flows with initially short streaks, and their subsequent lengthening is studied. The energy spectrum shows that the lengthening starts near the wall and proceeds upwards as $\mathrm{d}y/\mathrm{d}t \approx 1.5u_\tau$ (Fig. 1a). The process is fast, with elongation velocities of the order of $100u_\tau$ near the wall (Fig. 1b). This is much faster than any velocity present in the flow, and disagrees with models in which the streaks lengthen by advection, or as wakes of other structures. Although the details depend on the initial conditions, the effect is not sensitive to the Reynolds numbers, and extends into the logarithmic layer. An obvious mechanism to generate such fast elongation velocities is pressure acting to correct continuity failures at the ends of shorter streak fragments. Several such 'soldering events' are seen in the example in Fig. 1c, and strong causal events have been observed at those locations in natural flows [2], suggesting that they may also be important players in the natural elongation of the streaks.

Funded by the European Research Council under the Caust grant ERC-AdG-101018287.

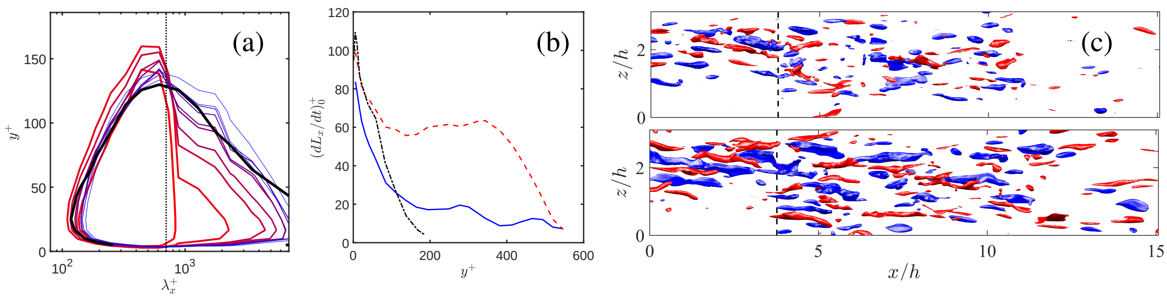

Figure 1: (a) One-dimensional premultiplied spectrum of the streamwise velocity as a function of time and y; $Re_\tau = 186$. Contours are $u_\tau t/h = 0.039$ to 0.39, from red to blue, and contain 70% of the energy. The thick black contour is a natural channel. (b) Initial elongation velocity of the wavelength containing 90% of the energy in the spectra in (a), as a function of wall distance. Red and blue lines are $Re_\tau = 550$; black, 186. (c) Evolution of the fast (blue) and slow (red) streamwise-velocity structures below $y^+ = 90$ in case (a). Top, $t = 0$; bottom: $u_\tau t/h = 0.11$. The frame of reference keeps structures approximately steady, and the dashed vertical line marks the damping length of the initial condition.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Linearized Processes Preceding Orr Bursts in Turbulence in Minimal Channels

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The Orr mechanism has proved of great relevance to intense bursts of wall-normal velocities in wall-bounded turbulence in the past decade [1, 2]. This mechanism can essentially be approximated by a linearized process of transient growth, in which an initially backward-inclined disturbance is sequentially amplified and attenuated while being gradually tilted forward by the shear of mean flow. With respect to this mechanism, the question naturally arises as to how an Orr burst restarts, which remains unclear. A thorough answer to this question must involve certain non-linear mechanisms to determine the magnitude and location of a new burst. However, before identifying the non-linear mechanisms, it can be insightful to reexplore the linearized process underlying the Orr mechanism and understand what it can indicate on the flow features both during and preceding an Orr burst.

In this study, we pose a set of linearized problems to investigate the pre-burst flow structures that can be effective in restarting bursts in minimal channels. Each problem is defined as finding the minimum impulsive perturbation to a spatial Fourier mode at the decaying stage of a typical Orr burst such that the perturbed mode, which evolves unperturbedly afterwards, can burst again at a later time. The results show that such a re-burst solution for a Fourier mode features multiple "bumps" of velocity magnitudes distributed in the wall-normal direction; each bump tends to have a uniform phase speed, thereby yielding an interface with a sharp change of phase speed between two adjacent bumps. The temporal evolution of the solution is characterized by a higher-phase-speed bump gradually catching up with a lower-phase-speed one, after which the in-between interface is smoothed out and a new burst starts. These characteristics resulting from the linearized framework are found to be qualitatively consistent with the observations from direct numerical simulations of turbulence in minimal channels. The linerized analysis also indicates that for an oblique Fourier mode, the "most effective perturbation" to restart a burst is a pair of oblique rollers that tend to intensify the existing lift-up effect.

Funded by the European Research Council under the Caust grant ERC-AdG-101018287.

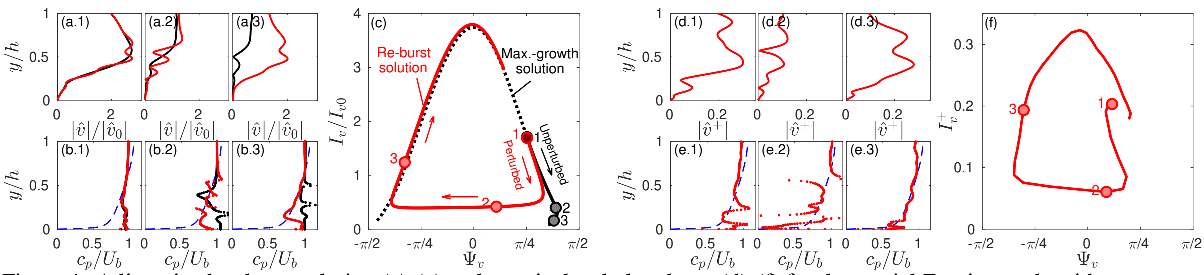

Figure 1: A linearized re-burst solution (a)-(c) and a typical turbulent burst (d)-(f) for the spatial Fourier mode with wavenumbers $k_x = 2\pi/L_x$ and $k_z = 0$ in a minimal channel with length $L_x = \pi h/2$ and $Re_\tau = 950$. The black lines and markers in (a)-(c) represent the classical maximum-growth solution for comparison. The wall-normal velocity is $\hat{v}$ and its phase speed is c_p. I_v and Ψ_v are the y-averaged magnitude and inclination angle, respectively, for $y/h \in [0.04, 0.6]$. The indices 1-3 in the I_v-Ψ_v charts correspond to the $|\hat{v}|$ and c_p profiles at three time instants whose increment is around $0.08h/u_\tau$, with the index 1 the instant when the impulsive perturbation is introduced. The dashed blue lines in (b) and (e) are the mean velocity profiles.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Energy transfer of energy-containing motions in zero-pressure gradient turbulent boundary layers

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In wall-bounded turbulence, the attached-eddy model (AEM) describes the flow as a superposition of self-similar, wall-attached eddies spanning a range of length scales within the boundary layer [1, 2]. Although the existence of such motions is supported by numerical and experimental studies, their precise structure and origin remain unclear.

To explore this, previous studies have used numerical experiments that isolate specific length scales, revealing self-sustaining regeneration mechanisms across the near-wall, logarithmic, and outer regions [7, 8]. Recent findings suggest that attached eddies consist of long streaky motions and vortex packets, forming a coherent structure hierarchy from buffer-layer streaks to very-large-scale motions (VLSMs) [10].

This study investigates the origin of these motions via direct numerical simulation (DNS) of a zero-pressure-gradient turbulent boundary layer (ZPG-TBL), where energy-containing motions are selectively removed at the inflow. By leveraging the spectral nature of the DNS in the spanwise direction, velocity fluctuations corresponding to key (y, λ_z) regions in the turbulent kinetic energy (TKE) spectrum are filtered out. These regions, identified by negative interscale energy transfer, are associated with energy-containing motions.

We focus on the statistical response of the flow to the absence of these motions, rather than isolating individual structures. The streamwise evolution of mean velocity, Reynolds stresses, and spectral energy densities is analyzed. Results are consistent with previous observations in turbulent channel flows [12], offering further insight into the autonomous regeneration of wall turbulence across scales.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Stability analysis of large-scale structures in highly confined turbulent wakes

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Accurate characterization of wall confinement effects in turbulent wakes is crucial for proper design of wind tunnel experiments. Blockage effects may significantly alter vortex shedding frequencies, modify aerodynamic forces, and promote the formation of complex coherent structures [1]. Whereas unsteady Reynolds-averaged Navier-Stokes (RANS) simulations are generally adequate for the evaluation of the aerodynamic forces in turbulent bluff-body wakes, this method is generally unreliable for the analysis of large-scale wake structures and the evaluation of the shedding frequency.

In this work, we carry out global stability analyses to characterize coherent structures in confined turbulent wakes. The stability analyses rely on a matrix-free algorithm based on the direct integration of the linearized Navier-Stokes equations (LNSE) from a random initial condition. The LNSE are implemented within an in-house solver embedded in OpenFOAM, to deal with the complex geometry under study. Physically meaningful stability modes are extracted from instantaneous LNSE velocity data using dynamic mode decomposition. The stability tool is applied to the analysis of the wake behind a thick plate in a wind tunnel of width W ([2], figure 1, left panel), at a Reynolds number $Re = 32000$ (based on the bulk velocity and trailing-edge thickness H). Uncertainties associated with the choice of the base flow are quantified using different steady/time-averaged solutions of the RANS equations (obtained by different turbulence models). In addition, quasi-laminar (ql) and frozen-viscosity approaches are both considered. The present SST results (figure 1, right panel) are in excellent agreement between the reference data in [2], which demonstrates the validity of the present stability tool. Finally, we determine the effect of the finite wind tunnel width on the shedding frequency by considering different H/W values.

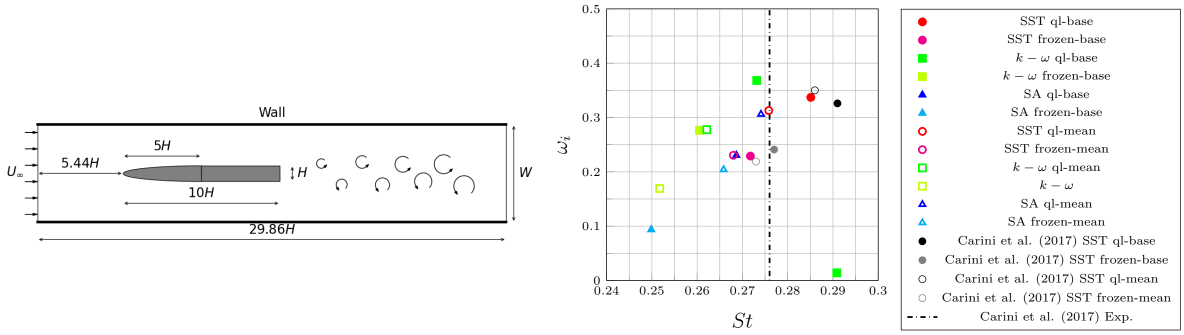

Figure 1: (left) Sketch of the numerical setup of the confined flow past a thick plate; (right) close-up view of the most unstable mode for different stability analyses. Baseline case, $H/W = 16\%$.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Lagrangian Areas of Minimal Stretching in a TBL

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The purpose of the present contribution is identifying and studying coherent, material-based fluid motions in a spatially evolving turbulent boundary-layer (TBL) flow obtained via DNS. To this end, the Finite-Time Lyapunov Exponent (FTLE) was computed in wall-parallel slices, spaced finely enough to cover the entire three-dimensional domain. In contrast to previous investigations the present work focuses on the eye-catching bright regions in the FTLE field (cf. Fig. 1), which have not yet been further considered in the turbulent boundary-layer literature. As these regions are detected using a Lagrangian technique and exhibit minimal local stretching in the Cauchy–Green tensor, the term *Lagrangian Areas of Minimal Stretching* (LAMS) has been proposed for them. The physical significance of LAMS lies in the fact that they track connected, material-bound fluid regions over finite time interval. This is found to be an equally relevant phenomenon of the turbulent boundary layer compared with areas of mixing and vortices.

Using this concept we were able to identify and track lumps of coherent fluid material through the boundary layer. An example is shown in Figure 1, which compares contours of the instantaneous streamwise velocity fluctuations *u'* on the left and FTLE on the right in a wall-parallel plane at a constant distance from the wall. The streamwise and the spanwise coordinates are denoted by *x* and *z*, respectively. The *u'* contours have been filtered by low FTLE values such that only *u'* associated with LAMS remains visible. This leads to the unexpected observation that LAMS are to a large extent linked to high- and low-speed streaks, with the former being particularly coherent. Further analysis of the data [1] has shown that these regions correspond to so-called sweep (Q4) and ejection (Q2) events with a pronounced dominance of Q4 vs. Q2 events above $y^+ \approx 20$ and vice versa below. Our analysis indicates that LAMS from both above and below are aspirated by the most intensive streamwise vortices at this wall distance. These processes and motions were identified through particle traces, cross-sectional views of the flow field, filtered statistical data, and the instantaneous temperature field, which acts as a passive scalar, tracking hotter fluid rising from the wall and cooler fluid descending toward it.

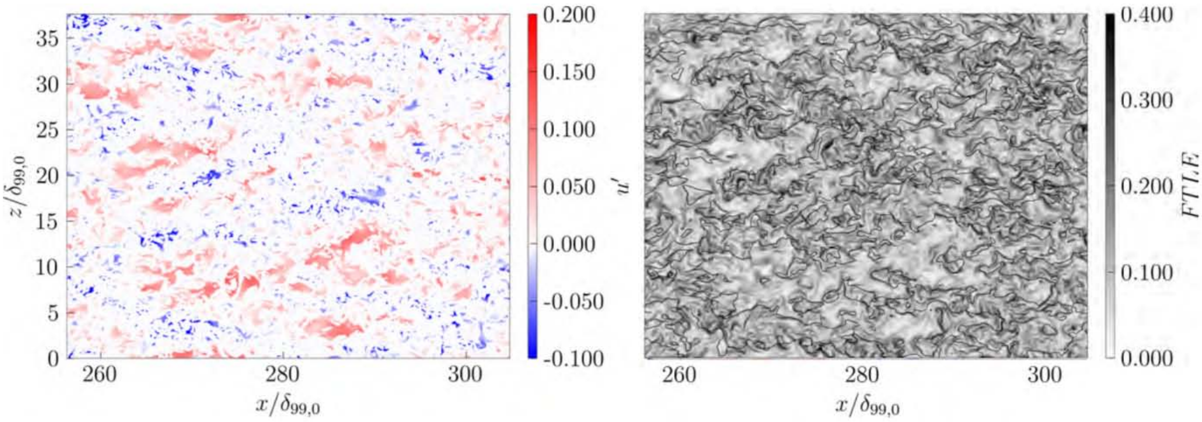

Figure 1: Contours of instantaneous streamwise velocity fluctuations *u'* (left) at $y^+ \approx 368$ filtered by low values of the FTLE field (right), FTLE<0.08. Red and blue indicate high- and low-speed streaks, resp.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Transition and self-sustained process in Couette-Poiseuille flow

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Active turbulence in wall-bounded shear flows is characterised by coherent structures, such as rolls and streaks. These elements interact to create a self-sustained process (SSP)[1]. We investigate the dynamics of this process using experiments and numerical analysis.

The experiments are performed in a plane Couette-Poiseuille channel. The streaks and rolls are quantified by the streamwise velocity fluctuation u_x and the transverse velocity u_y, respectively, measured by stereo-Particle Image Velocimetry (PIV). Direct numerical simulations (DNS) of the Couette-Poiseuille flow were performed with a pseudospectral code using the Fourier continuation method in the non-periodic direction, called SPECTER. [2].

We focus on the interaction resulting from the instability induced by the streak waviness. The streak waviness is a key part of the SSP and has been extensively discussed theoretically and numerically in the literature. However, experimental measurements of waviness are scarce.

To study the evolution of streaks from a straight to a wavy state we apply a spatial filter to separate the straight and wavy parts of the streak velocity. [3]. In parallel, we obtain a similar decomposition from the DNS results (see figure). In both cases we observe the relationship between the straight part of the streaks and the rolls ("laminar" lift-up effect). We introduce a new variable $\langle|\omega_{y,\mathrm{wavy}}|\rangle$ which quantify the wavines of the streaks. Then we show that the average of the absolute value of the wall normal velocity, increases as $\langle|\omega_{y,\mathrm{wavy}}|\rangle$ increases, as expected from the SSP. This new SSP analysis method does not rely on the specificity of Couette-Poiseuille flows and can be used to study this mechanism in other flows.

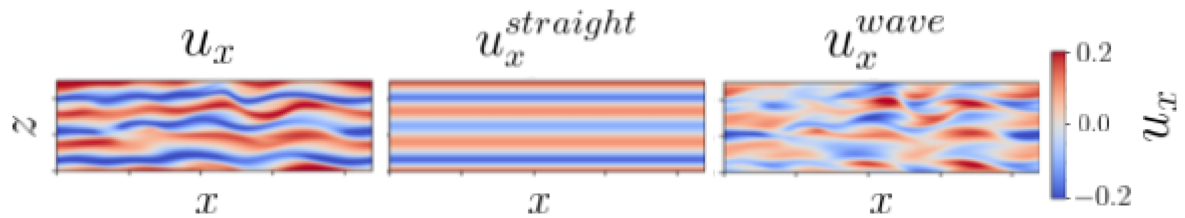

Figure 1: In the upper panels, the streamwise velocity field (left) and its decomposition into the straight part (middle) and wavy part (right) are displayed. The power spectra of each field are presented in the lower panels.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Mean resolvent analysis of periodic flows

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The *mean resolvent* operator predicts, in the frequency domain, the mean linear response to forcing, and, as such, it provides the optimal LTI approximation of the input-output dynamics of flows in the statistically steady regime [1]. In this work [2], we aim at providing numerical frameworks to extract optimal forcings and responses of the mean resolvent, also known as mean resolvent modes. For periodic flows, we propose a projection algorithm approximating those modes within a subspace of mean-flow resolvent modes. The projected problem is solved in the frequency domain, but we also discuss a time-stepper version that can bypass the explicit construction of the operator without recurring to direct-adjoint looping. We evaluate the algorithms on an incompressible axisymmetric laminar jet periodically forced at the inlet. For a weakly unsteady case, the mean-flow resolvent correctly approximates the main receptivity peak of the mean resolvent, but completely fails to capture a secondary receptivity peak (see Figure 1(e)). For a strongly unsteady case, even the main receptivity peak of the mean resolvent is incorrectly captured by the mean-flow resolvent (see Figure 1(f)). The input projection here proposed may be a key ingredient to extend mean resolvent analysis to more complex turbulent flows.

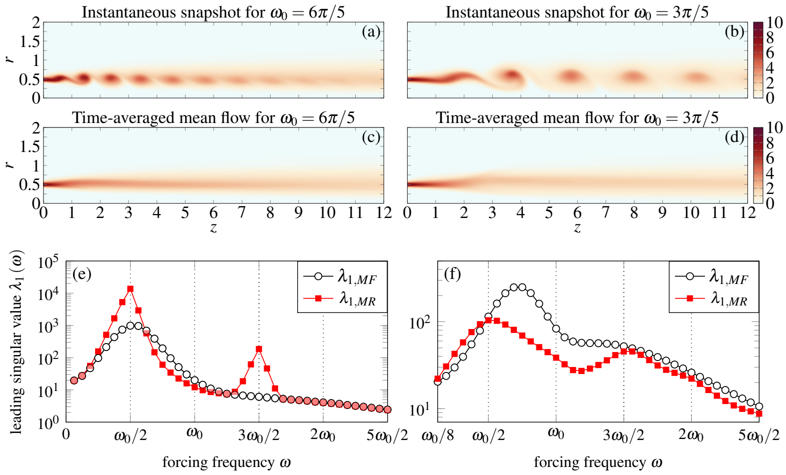

Figure 1: (a-d) Axisymmetric laminar jet at Reynolds number $Re = 1000$ periodically forced at the inlet with angular frequency ω_0 and amplitude $A = 0.05$. (a)-(b) Snapshots of the azimuthal vorticity magnitude for (a) $\omega_0 = 6\pi/5$ and (b) $\omega_0 = 3\pi/5$. (c)-(d) Corresponding time-averaged fields. (e)-(f) Leading singular value $\lambda_1(\omega)$ versus the forcing frequency ω of the infinitesimal external input. White circles: resolvent analysis about the mean flow (MF). Red squares: mean resolvent analysis (MR).

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Variational Framework for Approximating Chaotic Statistics and Sensitivities using Resolvent Analysis

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Low-dimensional chaotic dynamics can be viewed as a trajectory wandering through a dense set of unstable periodic orbits (UPOs) that form a dynamical "skeleton" for the strange attractor. An analogous structure is conjectured for fluid turbulence, where numerous recurrent solutions—equilibria, travelling waves, periodic and relative periodic orbits—have been numerically computed [1]. These so-called Exact Coherent Structures (ECSs) can be used to approximate turbulence statistics and have been linked to underlying dynamical processes [2]. However, ECSs are notoriously difficult to compute due to the high dimensionality and sensitivity to initial conditions, which together impact convergence rates, memory requirements, and the robustness of numerical solvers, especially at high Reynolds numbers. The variational method of Refs. [3, 4] is the most robust available, offering global convergence and a gradient-free formulation that avoids costly adjoint computations. However, this robustness comes at the expense of slow convergence and difficulties when handling non-periodic boundary conditions.

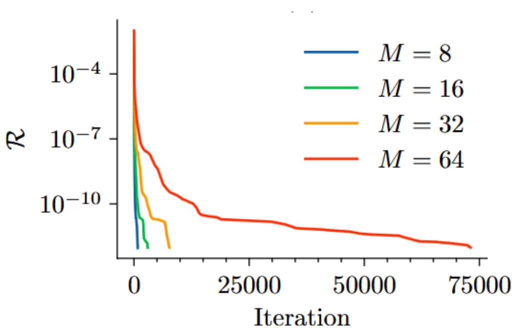

Figure 1: Convergence rate of the residual, using various numbers of resolvent modes for the low-order projection of the dynamics.

In this work, we extend the variational framework of Ref. [4] by projecting the dynamics onto a resolvent-based Galerkin basis [5], which addresses the difficulty of simultaneously imposing incompressibility and no-slip constraints. In addition, this projection permits low-order modelling: truncating the mode set reduces the problem size and, crucially, improves convergence by bounding the condition number of the Hessian matrix. This improved convergence is illustrated in Figure 1 on 2D3C rotating Couette flow.

Finally, we explore a heuristic method for approximating the statistics and sensitivities of chaotic systems by optimising "quasi-trajectories"—trajectories with non-zero residual—until their statistics match those from conventional simulations. We also examine how the sensitivities of observables along quasi-trajectories compare to the corresponding chaotic trajectories, similar to Ref. [6]. This avoids the need to compute large numbers of periodic solutions, as in the traditional cycle expansion method [7]. As a proof of concept, we apply this method to the chaotic Lorenz system .

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Linear and nonlinear receptivity of axisymmetric rotor-stator flow

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Rotor-stator flows exhibit instabilities in the form of circular and spiral rolls. The origin of the spirals is known as a standard supercritical bifurcation, however the dynamical origin of the circular rolls is still unclear. In the present work we propose an explanation for the circular rolls as a linear response of the system to external forcing. We consider two types of axisymmetric forcing: bulk forcing (based on the resolvent analysis) and boundary forcing (based on direct numerical simulation). Using the singular value decomposition of the resolvent operator the optimal response is computed and takes the form of circular rolls. The optimal energy gain is found to grow exponentially with the Reynolds number (based on the rotation rate and interdisc spacing H), in connection with huge levels of non-normality. The results for both types of forcing are compared with former experiments [1]. The linear response is also compared with the fully nonlinear self-sustained periodic and quasiperiodic solutions found for the unforced problem. Our findings suggest that at low Reynolds number typical of experimental observations, the circular rolls observed experimentally are the combined effect of the high forcing gain and the roll-like form (cf. fig. 1) of the leading response of the linearised operator [2]. At slightly higher Reynolds number, nonlinear receptivity can also lead to the nonlinear oscillatory states identified in the unforced problem.

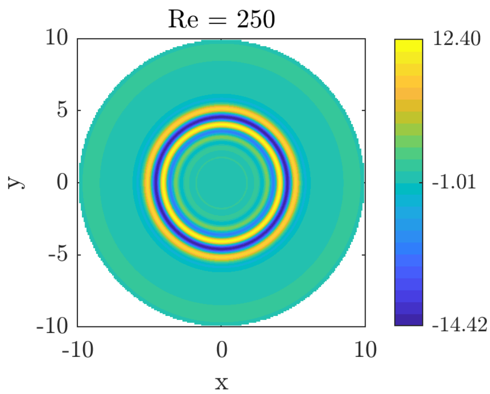

Figure 1: Vorticity of axisymmetric rolls forced externally at $Re = 250$.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Perturbed eddy-viscosity approach in resolvent analysis of a turbulent boundary layer

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Linear resolvent analysis has proven to be a successful approach for the identification of coherent structures in shear flows. Recent studies of turbulent wall-bounded flows have shown the importance of including the mean eddy viscosity $\bar{\nu_T}$ in the resolvent operator. In many cases the addition of eddy viscosity allowed to model empirically obtained SPOD modes more accurately, balancing the linear production of fluctuations with modeled non-linear dissipation [1]. Eddy viscosity depends on the flow variables, and if its inclusion in the linear model is pertinent, it would be consistent to account also for its unsteady fluctuations.

Therefore, we investigate the effect of including a perturbed eddy viscosity ν_T' in the resolvent analysis of turbulent boundary layers. A similar model coupled to data-assimilation has yielded promising results in the linear stability analysis of the flow around an airfoil [2]. The spatially-developing turbulent boundary layer is computed within the Reynolds-Averaged Navier-Stokes equations closed with the Spalart-Allmaras turbulence model. Both velocity and eddy-viscosity are decomposed into a mean and fluctuating component, denoted by $\bar{\nu}_T$ and ν_T' for the latter. Linearizing the RANS equations and the Spalart-Allmaras transport equation around the mean-flow solution, we obtain a perturbed eddy-viscosity approach (ν_T' resolvent) that may be compared to the existing molecular ($\bar{\nu}$-resolvent) and frozen eddy-viscosity ($\bar{\nu}_T$ resolvent) approaches. By comparing the leading disturbances derived from the ν_T'-resolvent with the $\bar{\nu_T}$-resolvent (Figure 1), we show that accounting for a perturbation in eddy viscosity leads to a reduction in the amplification of streaks. The dissipating effect is larger for the small scale structures in the inner layer. Following Symon et al. [3], we will discuss this damping effect from a Reynolds-Orr energy-budget analysis.

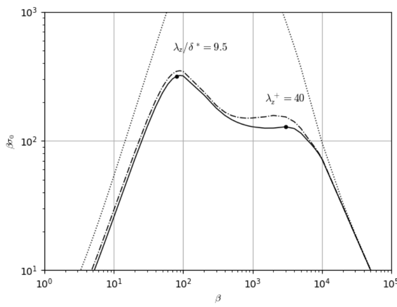

Figure 1: Scaled optimal resolvent gain at $\omega = 0$ as a function of the spanwise wavenumber β : ν-resolvent $(\cdot\cdot)$, $\bar{\nu_T}$-resolvent $(-\cdot)$, ν_T'-resolvent $(-)$.

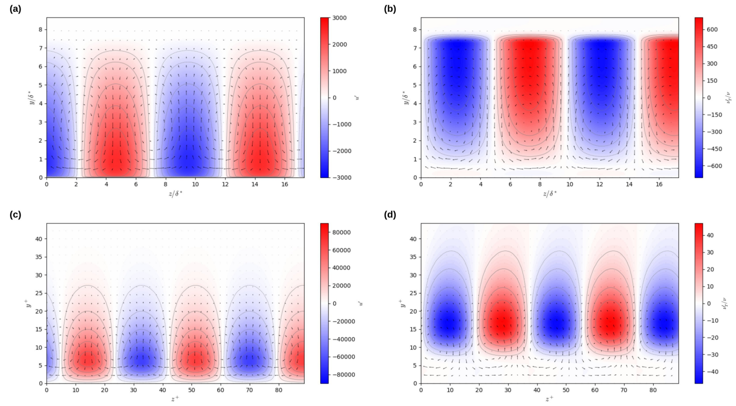

Figure 2: Cross-stream view of the ν_T'-resolvent optimal response, colored by streamwise velocity [eddy viscosity perturbation] for outer peak $\lambda_z/\delta^* = 9.5$ (a) [(b)] and inner peak $\lambda_z^+ = 40$ (c) [(d)].

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Experiments on roughness-induced laminar-turbulent transition with free-stream turbulence

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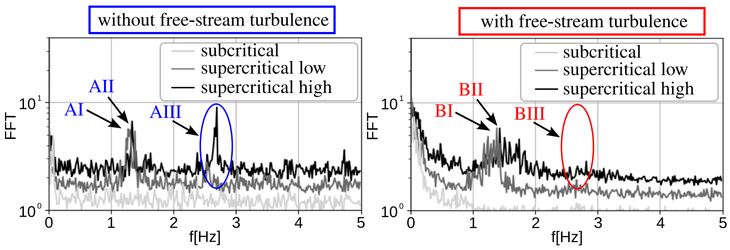
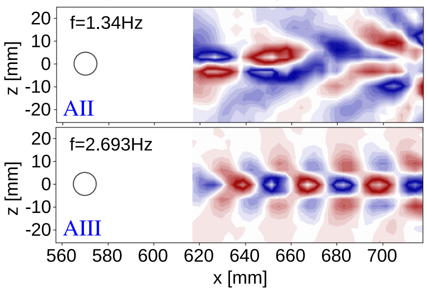
The effects of isolated surface roughness elements and free-stream turbulence (FST) on boundary-layer transition have both been studied extensively but mostly individually. Their interaction effects are however of relevance, for instance in flows over turbine blades.

To this end, roughness experiments with naturally low FST level conducted in our Laminar Water Channel (LWC) were systematically repeated under various FST-level conditions using turbulence grids. Particle Image Velocimetry (PIV) was used to measure the wake behind a cylindrical roughness element in the boundary layer, and the data were analysed using Fast Fourier Transform (FFT) and Dynamic Mode Decomposition (DMD). The top figures show FFT spectra with and without FST for a cylinder with a diameter-to-height ratio of 0.85. In the subcritical and low supercritical roughness-Reynolds-number regimes, only minor spectral differences are observed. At higher supercritical Reynolds numbers, two peaks (AII and AIII) are present without FST, of symmetric (varicose, AIII) and anti-symmetric (sinuous, AII) mode type, see bottom figures, matching the results from [1]. However, a clear difference in spectral content appears under FST conditions: only a single dominant peak (BII) remains, apart from f = 0 Hz, and the mode type at peak BII is varicose instead of sinuous (peak AII). Thus, the former peak at f = 2.693 Hz (AIII/BIII) is suppressed in the presence of FST. Thus, FST – in particular, the induced meandering Klebanoff modes in the boundary layer – have a significant influence on the wake modes of cylindrical roughness elements, an effect previously not looked at. Given that the behavior of these modes is closely linked to the critical Reynolds number [1, 2], the present study offers new insights into the underlying mechanisms of roughness-induced transition in the presence of FST, also in the case of non-meandering streaks, cf. [3]. A detailed discussion of these findings, including transition Reynolds numbers for various cylinder geometries, will be presented.





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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Experimental study of receptivity and transition to turbulence in consecutive asymmetrical bifurcating ducts

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The flow field in a bifurcation system is highly complex due to its strong dependency on geometrical features and its sensitivity to inlet conditions. However, its study is extremely relevant for various applications. One of them concerns the study of fluid motion in lung branches, extensively investigated from both a fluid dynamics and medical perspective. Lungs feature a tree-like structure with millions of branching airways of varying geometry. Consequently, the flow exhibits different flow regimes and features strongly related to the flow rate and the inlet geometry. Understanding the flow regime and the parameters that most affect it is essential to improve the effectiveness of drug delivery deposition [1].

This study introduces an experimental platform designed to investigate flow characteristics in a planar asymmetric lung geometry inspired by Möller et al. [2]. In particular, the 3d-printed airway model consists of 3 subsequent bifurcations, from generation 5 to 7, with the possibility to be extended until generation 0 (trachea). The objective of the investigation is to analyse the effect of inlet conditions on the turbulence characteristics and transition onset inside the model. To accomplish that, 3 inlet conditions were designed in order to recreate different velocity profiles and turbulence characteristics at the inlet (G5): a short (4D) and a long (10D) straight pipe, and a 90° bend. In addition, various Reynolds numbers were considered, ranging from 300 to 1200, representative of a wide range of respiration flow rates. The inlet ducts and the lung model include measurement stations for hand-made hot wire anemometers positioned at the centerline of the branches that allow the accurate study of turbulence characteristics and flow regimes.

The results show a strong influence of the inlet conditions on the flow field. In particular, for low Reynolds numbers ($Re = 300$), the flow is completely laminar and inlet perturbations propagate until G7. By increasing the Reynolds number ($Re > 600$), the inlet conditions assume a relevant role in determining the flow regime. Indeed, for a low inlet turbulence level, a transitional flow is observed; in contrast, for a highly turbulent flow at the inlet ($Tu = 12\%$), spectra assume a turbulent-like aspect and the energy tends to decay over generations.

This experimental platform establishes the basis for advanced analyses that consider the role of at least 7 lung generations in combination with various inlet conditions and measurement techniques.

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An automatic code generation framework applied to GSA of 3D screeching jets.

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High-Reynolds number supersonic wall-bounded flows are inherently multiscale. In addition to the convective and diffusive scales, these compressible flows often generate high-amplitude acoustic emissions, which are usually important for practical applications. However, the nonlinear dynamics can significantly influence their spatiotemporal evolution. Consequently, studying these flows often requires expensive experimental or numerical analyses. In some cases, particularly when dealing with complex geometrical configurations, separating spatiotemporal scales between turbulent small scales and larger scales that arise from the geometrical configuration may occur, allowing for using the URANS simulation framework. To address this class of problems, it is essential to have general numerical tools that can manage 1) complex geometries, 2) intricate physical models (such as compressible URANS equations), and 3) preferably both linear and nonlinear frameworks. This presentation will introduce dNami, an open-source framework that utilizes an automatic source code generation procedure to create a computationally efficient multiblock solver from a user-defined set of partial differential equations (PDEs), which can be provided symbolically (e.g. in LaTeX format). Combined with an automatic differentiation tool (i.e. Tapenade [1]), it allows for the simultaneous study of linear and nonlinear dynamics. The numerical framework will be briefly presented, followed by a detailed application that analyses acoustic emissions from high-Reynolds number 3D screeching under-expanded jets with rounded nozzles. The dNami framework will produce a 3D multiblock nonlinear compressible URANS solver, expressed using general curvilinear coordinates. High-order numerical methods for spatial discretization and shockwave treatment will also be generated symbolically using dNami, which is crucial for capturing acoustic radiation in the presence of shockwaves. The automatically generated linear counterpart will be utilized in a time-stepper framework to conduct a Global Stability Analysis of the 3D configuration around base flows, which are captured via a Newton-Krylov method using dNami. A globally unstable linear mode will be shown to capture acoustic screech emissions (see Figure 1).

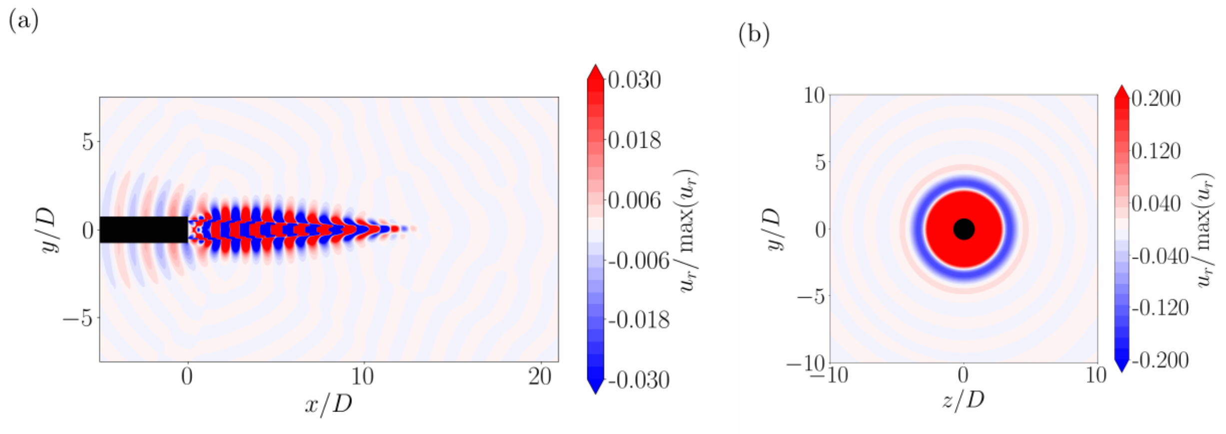

Figure 1: Normalised contour of the real part streamwise velocity of the unstable toroidal mode computed from a 3D under-expanded jet at Mach 1.1.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Noise-induced transitions after a steady symmetry-breaking bifurcation: the case of the sudden expansion

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Some nonlinear dynamical systems are metastable, switching randomly between two configurations under weak noise after long and unpredictable times. This behavior is observed in the barotropic quasi-geostrophic equations, which model quasi-stationary turbulent zonal jets. However, due to the large transition time between attractor states, detecting this through numerical models is challenging. Rare event algorithms based on large-deviation theory are typically used instead.

To compute flow statistics at a lower numerical cost, we propose extending the multiple-scale weakly nonlinear expansion technique from the Duffing oscillator to the Navier-Stokes equations. Specifically, the Navier-Stokes equations are forced by weak, narrow-band noise acting on the same slow time scale τ as the dominant mode's amplitude near a bifurcation point Re_c (with neutral eigenmode $\mathbf{q}(x)$). For a steady symmetry-breaking bifurcation, we derive a stochastically forced Stuart-Landau equation for the amplitude $A(\tau)$ premultiplying the dominant symmetry-breaking mode $\mathbf{q}(x)$

$$\frac{dA}{d\tau} = \lambda A(\tau) + \mu A(\tau)^3 + \eta\phi\xi(\tau), \tag{1}$$

where the coefficients λ, μ and η are all computed from scalar products of linearly computed fields, ϕ is the rescaled noise amplitude and $\xi(\tau)$ a rescaled band-limited white noise.

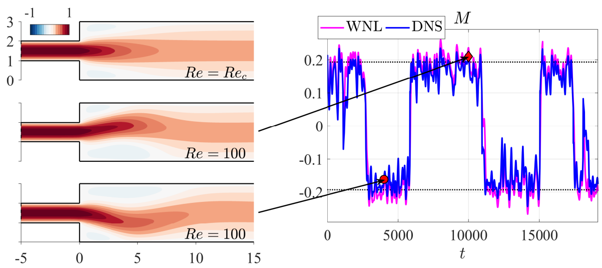

Figure 1: The flow past a sudden expansion at $Re = 100 > Re_c$, subject to a stochastic forcing. The flow switches from one attractor state to the other at random times.

The validity of the reduced-order model (WNL) is tested on the flow past a sudden expansion after the symmetry-breaking bifurcation $Re > Re_c$ [1] (see figure 1). The amplitude equation's dynamics (1) derive from a potential, and the probability density function of the solution is determined by solving the Fokker-Planck equation. At low numerical cost, the statistics obtained from this solution closely match those of a long-time direct numerical simulation (DNS) of the unsteady forced Navier-Stokes equations for varying noise amplitudes ϕ.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Coherent Structures in Axisymmetric Hypersonic Cavities

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Cavities are used in high-speed vehicles to enhance mixing and reduce heat transfer via flow separation, potentially halving heat transfer at hypersonic speeds [1]. Cavities can arise from a design perspective, or defects and affect flow through interactions between shear layers and acoustic waves. However, specific geometries can trigger turbulence, increasing heat transfer and pressure loads. Towards assessing the orientation of the coherent structures arising out of the instabilities along the shear layer of the cavity, current experiments are carried out in a Ludwieg tunnel mode [2] at $M_\infty = 6.0$ across a range of Reynolds numbers (23000 to 74000 based on cavity depth). The effect of uneven heights of the front and rear face of the cavity is shown in Figure 1). High-speed Schlieren and Planar Laser Rayleigh scattering techniques are used to capture the overall flow evolution and unsteady aspect of the flow field. Moreover, Proper orthogonal decomposition (POD) is adopted to demonstrate the dominant coherent structures (see Figure 1), Kelvin Helmotz votices (see Figure 1a), and a flapping mode (see Figure 1b).

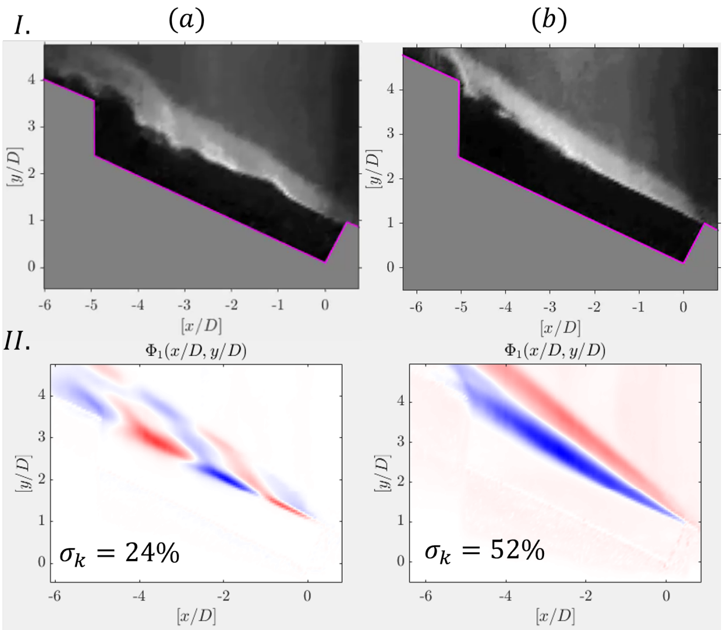

Figure 1: I. Instantaneous PLRS snapshots, and II. the dominant spatial mode obtained from POD for the case of (a) same front and rear cavity face height, (b) 50% higher rear face height. Length-to-depth ratio for the current experiments is 6.0.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Broadband quadratic couplings in a transitional shock wave–boundary layer interaction

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A recent study[1] on a transitional, separated shock wave–boundary layer interactions with a dichromatic deterministic forcing of the oblique boundary layer modes demonstrated that *a priori* selected spanwise mode arrangements induce distinct, nonlinear phenomena. While crossing modes (*i.e.* of opposite spanwise wavenumbers k_z) trigger efficiently the transition to turbulence, parallel modes promote unsteadiness of the separated region at a frequency equal to the difference of the forcing frequencies.

The purpose of the present work is to extend the analysis for a broadband distribution of oblique modes without specific spanwise arrangements. A broadband stochastic forcing set at the inflow of a LES leads to the development of a continuous family of oblique modes with Strouhal numbers $1.6 \leq St \leq 3.2$ (based on the length of the interaction), as revealed by a SPOD postprocessing. Such a processing is, however, inefficient in distinguishing between parallel and crossing modes, with decompositions varying from a pair of standing waves in spanwise quadrature to a pair of progressive waves of opposite k_z.

This difficulty is overcome by splitting the flowfield into positive, null, and negative wavenumbers k_z subfields prior to the SPOD decomposition. The dominant modes of this triple SPOD directly highlight the oblique modes ($1.6 \leq St \leq 3.2$, $|k_z| \neq 0$) and the breathing of the separated region ($St \leq 0.4$, $k_z = 0$). Quadratic mode couplings are then tracked back by projecting mode products onto the SPOD basis. From this *a posteriori* bispectral analysis, it is found that interactions between parallel modes are the dominant quadratic contributions to the low-frequency dynamics of the separated region, see Fig. 1.

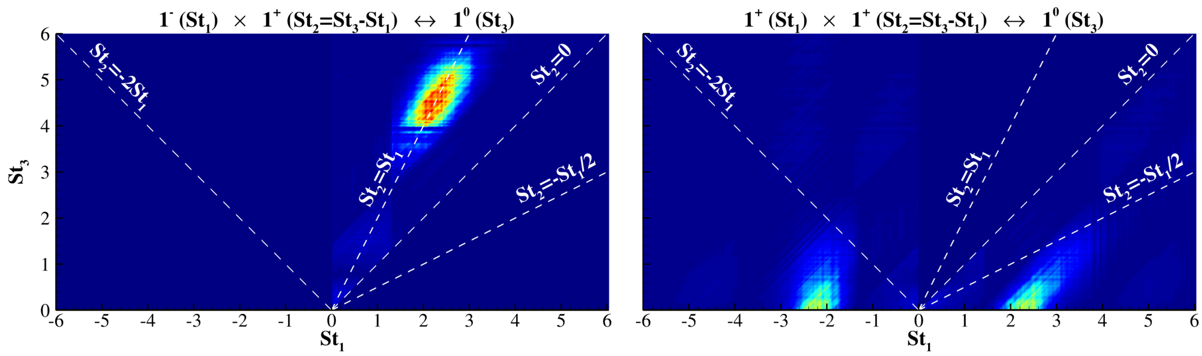

Figure 1: Semi–normalized SPOD bispectra: product of crossing dominant 3D modes ($k_{z_1} < 0$, $k_{z_2} > 0$, left) and of parallel dominant 3D modes ($k_{z_1}, k_{z_2} > 0$, right) matched with dominant 2D modes ($k_{z_3} = 0$).

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Global linear stability analyse of over-expanded nozzle

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Shock wave/boundary layer interactions inside over-expanded nozzles produce significant, unsteady, and non-axisymmetric flow separations, leading to non-axial forces known as side loads. These loads can damage the nozzle and even affect the trajectory of a launcher. It is therefore crucial to understand and characterize the mechanisms driving these unsteady behaviors. These phenomena appear to be self-sustained, suggesting that they may stem from a global instability of the flow. Therefore, a global linear stability analysis may provide valuable information to characterize the dynamics of such a configuration. A first attempt at global linear stability analysis was conducted in Cosimo Tarsia Morisco's thesis [1] and, contrary to experimental results presented in the manuscript, concluded that the flow was stable. This raises questions, particularly regarding the relevance of the turbulence model used. The present study will show a continuation of this work with a parametric global linear stability analysis for NPR (Nozzle Pressure Ratio) values ranging from 6 to 12 and using several turbulence models. This will allow for comparison with the results of C. Tarsia Morisco's thesis and experimental data [2]. To this end, the open-source software BROADCAST [3], developed by ONERA, is used. This software employs second-order finite volume methods with reconstruction, enabling up to ninth-order accuracy. It also utilizes automatic differentiation to linearised the URANS equation and to extract the Jacobian matrix.

Figure 1: Pressure field for NPR = 9

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Large-Scale Input/Output Analysis of High-Speed Boundary Layer Instability and Receptivity

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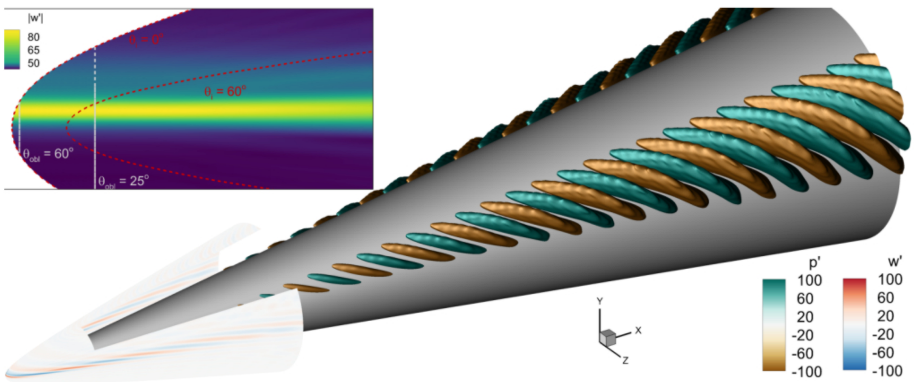
When a high-speed boundary layer transitions to turbulence, both the drag and the wall heat flux increase significantly. Understanding how and predicting when a high-speed boundary layer willtransition to turbulence is therefore crucial to the design of safe and performant aerospace vehicles. Boundary layers at high Mach numbers (such as those encountered during atmospheric reentry) support multiple instabilities that may cause a laminar boundary layer to transition to turbulence. These include oblique Mack 1st mode instability, Mack 2nd mode instability, crossflow instability, and entropy layer instability – all of which may occur simultaneously and interact with one another to precipitate transition. The presence of complex geometry, such as fins and flaps, complicate the physics of boundary layer transition yet further. Finally, while many studies focus on these various instabilities in canonical configurations, less attention has been paid to the receptivity problem of how these instabilities are triggered by environmental disturbances. This talk will present our research group's recent work on Input/Output (I/O) analysis (closely related to resolvent analysis) as a tool to study instability and receptivity of high-speed boundary layers. As a global method, I/O analysis captures effects of complex geometry directly and provides a way to decompose multiple instabilities into separate components. By restricting inputs to realizable disturbances in the freestream, I/O analysis also reveals how instabilities are triggered by the environment. As freestream disturbances must pass through bow-shock of a high-speed vehicle before they can boundary layer instabilities, accurate shock-perturbation models are essential. For this purpose, we employ a shock-kinematic boundary condition, following the work of Robinet (1999). As a global method, computational expense remains a pacing challenge for I/O analysis. We will discuss some recent advances that address this challenge, including Hierarchical I/O analysis which has enabled receptivity calculations of 3D oblique Mack 1st mode instability on blunt cones, using 300 million degrees of freedom (Cook Nichols, 2024). As the nosetip bluntness increases, we show that the receptivity shifts from slow acoustic freestream disturbances to vorticity and entropy freestream disturbances. In both cases, instabilities close to the surface are sensitive to freestream perturbations interacting with the bow shock close to the nosetip and in a narrow band downstream.



Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Resolvent analysis of overexpanded nozzle

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In the domain of aerodynamics, there are several configurations in which shocks interact with the boundary layer. In some of these cases, a low-frequency oscillation is established, which can be dangerous, as in the case of an overexpanded nozzle. In this scenario, lateral loads are generated that can damage the structure. The aim of this work is to understand what causes this low-frequency phenomenon to predict certain physical characteristics through a model based on linear stability and resolvent analysis.
This work is based on the experiments conducted by Sajben [1] in the 1980s and the corresponding numerical simulations by Hsieh [2]. A G-type structure with a rectangular cross section is used, and different pressure ratios p_i/p_0 are considered. In particular, it has been seen that for $p_i/p_0 = 0.72$ the shock generates a recirculation zone and oscillates with a frequency of approximately $210Hz$. This configuration was then studied with a Mach number $Ma_i = 0.46$ and a Reynolds number $Re = 5.22 \times 10^6$ using dNami, a code developed at DynFluid that, through TAPENADE, allows automatic differentiation of the URANS equations with the Spalart Allmaras turbulence model.
To perform the global stability analysis, a fixed point is found using the Newton/GMRES method. Then, the eigenvalues are computed using a shift and invert method, after the Jacobian is reconstructed. As it can be seen in Figure 1, there are no unstable modes, but nevertheless there is one marginally stable mode that matches the frequency of the experiments. It has been therefore necessary to go further by means of the resolvent analysis. The latter has showed how the low frequency oscillation is due to an acoustic feedback loop which is not self-sustaining but is very sensitive to external disturbances.

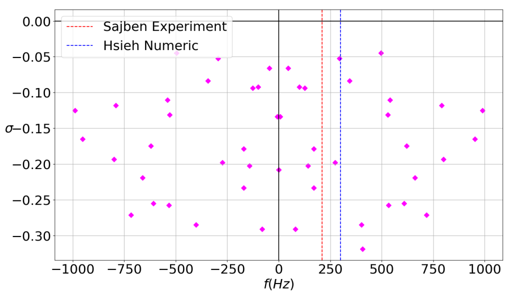

Figure 1: Eigenspectum with experimental and numerical frequencies superposed

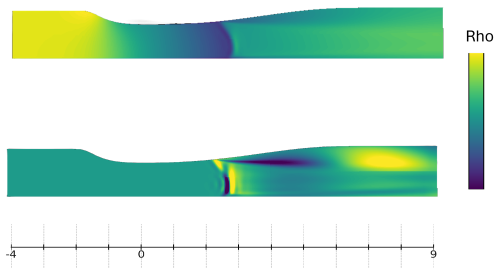

Figure 2: Fixed point ρ (up) and real part of density $R(\rho')$ of mode at $300Hz$ (down)

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Thermoacoustic Instability Analysis of Hydrogen-Enriched Premixed Methane–Air Flames Using FGM

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Hydrogen enrichment (HE) is a promising strategy to reduce carbon emissions in power generation systems, but it also alters flame dynamics and can destabilize otherwise thermoacoustically stable combustors. Even small changes in fuel composition may trigger large-amplitude acoustic oscillations associated with the natural modes of the combustion chamber. Linear stability analysis provides insight into system behavior under small perturbations by solving an eigenvalue problem [1]. This study investigates the linear stability of a hydrogen-enriched premixed methane–air flame confined in a cylindrical duct with open ends. The open-source solver SU2 [2] is used to compute the flame response to harmonic acoustic perturbations, using the Flamelet-Generated Manifold (FGM) approach to represent detailed chemistry. Acoustics are modeled via a one-dimensional low-order system, coupled to the flame through the Flame Transfer Function (FTF), which links velocity perturbations to heat release fluctuations. At fixed power output, the hydrogen molar fraction is varied. Results show that hydrogen addition shortens the flame and affects the FTF by shifting gain drop-off to higher frequencies and reducing phase lag. The resulting changes in flame response alter the eigenvalues of the coupled system, which can transition between stable and unstable regimes depending on the interaction between the FTF and acoustic modes. This behavior is illustrated in Figure 1, highlighting how hydrogen content can act as a tunable parameter for thermoacoustic stability.

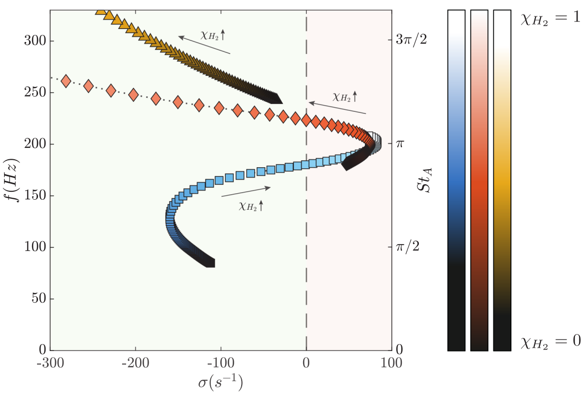

Figure 1: Effect of hydrogen enrichment on system eigenvalues at constant power output. Marker brightness increases with hydrogen molar fraction; green and red areas indicate stable and unstable regions.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Novel transient growth mechanism in variable-density q-vortices

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Aircraft trailing vortices, characterised by high Reynolds and swirl numbers, play a crucial role in wake dynamics and pollutant dispersion. The q-vortex model has emerged as a more representative framework for wake vortices compared to the classical Lamb–Oseen (LO) columnar vortex because it includes an axial flow [1]. Although the LO vortex is asymptotically stable, the presence of a denser core triggers the development of Rayleigh–Taylor instabilities [2, 3]. In addition, non-modal stability analysis revealed strong transient energy growth in the constant-density LO vortex [4, 5]. In the present study, we look for short-time energy growth in a radially-stratified q-vortex at Reynolds number of $Re = 10^6$ and swirl number of $q = 10$, representative of real aircraft wakes. Density stratification is monitored by the Atwood number $At = (\rho_c - \rho_b)/(\rho_c + \rho_b)$ where ρ_c and ρ_b represent the core and background density, respectively. Stemming from a non-modal stability analysis approach, the extra-gain $\Delta G^{\text{opt}} = \mathcal{G}(T)/G^{\text{adj}}(T)$ of the optimal perturbations with respect to the adjoint modes is thus computed to identify transient mechanisms inducing the strongest drift of the dynamics at short horizon times T. Whereas previous studies in variable-density flows [6] have exclusively focused on optimising disturbance kinetic energy, this work optimises the gain of the full state vector norm over the period $[0, T]$.

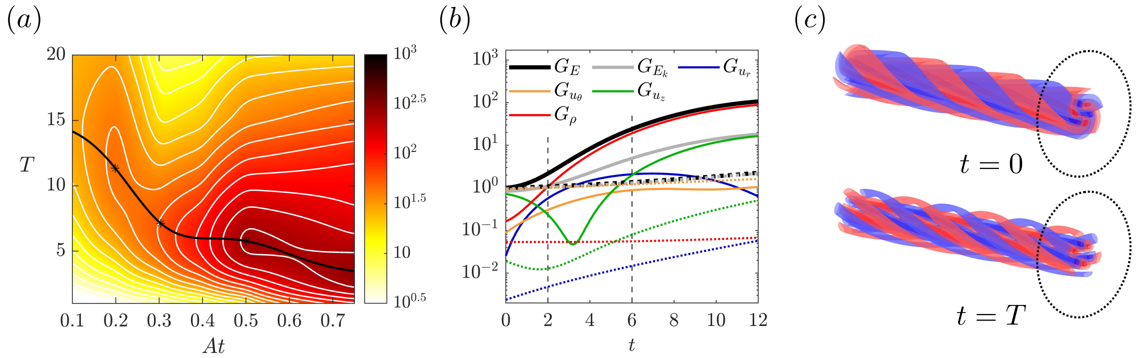

Figure 1: (a) Ratio ΔG^{opt} in the $(At,\, T)$ plane for $m = -3$. The black line represents the regions of maximum extra-gain for each At. (b) Temporal evolution of the generalised energy gain with component-wise contributions of the optimal perturbation (solid) and adjoint mode (dotted) at $At = 0.2$. (c) Contour of axial vorticity ($\pm 0.8 \max(\omega_z')$ and $\pm 0.2 \max(\omega_z')$) of the optimal perturbation at $m = -3$, $k^{\text{opt}} = 3.1$ and $T^{\text{opt}} = 12$. The dotted circle corresponds to the location of the maximum azimuthal velocity of the base flow.

Through an in-depth investigation in the parametric space (At, T) (see figure 1*a* for $m = -3$), we identify a novel transient mechanism driven by inter-component energy transfers through pressure fluctuations and the self-sustained interaction between radial velocity and density perturbations. This mechanism has been observed for all the Atwood numbers and azimuthal wavenumbers explored. As evidenced in figure 1(b) for $At = 0.2$ and $m = -3$, our results highlight a fundamental difference between the constant-density and variable-density cases: while the constant-density vortex follows a transient mechanism analogous to the anti-lift-up one [5], *i.e.* dominated by the creation of azimuthal vorticity outside of the vortex core, the variable-density vortex exhibits core-localised disturbances, as illustrated in figure 1(c). In addition to providing valuable information on the dynamics of variable-density wake vortices, these results can lay the ground for the design of density-based aircraft wake vortex disturbances.

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EUROPEAN MECHANICS SOCIETY

Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Influence of porous material on the flow behind a backward-facing step: experimental study

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We investigate effect of porous insert located upstream of the separation edge of a backward-facing step (BFS) in early transitional regime as a function of Reynolds number (Fig. 1). This is an example of hydrodynamic system that is a combination of separated shear flow with large amplification potential and porous materials known for efficient flow destabilisation. Spectral analysis reveals that dynamics of BFS is dominated by spectral modes that remain globally coherent along the streamwise direction. We detect two branches of characteristic frequencies in the flow and with Hilbert transform we characterise their spatial support. For low Reynolds numbers, the dynamics of the flow is dominated by lower frequency, whereas for sufficiently large Reynolds numbers cross-over to higher frequencies is observed. Increasing permeability of the porous insert results in decrease in Reynolds number value, at which frequency cross-over occurs. By comparing normalised frequencies on each branch with local stability analysis, we attribute Kelvin–Helmholtz and Tollmien–Schlichting instabilities to upper and lower frequency branches, respectively. Our results show that porous inserts enhance Kelvin–Helmholtz instability and promote transition to oscillator-type dynamics (Fig. 2). Specifically, the amplitude of vortical (BFS) structures associated with higher-frequency branch follows Landau model prediction for all investigated porous inserts [1].

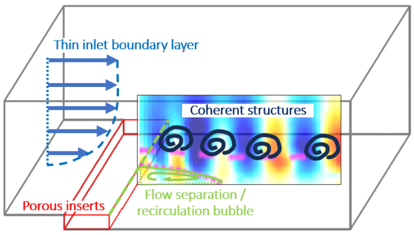

Figure 1: Schematic representation of BFS configuration under investigation.

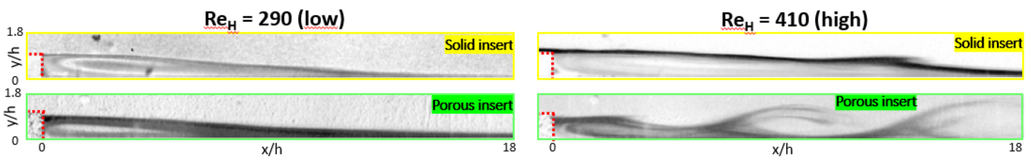

Figure 2: Visualisations for low and high Reynolds numbers, from left to right. The solid impermeable reference case (in yellow) and the most permeable porous insert (in green) are presented in the top and bottom rows. The bottom-right panel illustrates roll-up due to Kelvin-Helmholtz instability.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Effect of a regularly micro-structured inner wall on the onset of the Taylor-Couette instability

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The flow in the gap between two co-axial cylinders of different radii which are differentially rotating is a prototypical example of hydrodynamic instability; the seminal work by G.I. Taylor [1] demonstrates that excellent agreement exists between experimental and theoretical results when the no-slip condition is adopted at the two smooth walls bounding the fluid. Here, we endeavor to study how the instability is modified when the inner, rotating cylinder is micro-structured. The micro-structure adopted is azimuthally invariant; since the primary instability takes the form of toroidal vortices, the problem considered permits to address also the question of how riblet-like wall corrugations affect the exponential growth of vortices aligned with the mean flow.

The problem is studied experimentally and theoretically. A rheometer is used to conduct experiments with the inner cylinder covered by different 3D-printed *sleeves* displaying microstructures of different forms and dimensions. Torque measurements are made with the increase of the angular velocity of the rotating cylinder, permitting to easily infer the critical Taylor number for the onset of the vortices. Flow visualizations permit to obtain the critical wavenumber at onset. The theoretical analysis starts with an upscaling theory to obtain the *effective* boundary conditions to be used at an inner, *virtual* surface in place of the real, micro-structured geometry. This theory is based on the separation between the length scale of the Taylor vortices and that of the wall roughness. Finally, a linear stability analysis (with slip conditions at the inner wall) is conducted, showing postponement of the instability when the surface of the inner cylinder is micro-structured. The theoretical results compare successfully to laboratory measurements, demonstrating that, at least for laminar flows, mildly corrugated walls can be very effectively modelled using Navier-slip conditions.

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows, 15-17 September 2025, Bari, Italy

Coherent structures in the wake of a wind-turbine with Coriolis force

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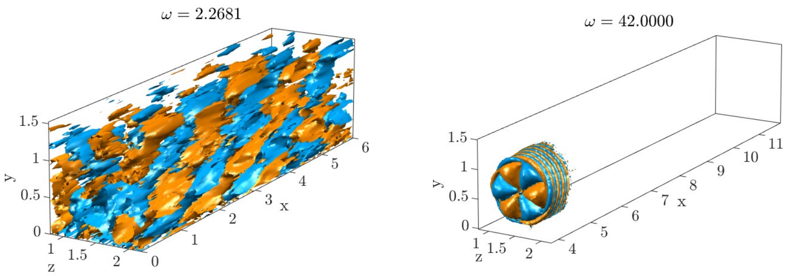
This study investigates the coherent structures in the wake of an NREL 5-MW reference wind turbine. In particular, the effect of the wind veer — the lateral variation of wind velocity with height caused by Coriolis acceleration — on the development of the coherent structures will be studied. To identify dynamically relevant flow structures, the Sparsity-Promoting Dynamic Mode Decomposition (SP-DMD) technique [1] is used. The flow around the turbine is simulated using large eddy simulation (LES), by solving the filtered incompressible Navier–Stokes equations. The effects of both the tower and nacelle are incorporated into the simulation through the immersed boundary method. The simulations are conducted at a Reynolds number of approximately $Re \approx 10^8$, with the inflow velocity profile generated from a precursor atmospheric boundary layer simulation that includes Coriolis effects.

Through DMD analysis, we assess how Coriolis acceleration influences the dominant dynamic modes within the atmospheric boundary layer and turbine wake, shedding light on the mechanisms by which wind veer affects wake recovery. The SP-DMD method enables the extraction of the most dynamically significant modes, allowing for the identification of a compact set of flow features that optimally approximate the full dataset [2]. This reduced set of modes provides the foundation for constructing an accurate reduced-order model of the turbine wake.



(a) Pair 1 (b) Pair 2

Figure 1: Iso-surfaces of SP-DMD modes of precursor (left) and wind turbine (right).

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Coherent structures and instabilities in transitional and turbulent wall-bounded flows

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