

Coherent Structures in Multiphysics Flows: Modelling, Control, and Interpretation

1 – 3 July 2026

Berlin, Germany



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Institute of Fluid Dynamics and Technical Acoustics
Technische Universität Berlin, Germany

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Dr. Olivier Marquet
Prof. Santosh Hemchandra
Dr. Petronio Nogueira

Host Institutes



Conference Venue

The colloquium will take place in the Charlottenburg district of Berlin, Germany, adjacent to the campus of Technische Universität Berlin.

The scientific sessions will be held at the facilities of the Physikalisch-Technische Bundesanstalt (PTB) campus ([Abbestraße 12, 10587 Berlin](#)), located just next to the TU Berlin campus.

Access from Public Transport

The PTB's main campus is easy to reach using Berlin's excellent public transport system:

- 🚇 **U-Bahn Ernst-Reuter-Platz** (U2 line) – [~ 10 minutes walk](#) to conference venue.
- 🚆 **S-Bahn Zoologischer Garten** – [~ 10 minutes walk](#) to campus.
- 🚌 **Bus connections** – lines M45, 245, X9 stop directly at or near the campus
- 🚆 **From Berlin Central Station (Hbf)** – [~ 20 minutes by S-Bahn](#) (S3, S5, S7, S9) to Zoologischer Garten.
- ✈️ **From Berlin Brandenburg Airport (BER)** – [~ 1 hour by regional train or S-Bahn](#) to Zoologischer Garten. A taxi/Uber/Bolt from the airport to the city center costs around 60€.

💡 **Travel tip:** We recommend using the official BVG app (available in English and German) for buying tickets, and travel updates in Berlin.

The map below shows the campus layout and nearby stations for your orientation:



Social Events



Reception at Schleusenkrug (1. July)



Dinner at Spreefeld Bootshaus (2. July)

Reception — Wednesday, 1 July 2026

At **19:00** you are warmly invited to the **Schleusenkrug**, a traditional beer garden right next to the TU Berlin campus and on the edge of the Tiergarten park next to a canal lock. Join us for a relaxed evening of food and drinks. [📍 Location](#)

Boat Trip and Dinner — Thursday, 2 July 2026

As our main social event we have organised a **private boat trip** along the River Spree. We board near the conference venue and cruise eastbound past the governmental district and the historic centre of Berlin. We arrive close to the dinner location, the “**Spreefeld Bootshaus**”, a former border-police boat house right on the river front.

After the **last talk ends at 17:00**, we leave the conference venue **together at 17:10** and walk to the jetty (approx. 20 min). [📍 Walking route](#) The **meeting point** is the **jetty at Caprivibrücke** (Iburger Ufer 1, 10587 Berlin) at **17:35**. Please be on time — the **boat departs at 17:45!**

On board you can enjoy **one complimentary drink**: the paper ticket from registration serves as both your **entry ticket** and **drink voucher**. Additional drinks can be purchased on board - **cash only**. The group will be split between two boats, the larger “*Golda*” and the smaller “*Jimmy*”. If it’s sunny and hot, please bring a water bottle, a hat and sun screen.

The boat arrives at **Schillingbrücke**, from where we walk together (approx. 5 min) to the dinner location at Wilhelmine-Gemberg-Weg 14, 10179 Berlin. [📍 Walking route](#) **Dinner begins at 20:00** and ends at **24:00**. Please note that the venue is in a residential area, so we kindly ask you not to stay and chat in front of it. If you would like to continue the evening, we are happy to recommend bars nearby.

Getting back

After midnight you are free to make your own way back. Please keep in mind that public transport stops running after around 00:45. We recommend the following options:

🚆 **S-Bahn** – approx. 12-minute walk to **Ostbahnhof**. The last S-Bahn departs Ostbahnhof at **01:18** westbound and **01:29** eastbound. [📍 Walking route](#)

🚇 **U-Bahn** – the U8 line is reachable at **U Heinrich-Heine-Straße** (approx. 11-minute walk) or **S+U Jannowitzbrücke** (approx. 17-minute walk). The last U8 departs Heinrich-Heine-Straße at **00:43** southbound and **00:45** northbound.

🚗 **Taxi, Uber or Bolt** – readily available throughout the night.

List of Participants

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Conference Program

Wednesday, 1 July 2026

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08:45	K. Oberleithner & P. Jordan	<i>Welcome and opening remarks</i>	–	
Session 1 — Resolvent and Stability Frameworks for Turbulent Coherent Structures				
09:00	C. Wang	Prediction of coherent structures in turbulent flames from sparse mean flow measurements: data assimilation and resolvent analysis	13	L. Lesshafft
09:15	A. Franchini	Mean resolvent analysis of a stochastic axisymmetric jet	16	
09:30	C. Douglas	On the role of eddy viscosity dynamics in mean-flow stability and resolvent analysis	17	
09:45	Z. Zhang	Strongly and weakly nonlinear dynamics of three-dimensional coherent structures in a round jet	30	
10:00	R. Peron	Resolvent Analysis of Assimilated Mean Flow for Capturing Airfoil's Tonal Fluctuations	36	
10:15	M. P. Ribeiro	Resolvent Analysis and Spectral Proper Orthogonal Decomposition of rotating turbulent channel flows	54	
10:30	A. Villié	Linear amplification mechanisms in axisymmetric stenotic flows: from LES to MRI data	67	
10:45		<i>Coffee break</i>	10:45–11:15	
Session 2 — Coherent Structures and Causality in Wall Turbulence				
11:15	P. Chen	Causal significance of quadrant structures in channel turbulence	06	S. Symon
11:30	Z. Hao	Restarts and sustainment of bursts in turbulence in minimal channels	12	
11:45	A. Schulz	Dynamic response of the turbulent boundary layer to an unsteady boundary condition	34	
12:00	K. Schäfer	On the Meandering of Convective Rolls in Turbulent Channel Flow over Streamwise Ridges	48	
12:15	G. Hasanuzzaman	Influence of uniform blowing on turbulent boundary layers: POD analysis of large scale structures	51	
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Session 3 — Coherent Structures in Time-Varying and Non-Stationary Flows				
14:00	R. Klopsch	Wake interaction between porous discs: linear nowcasting and forecasting from sparse experimental data	49	O. Schmidt
14:15	I. Padilla-Montero	Detecting non-stationary dynamics in supersonic twin jets by modal decomposition of high-speed schlieren images	20	
14:30	M. Raiola	Wavepackets eduction in turbulent jets using Hilbert POD	32	
14:45	A. Gesla	Vortex breakdown of a swirling jet	31	
15:00	L. Franceschini	Identification and reconstruction of high-frequency fluctuations evolving on a low-frequency base-flow	57	
15:15	N. Puff	Lifecycle Statistics of Cavitating Structures	61	
15:30		<i>Coffee break</i>	15:30–16:00	
16:00	Petronio Nogueira & Olivier Marquet	Round Table 1 — How far can reduced-order modelling take us?		
19:00		<i>Reception at Schleusenkrug</i>	19:00–21:00	

Thursday, 2 July 2026

Time	Presenter	Title	#	
Session 4 — Wave Dynamics and Coherent Structures in Compressible Flows				
09:00	F. Pagaud	Chirality of azimuthal aeroacoustic instability in axisymmetric cavity	08	P. Nogueira
09:15	C. Bogey	Numerical modelling of acoustic waves guided in a jet	09	
09:30	G. Lu	Global stability analysis of twin planar jets	14	
09:45	J.-C. Robinet	Linear PSE modelling of wavepackets in installed jets	25	
10:00	T. Bergeon	Global linear stability and resolvent analyses of over-expanded nozzle	46	
10:15	P. Jordan	Jet–edge interaction tones: a stochastically forced Stuart–Landau Oscillator?	65	
10:30	S. Demange	A low-order model of the coherent structures driving airfoil broadband trailing-edge noise	66	
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Session 5 — Coherent Structures in Fluid-Structure and Multiphase Systems				
11:15	J. Sierra-Ausin	Exceptional points in flutter and Vortex-Induced-Vibrations	37	O. Marquet
11:30	E. Martini	Effects of flexibility in airfoil self-noise	64	
11:45	Y. Goodwin	Space-time resolved coherent structures of LEVs on a 6-axis robotic flapper	27	
12:00	M. Chiatto	On the analysis of vortex and particles dynamics in a square microfluidic T-junction	33	
12:15	E. Pratschke	Coherent structures in multirotor hover flight	35	
12:30	C. Cardinale	Vortex instabilities leading to turbulence in slender delta wings	43	
12:45	Lunch break		12:45–14:15	
Session 6 — Coherent Structures in Reacting Multiphysics Flows				
14:15	P. Sirmalla	Global instability and non-modal mechanisms of an inductively coupled plasma jet	02	W. Polifke
14:30	S. Nandi	Mean field resolvent analysis based modeling for the flame transfer function	24	
14:45	L. Lesshafft	Interaction between thermoacoustic and hydrodynamic instabilities in a bluff-body wake inside a channel	42	
15:00	P. Brokof	Flow oscillators vs. amplifiers in thermoacoustic instabilities – a global weakly nonlinear approach	58	
15:15	A. R. Talasikar	Modeling of Reaction Dynamics in a Turbulent Hydrogen-Air Slot Flame Using Resolvent Analysis	59	
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16:00	Oliver Schmidt & Miguel Mendez	Round Table 2 – Data-driven discovery of coherent structures: from spectral methods to AI		
17:00	Boat Trip and Dinner		17:00 onwards	

Friday, 3 July 2026

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Session 7 — Reduced-Order Models for Prediction and Control				
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09:45	Y. Song	Data-Driven Optimal Harmonic Response and Resolvent Analysis of Turbulent Channel Flow	01	
10:00	J. S. Kern	Control-then-Reduce approach to optimal control using Dynamical Low-Rank Approximation	21	
10:15	Y. Kim	Data-driven oscillator-based modeling and prediction of multi-frequency turbulent flows	03	
10:30	L. Freire	Spectral Proper Orthogonal Decomposition of a turbulent channel flow from a coarse Wall-Modeled LES	55	
10:45	Coffee break		10:45–11:15	
Session 8 — Modal Decomposition and Structures Identification in Complex Flows				
11:15	A. Zarri	Toward a multiscale resolvent framework for unsteady and aperiodic flows	05	P. Jordan
11:30	Q. Huynh	Characterisation of coherent structures in chevron jets	10	
11:45	D. G. Smith	Analysis of the helical and flapping modes in screeching round jets using background-oriented schlieren	15	
12:00	M. Navarro-González	Dual-Time SPOD for experimental identification of spatio-temporal pattern	26	
12:15	H. Kalyankar	On Self-similarity of a Leading Edge Vortex	22	
12:30	Lunch break		12:30–14:00	
Session 9 — Physics-Informed Inference and Data Assimilation				
14:00	J. M. Reumschüssel	Bayesian inference of model parameters for quantitatively correct CFD modeling of a reacting flow	04	M. Juniper
14:15	J. I. Rawden	Improving Physics-Informed Neural Network Inference for Turbulent Pollution Modelling Through Nonlinear Normalisation of Mean Flow Data	18	
14:30	V. Mons	An adjoint-based Bayesian approach to address non-parametric uncertainties in Reynolds-Averaged Navier-Stokes modeling	19	
14:45	U. Cadambi Padmanaban	Efficient and interpretable mean flow data assimilation of porous plates	28	
15:00	C. Namuroy	Adjoint-accelerated Bayesian inference of two-equation turbulence models from noisy Flow-MRI data	41	
15:15	Z. Wang	Multimodal Learning for Fluid Flows: Joint Representation and Bidirectional Inference from Heterogeneous Measurements	52	
15:30	I. Tirelli	Event-Driven Flow Reconstruction via Physics-Informed Spiking Neural Networks	53	
15:45	Awards and Goodbyes			



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Data-Driven Optimal Harmonic Response and Resolvent Analysis of Turbulent Channel Flow

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Keywords: turbulence modelling, resolvent analysis, data-driven method, flow control

Resolvent analysis provides an input–output framework for interpreting coherent structures in wall turbulence, but it is most often used by treating the nonlinear term as unknown forcing. In this presentation, we focus on a comparatively less explored scenario, where the forcing is prescribed as an explicit external body force and the coherent motion is described within the triple decomposition [1] using the linearised Navier–Stokes operator with eddy viscosity (eLNS). Building on the external forcing formulation of Hwang and Cossu [2], we develop an approach based on DNS to design optimal harmonic forcing and to identify the corresponding coherent response without any ad-hoc model (i.e. eddy viscosity). The first six forcing modes are computed from the eLNS at prescribed (k_x, k_z, ω) (k_x , k_z and ω are the streamwise wavenumbers, spanwise wavenumbers and the frequency respectively) and applied in DNS of turbulent channel flow at $Re_\tau = 100$. Small amplitude forcing and ensemble averaging are used to isolate the linear response. By solving a generalised eigenvalue problem, the optimal linear combination of specified responses is identified to maximize the DNS-based resolvent norm. Finally, the frequency response of the eLNS operator is evaluated by sweeping ω and comparing the resulting DNS-based resolvent norms. The results show that, for selected k_x , k_z , the DNS-based resolvent norm peaks at $\omega \neq 0$, which does not coincide with that predicted by the theoretical eLNS operator. In the presentation, a detailed discussion on the approach we developed will be provided, including the assessment of the previous eddy viscosity model using the directly calculated Reynolds stress with DNS.

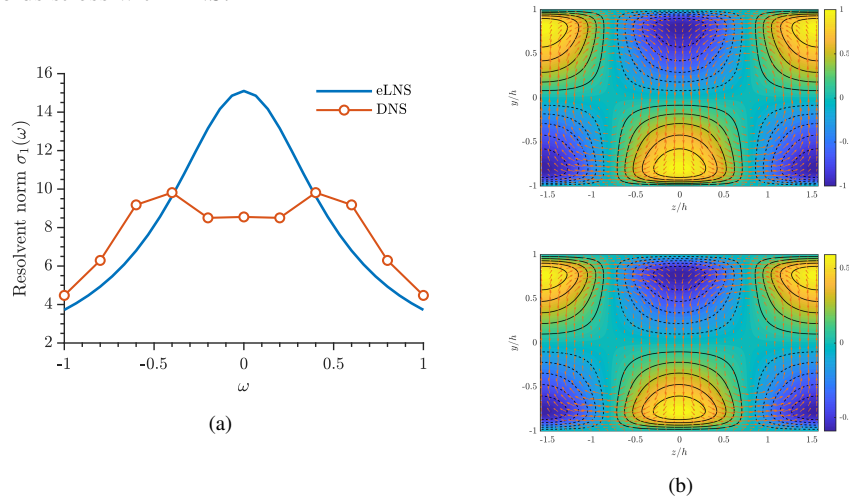


Figure 1: (a) The first resolvent norm σ_1 as a function of ω . The blue solid line represents the theoretical eLNS prediction peaking at $\omega = 0$. Orange circles correspond to DNS data. (b) Cross-stream ($y - z$ plane) views of the streamwise velocity response. Top: The normalised baseline mode predicted by eLNS at $\omega = 0$. Bottom: The optimal response structure identified via the data-driven approach.

References

- [1] W. C. Reynolds and A. K. M. F. Hussain. The mechanics of an organized wave in turbulent shear flow. part 3. theoretical models and comparisons with experiments. *Journal of Fluid Mechanics*, 54(2):263–288, 1972.
- [2] Y. Hwang and C. Cossu. Linear non-normal energy amplification of harmonic and stochastic forcing in the turbulent channel flow. *Journal of Fluid Mechanics*, 664:51–73, 2010.



EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
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Global instability and non-modal mechanisms of an inductively coupled plasma jet

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Keywords: Plasma jet, ICP, MHD flow, Global linear modes, Global stability boundary.

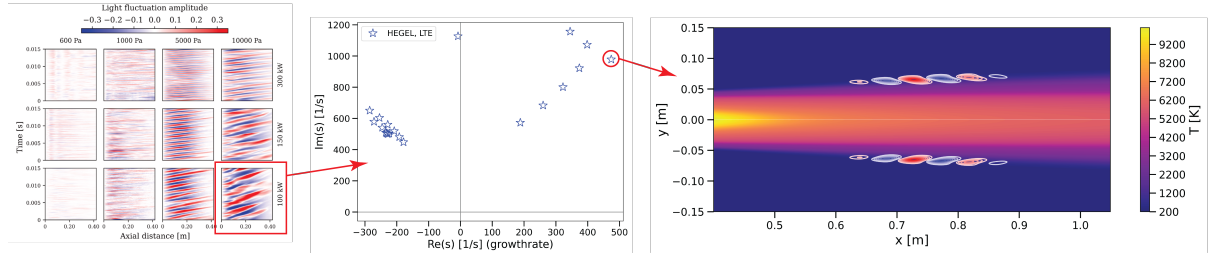


Figure 1: (Left) Space-time diagrams of emitted light along ICP centerline across $\mathcal{P}$ – P_c space. (Center) Partial eigenvalue spectrum at the 100 kW condition. (Right) Most unstable eigenvector and mean temperature field.

Inductively Coupled Plasma (ICP) wind tunnels are commonly used for experiments and tests of heat shield materials in hypersonic and near re-entry environments. Because the inherent dynamics of an ICP jet directly affect the flow field and heat flux seen by a model placed within it, it is imperative that the jet's dynamics be fully characterized across the facility operating range. In this work, we study the global stability and non-modal characteristics of UIUC's 350 kW ICP jet in both the local thermodynamic equilibrium (LTE) and non-LTE (NLTE) regimes to provide mechanistic explanations for the jet's observed behavior [1].

An ICP facility heats the working gas using electromagnetic induction. The thermal plasma jet is generated within a cylindrical torch and exhausted into a settling chamber through a nozzle. The jet exit centerline temperature is of the order 10^4 K with significant chemical and electronic reactions in the fluid. The thermo-chemical effects are modeled using an LTE fluid model when local equilibrium is justified, or a NLTE non-equilibrium fluid model to account for finite rate chemical and electronic dynamics. The ratio of the centerline jet density and temperature to those on the jet boundary is approximately 100, and the jet exit velocity is of order 10^3 m/s, thus generating severe axial and radial gradients of these quantities that are known to destabilize low-density round jets [2].

We study the global stability and non-modal characteristics of UIUC's 350 kW ICP plasma jet over a range of torch power $\mathcal{P}$ and chamber pressure P_c conditions using an 11-species air model. We obtain the linear operator by numerically linearizing the non-linear fluid model [3] which includes the electromagnetics of the torch coils generating heat via Joule heating, the co-annular torch gas inlet swirlers, the (N)LTE thermodynamic fluid model, and the ICP tunnel geometry. This general approach allows us to work with the complex fluid models and multi-dimensional flow field, and sample results are in Figure 1. Using this technique, we obtain the global stability curves in the $\mathcal{P}$ – P_c parameter space of the ICP facility and develop a mechanistic understanding of the jet's physical instability and amplification mechanisms.

References

- [1] Capponi, L., Padovan, A., Elliott, G. S., Panesi, M., Bodony, D. J., and Panerai, F. Multi-domain analysis and prediction of the light emitted by an inductively coupled plasma jet: influence of torch power and chamber pressure on jet dynamics through high-speed imaging. *Experimental Thermal and Fluid Science*, Vol. 157(111232).
- [2] Lesshafft, Lutz and Huerre, Patrick. Linear impulse response in hot round jets. *Physics of Fluids*, 19(2), 2007.
- [3] Kumar, Sanjeev, Munafò, Alessandro, Bodony, Daniel J. and Panesi, Marco. Numerical analysis of three-dimensional magneto-hydrodynamic effects in an inductively coupled plasma wind tunnel. *Journal of Physics D: Applied Physics*, 58(34):345208, Aug 2025.



Data-driven oscillator-based modeling and prediction of multi-frequency turbulent flows

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Keywords: Reduced-order modeling, Data-driven method, Turbulent flows.

Phase-reduction analysis reduces high-dimensional complex flow physics to simple oscillator models, providing valuable physical insights into understanding the perturbation dynamics of periodic fluid flows [1]. Recently, it has been used to theoretically predict synchronization conditions between fluid flows and structural motion [2] as well as to develop control strategies [3, 4]. However, previous applications of phase-reduction analysis are limited to laminar flows due to challenges in addressing chaotic flow behavior induced by multiple dominant frequencies with broadband spectra, such as turbulent flows in realistic engineering problems that exhibit multiple frequencies. In this study, we propose a data-driven framework that models unsteady flows with oscillators reflecting the dominant oscillatory flow components. Using autoencoders, we extract latent oscillators by compressing a time series of flow snapshot data. The dynamics of extracted oscillators are modeled by employing a neural network, which can offer an accurate long-term prediction of the oscillatory behavior of turbulent flows combined with an observation-based correction term. We verify that the developed framework can successfully reduce the oscillatory dynamics of turbulent flows to representative oscillators by applying it to a supersonic turbulent cavity flow, one of canonical multi-frequency turbulent flows. The proposed method further extends phase-reduction analysis for more complex flows.

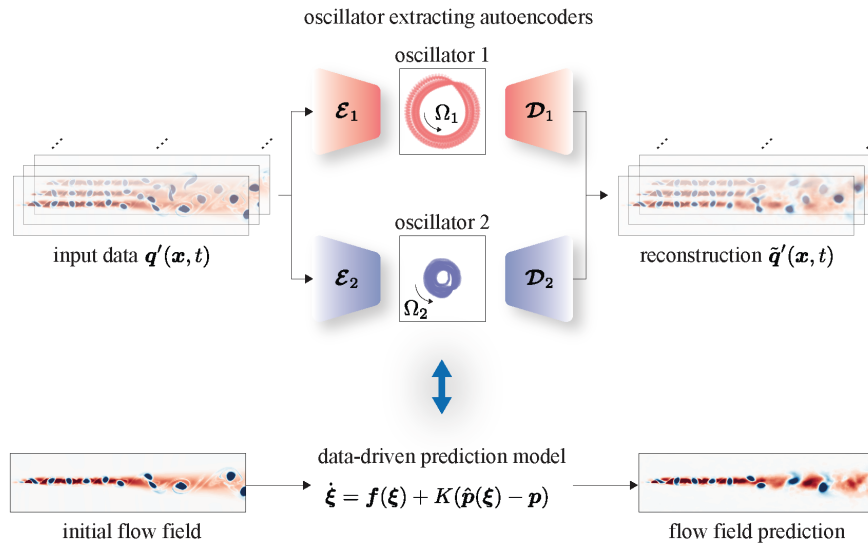


Figure 1: Data-driven framework for oscillator-based modeling of turbulent flows.

References

- [1] K. Taira and H. Nakao. Phase-response analysis of synchronization for periodic flows. *J. Fluid Mech.*, 846:R2, 2018.
- [2] Y. Kim, V. Godavarthi, L. V. Rolandi, J. T. Klamro, and K. Taira. Influence of three-dimensionality on wake synchronisation of an oscillatory cylinder. *J. Fluid Mech.*, 1001:A24, 2024.
- [3] K. Fukami, H. Nakao, and K. Taira. Data-driven transient lift attenuation for extreme vortex gust–airfoil interactions. *J. Fluid Mech.*, 992:A17, 2024.
- [4] V. Godavarthi, Y. Kawamura, L. S. Ukeiley, L. N. Cattafesta III, and K. Taira. Phase-based analysis and control of supersonic turbulent cavity flows. *arXiv:2502.05753*, 2025.



EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
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Bayesian inference of model parameters for quantitatively correct CFD modeling of a reacting flow

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Keywords: Bayesian inference, data assimilation, reacting flows, flame dynamics

Analysis and optimization of reacting flows is a complicated endeavour due to the intricate interaction of fluid dynamics and reaction chemistry. In general, studies on combustion cannot solely rely on simulations, as the usefulness of the results is inherently limited by the quality of the model, which is limited by errors from underlying model assumptions. These errors can be particularly high in models of reacting flows because simulations of flames typically require significant simplifications regarding chemical reactions and turbulence modelling to be feasible. Furthermore, some of the quantities that significantly affect combustor performance, such as wall temperatures and inflow conditions, can only be estimated with high uncertainty. An alternative approach to study combustion processes is through experiments. These are generally free from the aforementioned modelling limitations. However, experiments only allow limited access to flow variables, require elaborate setups and are subject to measurement errors. Additionally, designing experiments for optimization is complicated because variations are strongly limited by the experimental setup, which usually does not allow continuous changes in combustor geometry.

We present an approach that overcomes these limitations by combining experimental fidelity with computational comprehensiveness. It involves calibrating the parameters of a computational fluid dynamics (CFD) model for a reactive flow based on experimental data, using a Bayesian inference method. Prior assumptions about the model parameters are updated based on experimental data, yielding probabilistic parameter estimates that incorporate uncertainty from measurements and prior parameter estimates. When these estimates are plugged into the CFD model, a flow solution is obtained that balances data fit and deviations from prior parameter estimates in a rigorous manner. Propagating the parameter uncertainty through the model also yields an uncertainty estimate that can, for example, be used for design optimization.

The efficiency of the method is achieved through the use of the differentiable CFD code SU2[1]. This enables the computation of gradients of the model's discrepancy to the experimental data with respect to the model parameters by means of automatic differentiation. We apply the method to a laminar premixed methane flame, anchored to a centerbody and infer model parameters based on flame images. We compare the calibrated model's output to experimental velocimetry data and assess the capability of the calibrated model to predict the flame response to acoustic forcing.

References

- [1] Thomas D. Economou, Francisco Palacios, Sean R. Copeland, Trent W. Lukaczyk, and Juan J. Alonso. Su2: An open-source suite for multiphysics simulation and design. *AIAA Journal*, 54:828–846, 2016. ISSN 00011452. doi: 10.2514/1.J053813.



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Toward a multiscale resolvent framework for unsteady and aperiodic flows

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Keywords: resolvent analysis; unsteady flows; multiscale dynamics; coherent structures; modal decomposition

Resolvent analysis provides a powerful input–output framework for interpreting turbulent and transitional flows, identifying the most amplified coherent structures associated with a given linearized operator and forcing frequency.

In its standard formulation, resolvent analysis is closely related to spectral proper orthogonal decomposition (SPOD) and is naturally defined for statistically stationary flows governed by a steady or mean base state [1]. Recent interest in unsteady, modulated, and aperiodic flows has motivated extensions of modal and input–output analyses to time-dependent settings [2].

A notable step toward relaxing the statistical stationarity assumption is the wavelet-based resolvent analysis introduced by Ballouz et al. [3], which extends resolvent analysis to non-stationary flows through a joint time-frequency formulation. This approach enables the identification of transient amplification mechanisms with localized temporal and spectral resolution, but at the cost of repeated resolvent evaluations over many time-frequency windows, leading to a significant computational burden for high-dimensional systems. In this work, we introduce a *multiscale resolvent* (m-Resolvent) framework aimed at extending resolvent analysis to time-dependent linearized operators through a scale-based decomposition in time. Inspired by the multiscale proper orthogonal decomposition (mPOD) [4], the proposed approach separates the dynamics of a time-varying operator into distinct temporal bands using correlation-based scale separation, rather than time-localized windowing or wavelet transforms. For each temporal scale, a representative linear operator is constructed by weighting instantaneous operators over the full observation interval, yielding a scale-dependent resolvent operator. Standard resolvent analysis is then performed independently at each scale, producing spatial amplification mechanisms associated with distinct temporal dynamics. The temporal activity of each scale is quantified through time-dependent weights derived from the underlying correlation analysis. These weights provide a direct indication of when a given resolvent structure is dynamically relevant, or “active”, during the evolution of the flow.

Compared to wavelet-based resolvent formulations for non-stationary flows [3], the m-Resolvent framework avoids repeated time-localized operator inversions and yields spatial modes that are defined consistently over the full time horizon associated with each scale. This results in a computationally efficient and scale-separating formulation of the resolvent operator.

Ongoing work focuses on assessing the robustness of the scale-dependent operators in high-dimensional flows, with the aim of building a method that can analyze time-dependent linear operators, for example, obtained by unsteady RANS solutions.

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Causal significance of quadrant structures in channel turbulence**Peng Chen¹, Javier Jimenez¹**¹ School of Aeronautics, Universidad Politécnica de Madrid, 28040 Madrid, Spain

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Keywords: Causality, quadrant structure, wall-bounded turbulence

Quadrant structures (Qs) are believed to play a key role in momentum transfer [1] and in the self-sustaining mechanism of wall-bounded turbulence [2]. Their properties have been extensively studied since the 1970s [3]; nevertheless, their causal role in turbulence dynamics remains unclear. Thanks to advances in high-performance computing, particularly GPU acceleration, it has become possible to perform interventional experiments directly in turbulent flows [4]. In this project, we modify the velocity field within quadrant structures while keeping the rest of the flow unchanged. By monitoring the growth of perturbation energy, the causal significance of each type of structure is quantified. Our results show that Q4 structures are more significant than Q2 structures. Further analyses are conducted by conditionally averaging the perturbation energy over wall-attached and wall-detached cases, as well as other geometric classifications. The influence of structural dynamics is clarified by comparison with shifted-structure cases, in which the same modification is applied to a region of identical shape but at a random location. For wall-attached structures, the significance follows the sequence: short Q4 < short Q2 $\approx$ tall Q2 < tall Q4. Structural dynamics suppress dynamically irrelevant cases while enhancing the most significant ones. For wall-detached structures, the dominant factor determining significance is the time at which the structures attach to the wall. Two distinct temporal scales associated with this attachment process are identified. These results complement those in [5], which focused on the structure-less flow regions, and may be used to optimize flow-control strategies.

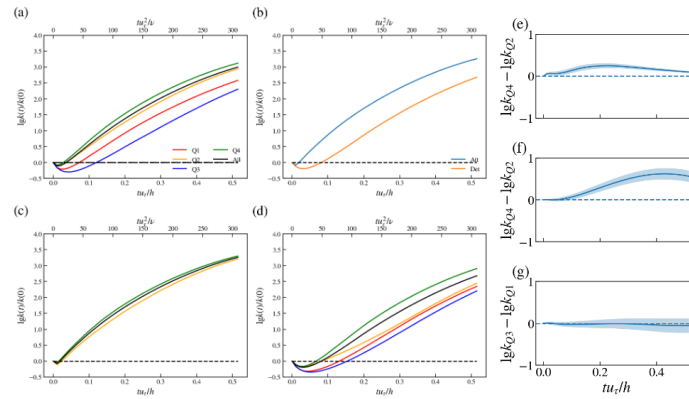


Figure 1: (a-d) Perturbation energy. (a) Conditioned on structure type; (b) Conditioned on wall-attached/wall-detached classification; (c) Attached structures and (d) Detached structures by type. (e-f) Log-mean of the difference and 95% confidence interval between (e) attached Q4 and Q2; (f) detached Q4 and Q2; (g) detached Q3 and Q1.

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Chirality of azimuthal aeroacoustic instability in axisymmetric cavity

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Keywords: Aeroacoustic instability, Large Eddy Simulation, Swirling flows, Axisymmetric cavity, Symmetry breaking.

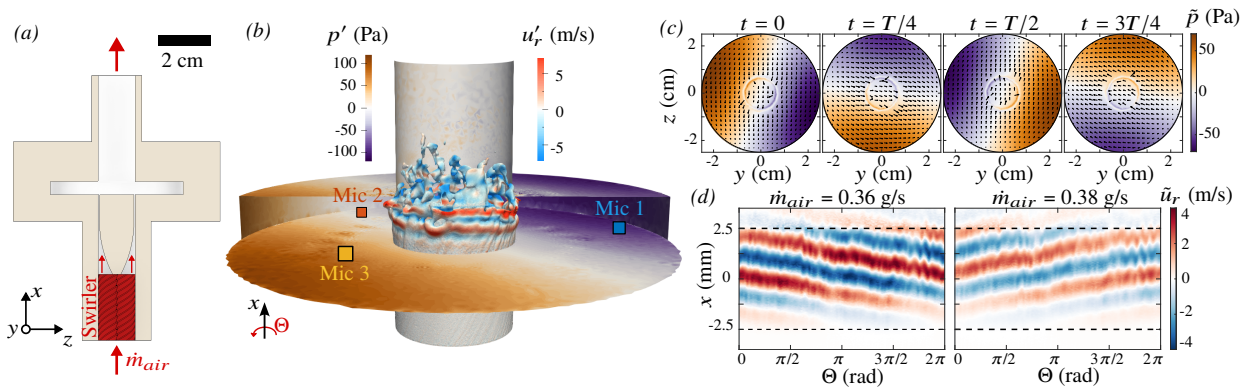


Figure 1: (a) Resonator cross-section. (b) Three-dimensional simulation output snapshot. (c) Phase-averaged pressure and velocity field in the cylindrical cavity. (d) Phase-averaged radial speed at the annular jet location.

The introduction of an air jet in an axisymmetric cavity can excite strong aeroacoustic instabilities. It causes intense vibrations in many industrial applications (gaseous flows in pipes, turbomachines...), thus leading to operation challenges and mechanical strain. This instability arises from a **feedback loop**: the application of a low Mach air jet in a cavity generates vorticity fluctuations via Kelvin-Helmholtz instability in a thin shear layer. They interact with the cavity acoustic eigenmodes, modulating back the flow itself. Recent research showed that in axisymmetric cavities, an azimuthal aeroacoustic instability (AAI) emerges from the constructive interaction between the azimuthal pressure wave and helicoidal oscillations of the jet [1]. However, the impact of an azimuthal flow on the emergence of coherent structures and the selectivity of quasi-degenerate azimuthal modes (standing vs. spinning) remains poorly understood in aeroacoustic and beyond (e.g. axisymmetric combustion chambers).

During this presentation, we will present the analysis of an AAI generated by a swirled annular air jet in a deep cylindrical cavity. Experiments using the resonator displayed in figure 1a demonstrate that low mass flow rates excite a self-sustained acoustic wave, which spins in the same direction as the azimuthal flow (**co-swirl mode**). This propagation direction reverses suddenly for flow rates beyond a specific threshold, leading to a **counter-swirl mode** without discontinuity in frequency or amplitude. Large Eddy Simulations of the compressible flow are performed to resolve the three-dimensional flow structures and interactions with the acoustic wave (Fig. 1b). The switch in chirality is reproduced with an excellent agreement, as shown by figures 1c and 1d where phase-averaged pressure and velocity are shown for the co-swirl ($\dot{m}_{air} = 0.36$ g/s) and counter-swirl modes ($\dot{m}_{air} = 0.38$ g/s). Two-dimensional Fourier Transform (2DFT) is used as a modal decomposition technique to characterize the coherent structures features. Additionally, by numerically introducing a new acoustically absorbing wall, instability growth rate is controlled and instability structural evolution over the transient regime is investigated. These results provide valuable insights into the impact of mirror symmetry breaking on the flow structures and acoustic mode selectivity.

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Numerical modelling of acoustic waves guided in a jet**C. Bogey, E. De Staercke**CNRS, Ecole Centrale de Lyon, INSA Lyon, Université Claude Bernard Lyon I,
Laboratoire de Mécanique des Fluides et d'Acoustique, UMR 5509, 69130 Ecully, France*Corresponding author: C. Bogey (christophe.bogey@ec-lyon.fr)***Keywords:** jet, acoustic propagation, guided jet waves, instability waves

The acoustic waves essentially confined in jets, called neutral acoustic waves or guided jet waves (GJW), have been shown to play a major role in the development of instability waves and coherent structures in jet flows. Their properties are usually described using linear stability analyses [1, 2]. It has been found that they can travel in the upstream or in the downstream directions and that they can be entirely or partially contained in the jet. They can be referred to as free-stream (FS) GJW in the first case and duct-like (DL) GJW in the second [3]. Complementarily, GJW can also be investigated by solving a problem of sound propagation in presence of a sheared flow, as in recent studies [4, 5]. This is the case in the present work where simulations are performed by solving the Euler equations to compute the waves radiated by an acoustic source placed inside or outside of a cylindrical shear layer for different Mach numbers M and source Strouhal numbers St_D . The objective is to identify and characterize the GJW generated in this way. For illustration, results are provided in figure 1 for $M = 0.95$ and a source on the jet axis. GJW are clearly observed both upstream and downstream of the source for $St_D = 0.95$ in figure 1(a). Their amplitudes obtained upstream of the source inside and outside of the jet are represented in figures 1(b,c) as a function of St_D . High levels emerge at the St_D of the zero-group-velocity (ZGV) GJW. The contributions of the different GJW, depending on their radial mode and on their FS or DL nature, are also presented.

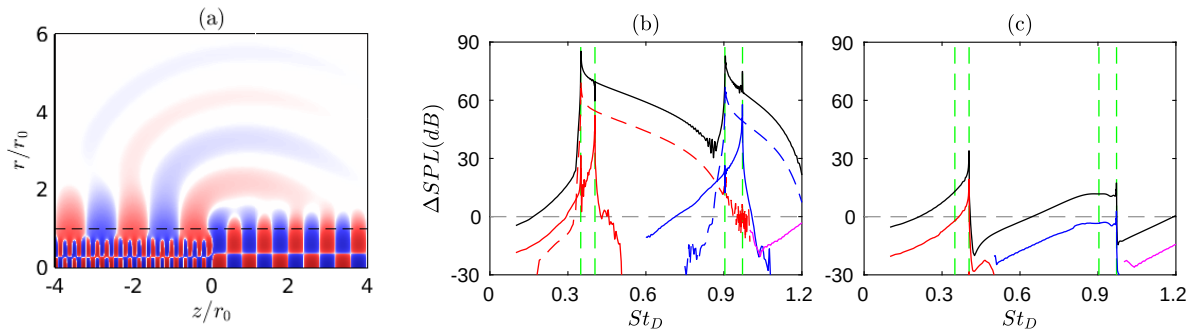


Figure 1: Source at $z = 0$ and $r = 0$ and $M = 0.95$: (a) pressure field for $St_D = 0.95$; — difference between SPL with and without flow at $z = -10r_0$ and (b) $r = 0$ and (c) $r = 2r_0$, contributions of (solid) FS and (dashed) DL GJW modes (red) $n_r = 1$, (blue) $n_r = 2$, (magenta) $n_r = 3$ using a -15 dB offset, - - - St_D of ZGV GJW.

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
Berlin, Germany 1–3 July 2026

Characterisation of coherent structures in chevron jets

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Keywords: Jet dynamics, coherent structures, linear modelling.

Coherent structures, particularly wavepackets, are known to play an important role in turbulent-jet noise generation [1–3]. The application of serrations (chevrons) have been shown to reduce jet noise relative to round nozzles, but the effect of these devices on the wavepacket structure is still unclear. Here, schlieren measurements were performed for a round jet and two chevron jets with different penetration angles over Mach numbers from 0.6 to 1.2. Spectral proper orthogonal decomposition is then used to extract the dominant coherent structures and quantify their modal energy and rank as functions of Mach number and frequency. A comparison between the leading modes of round and a high-penetration chevron jet at two representative frequencies ($St = 0.3$ and $St = 0.6$) are shown in figure 1.

Parabolised stability equations are used to interpret the experimental observations. By comparing the measured coherent structures with linear-instability-based predictions, we assess whether the dominant SPOD modes are consistent with linear dynamics and identify which predicted instability modes, or combinations of modes, are most strongly expressed in the jet. This combined experimental and modelling approach clarifies how chevrons modify coherent wavepackets, especially concerning their structure, energy and acoustic efficiency.

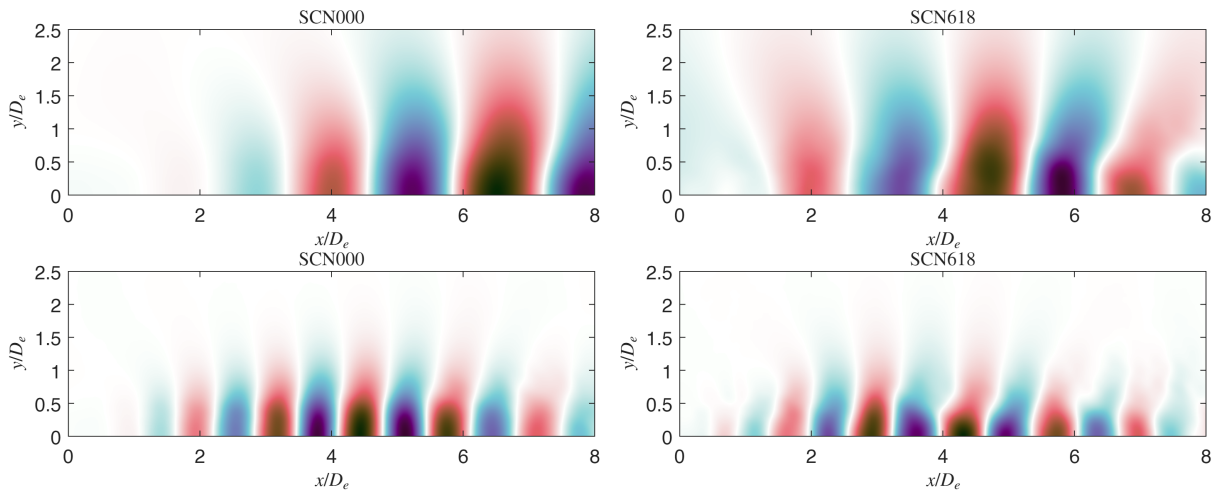


Figure 1: First SPOD mode at $St = 0.3$ (first row) and $St = 0.6$ (second row) of axisymmetric jet (SCN000) and high-penetration chevron jet (SCN618)

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
Berlin, Germany 1–3 July 2026

Restarts and sustainment of bursts in turbulence in minimal channels

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Keywords: Bursts in turbulence, self-sustaining process, linearised Navier-Stokes system.

For wall-bounded turbulence, the sustainment of bursts of wall-normal velocity has long been viewed as a manifestation of the more general self-sustaining process, which involves other flow structures, typically the streaks of streamwise velocity. However, studies in recent years (e.g. [1]) have challenged the picture of burst sustainment that directly depends on the presence of streaks, implying that the problem of burst sustainment needs to be approached without relying on specific *a priori* knowledge – or bias – regarding other structures.

In this study, we discuss the burst sustainment for turbulence in minimal channels within the framework of a linearised Navier-Stokes system with forces that encapsulate the nonlinear effects of all the other structures. Two generic questions are addressed. The first question is, for the forced linearised system itself, what conditions are required to yield solutions that exhibit burst restarts and sustainment? We pose three sets of optimisation problems to obtain the ‘minimal requirements’ for, respectively: restarting a decaying burst, full recovery to a burst-ready state, and sustaining periodic bursts. The optimal solutions exhibit several relevant features, including wall-normal split of spanwise eddies at a burst-decaying stage, counter-rotating eddies in a pre-burst latent period, and co-rotating eddies catching up and merging to yield a burst-ready state. The second question is, for real turbulence, what specific features of flows and nonlinear forces contribute to the observed burst restarts and sustainment? We project the real turbulence data onto a newly defined subspace, where the process of a burst restart is characterised by an increase of ‘burst potential’, and extract patterns of flows and nonlinear forces in this process. The patterns show some features similar to the forced linearised optimal solutions above, suggesting that these contributory features are manifestations of the real burst-restarting/sustaining structures.

This study is funded by the European Research Council under the Caust grant ERC-AdG-101018287.

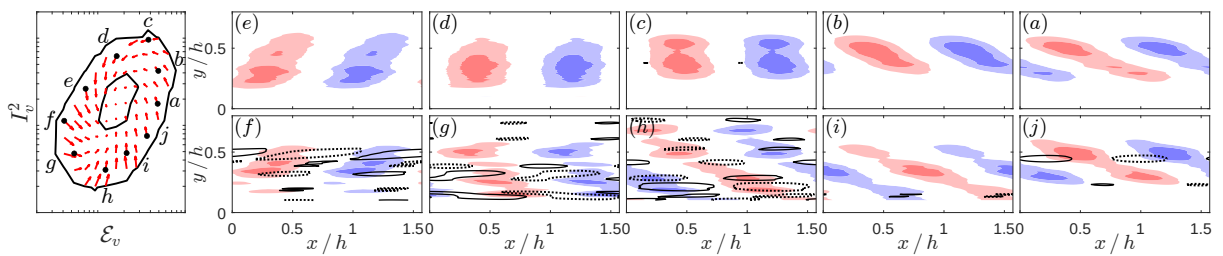


Figure 1: Patterns of flows and nonlinear forces conditioned to different stages in a burst cycle for the spatial Fourier mode with wavenumbers $k_x = 2\pi/L_x$ and $k_z = 0$ for turbulence in a minimal channel with length $L_x = \pi h/2$ and $Re_\tau = 950$. Red arrows in the left panel indicate mean displacements of states over a time interval $\Delta t = 0.05h/u_\tau$ in the intensity-potential (I_v^2 - E_v) subspace. The panels (a)-(j) correspond to the states marked in the left panel. The shades with colours red and blue represent clockwise and anticlockwise vorticities, respectively, and the solid and dashed contours represent clockwise and anticlockwise curl of nonlinear forces, respectively. The panels (a)-(e) conceptually visualise an Orr burst process whereas (f)-(j) visualise a burst restart process.

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
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Prediction of coherent structures in turbulent flames from sparse mean flow measurements: data assimilation and resolvent analysis

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Keywords: Turbulent reacting flow; Combustion; Resolvent analysis; Physics-informed neural networks.

Coherent structures in turbulent flames have received increasing attention in recent years, as their large-scale hydrodynamic motion is tightly linked to heat release fluctuations, frequency selection, and intermittent flame dynamics [1]. While resolvent analysis is a powerful tool for studying coherent flow structures, its application to reacting flows is more demanding because additional scalar variables, such as the mean density field and species concentrations, are required as inputs. These scalars strongly influence instability predictions, yet they are difficult or even impossible to measure accurately in experiments. Here, we present a complete workflow that enables physics-based modeling of coherent structures in premixed turbulent flames using mean field data derived from sparse experimental measurements. The prediction framework requires only the time-averaged velocity field obtained from PIV measurements. A physics-informed neural network (PINN) is applied to preprocess the PIV measurement for the subsequent linearized analysis; specifically, it assimilates the unknown density field from velocity measurements and smooths the velocity field [2]. A dual-step PINN strategy is further developed to robustly reconstruct the turbulent eddy viscosity [3]. Nonlinear chemical source terms are closed by leveraging a turbulent combustion model, in which a novel expression of the related linearized chemistry removes singularities. Using the assimilated mean, the resolvent model accurately predicts turbulent structures related to coherent flame motions, as observed through time-resolved measurements.

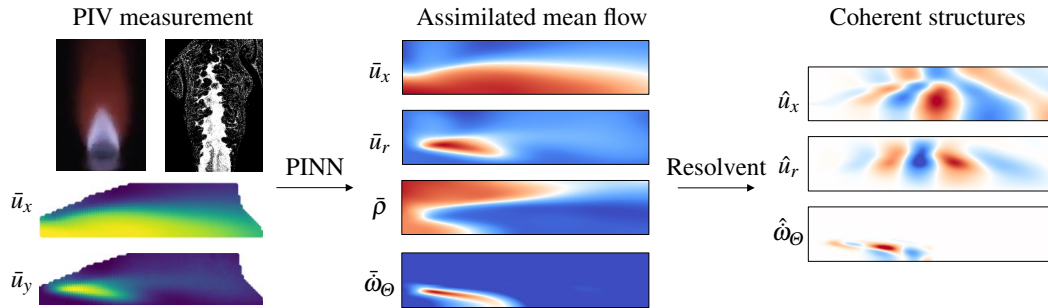


Figure 1: Prediction workflow.

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Global stability analysis of twin planar jets**G. Lu¹, J. L. Weightman¹, K. Oberleithner², D. M. Edgington-Mitchell¹, P. A. S. Nogueira¹**¹ Monash University, Australia, ² Technische Universität Berlin, Germany

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Keywords: Stability analysis, screech, rectangular twin jets

This work aims to evaluate a global stability of an $AR = 2$ rectangular overexpanded twin-jet system. In non-ideally expanded jets, aeroacoustic resonance generates a high-amplitude tone known as screech [1]. Screech is manifested through a triadic interaction mechanism involving the Kelvin-Helmholtz wave, the quasi-stationary shock-cell structure, and the guided jet mode. When two identical isolated jets are placed in close proximity, the resonance intensifies due to the coupling between the jets [2]. The coupling behaviour between the two jets can vary, ranging from a steady coupling, to rapid switching in the coupling symmetries, or complete decoupling between the jets [3]. This study will analyse how the coupling dynamics in rectangular twin-jet is closely related to the minor asymmetries in the flow field, linking the resonant behaviour observed in the global stability with the characteristics of the waves in the locally parallel framework. Following the work of Rodríguez [4], the twin jet mean flow is modelled as planar jets, combining the velocity fields of two isolated jets calculated from particle-image velocimetry. This method enables us to artificially introducing shear-layer thickness offsets between the jets, and examine the sensitivities of the coupling mode to flow asymmetries. Sample preliminary results are shown in figure 1, where a clear resonant mode is obtained from the global stability of the twin jets. The standing wave behaviour and general shape of the mode are in good agreements with previous results in the literature for these jets.

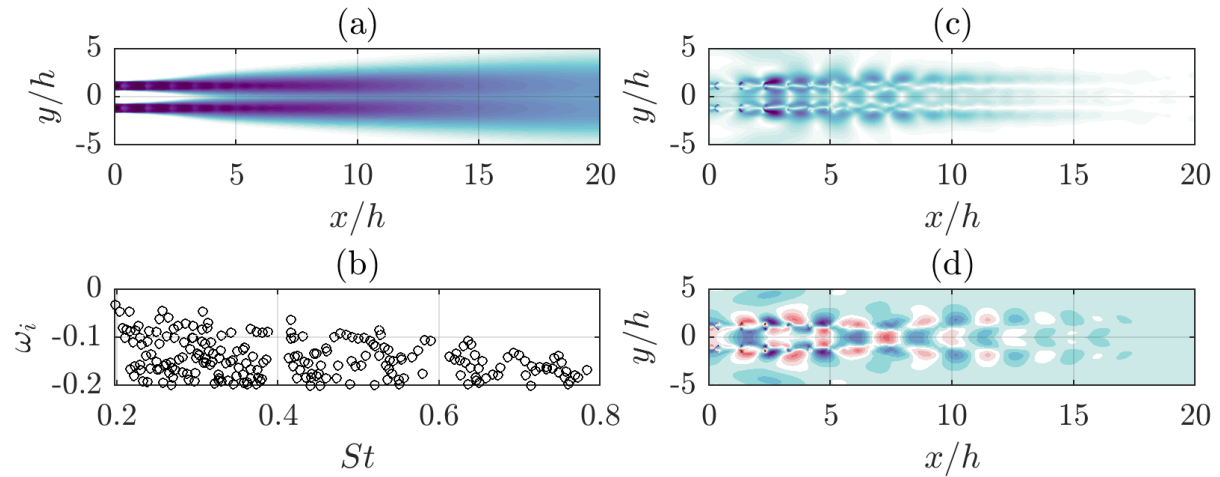


Figure 1: $AR = 2$ rectangular twin-jet at $NPR = 2.5$ with inter-nozzle spacing of $s/D = 2.22$. The baseflow (a) and the associated eigenspectrum (b), the absolute (c) and real (d) component of the global mode associated with screech.

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Analysis of the helical and flapping modes in screeching round jets using background-oriented schlieren

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Keywords: Jet screech, background-oriented schlieren, reduced-order modelling

This work investigates the structure of $m = \pm 1$ azimuthal modes in screeching round jets through decomposition of data from a 15-camera tomographic background-oriented schlieren (BOS) experiment. The measurements are taken at a nozzle pressure ratio of 3.4, where the “C” screech mode is active and is known to be associated with a helical coherent structure [1]. The azimuthal Fourier transform and a modified version of proper orthogonal decomposition (POD) are used to extract hydrodynamic structures representative of travelling $m = +1$ and $m = -1$ modes (figure 1 a,b). Over the duration of the experiment, these modes interact to produce three distinct regimes of operation, as shown in figure 1e. In two of these regimes (coloured in orange and blue), one mode dominates over the other, together these describe a helical structure that switches its direction of rotation, similar to results found in [2]. The third regime (circled in purple) shows both the $m = +1$ and $m = -1$ modes active with similar amplitude, indicative of a flapping mode. Analysis of the phase relationship between the modes in this regime shows that the jet flaps along a preferred plane, contrary to the typical precession of the flapping mode in a round jet. As part of this work, we propose a POD-based methodology for differentiating BOS measurements of helical, precessing flapping, and fixed-axis flapping structures from a single-camera perspective.

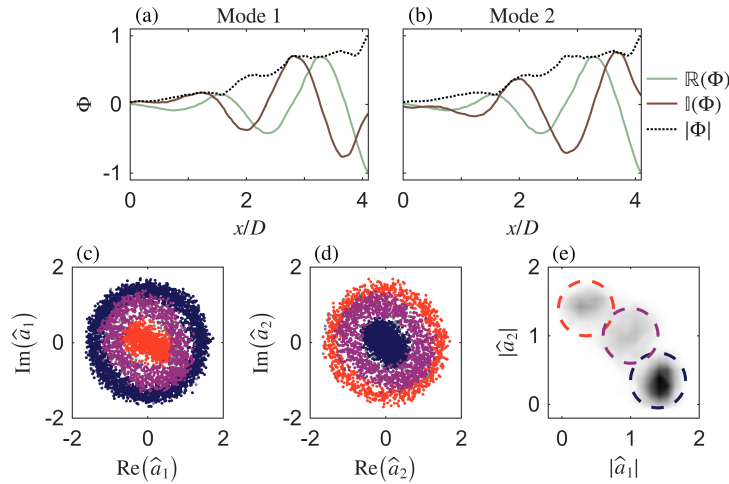


Figure 1: Results of POD on the complex $m = 1$ data from the 15-camera tomographic BOS experiment. Slices along $r/D = 0.7$ of mode 1 (a) and 2 (b). Temporal coefficients of modes 1 (c) and 2 (d), coloured based on the position of each snapshot in (e). 2D histogram (e) of the relative radius of the mode 1 and 2 temporal coefficients.

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Mean resolvent analysis of a stochastic axisymmetric jet.

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Keywords: Mean resolvent, Jets, Linear response

Classical resolvent analysis of turbulent flows is based on the singular value decomposition of the operator $\mathbf{R}_{\bar{\mathbf{Q}}} = (i\omega\mathbf{I} - \mathbf{J}_{\bar{\mathbf{Q}}})^{-1}$, where $\mathbf{J}_{\bar{\mathbf{Q}}}$ is the Jacobian of the Navier–Stokes equations linearized about the mean flow. For each forcing frequency ω , this framework provides optimal forcing and response modes, as well as associated energy gains. However, the approach is known to be formally ill-posed [1]: the poles of $\mathbf{R}_{\bar{\mathbf{Q}}}$ depend on the chosen formulation of the compressible Navier–Stokes equations. An alternative and rigorous framework has recently been proposed in the form of the mean resolvent operator $\mathbf{R}_0$ [2]. Instead of linearizing about the mean flow, the dynamics are linearized along unsteady trajectories, leading to an operator that predicts the mean linear response of the unsteady flow (Figure 1(a-b)). Importantly, the poles of $\mathbf{R}_0$ are intrinsic and independent of the governing-equation formulation [2]. The formalism is rooted in the well-established linear response theory of statistical physics [3, 4]. Recent developments have demonstrated the feasibility of this approach for periodic flows and highlighted, in some cases, significant differences between classical and mean resolvent analyses in terms of optimal gains and mode shapes [5]. The present work aims at extending mean resolvent analysis to a stochastically forced axisymmetric jet at $M = 0.1$ and $\text{Re}_D = 1000$ (Figure 1). The methodology relies on time-averaged harmonic responses extracted from linearized simulations forced along stochastic trajectories, enabling the evaluation of matrix–vector products with $\mathbf{R}_0$ without explicitly forming the operator. A projection strategy onto a low-dimensional subspace spanned by optimal modes of the classical resolvent $\mathbf{R}_{\bar{\mathbf{Q}}}$ is used to solve the associated eigenvalue problem at an affordable computational cost, as in [5].

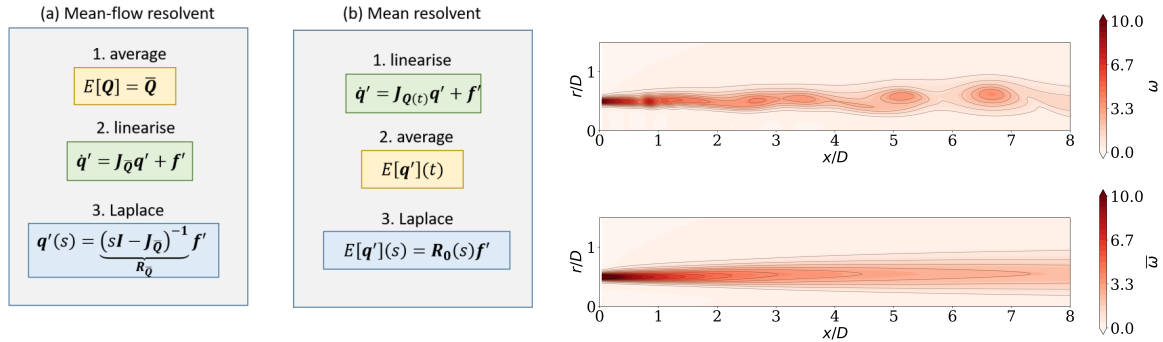


Figure 1: Left: (a) Resolvent about mean flow (b) Mean resolvent [5]. Top right: instantaneous snapshot of the vorticity ω of the stochastically forced jet. Bottom right: mean vorticity $\bar{\omega}$.

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On the role of eddy viscosity dynamics in mean-flow stability and resolvent analysis

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Keywords: Linear analysis, Reduced-order modeling, Turbulence closures, Triple decomposition

Mean-flow stability and resolvent analysis are popular physics-driven approaches for reduced-order modeling of coherent structures in turbulent shear flows. These techniques project high-dimensional measured or simulated flow data onto the Reynolds-averaged Navier–Stokes (RANS) equations and compute the ensuing linear dynamics about a time-averaged reference state, often further invoking a simplified or decoupled turbulence closure. However, projection, linearization, and closure reduction all introduce potentially significant errors that cannot be quantified *a priori*. Building on recent related efforts [1–3], this work formulates a continuation and bifurcation analysis of the RANS system to examine linearized eddy viscosity dynamics about turbulent mean flows. Such an approach ensures that (i) the reference state is a bona fide solution of the full RANS system and (ii) that the linear dynamics are a fully consistent asymptotic expansion of the closure model. Consequently, errors associated with both the projection of the true dynamics onto the RANS system and the use of inconsistent or decoupled turbulence closures may be eliminated, allowing their respective roles to be isolated and studied independently. The results demonstrate that eddy viscosity perturbations introduce nontrivial velocity couplings when non-algebraic eddy viscosity models are employed, yielding enriched dynamics that can significantly modify mean-flow stability and resolvent predictions.

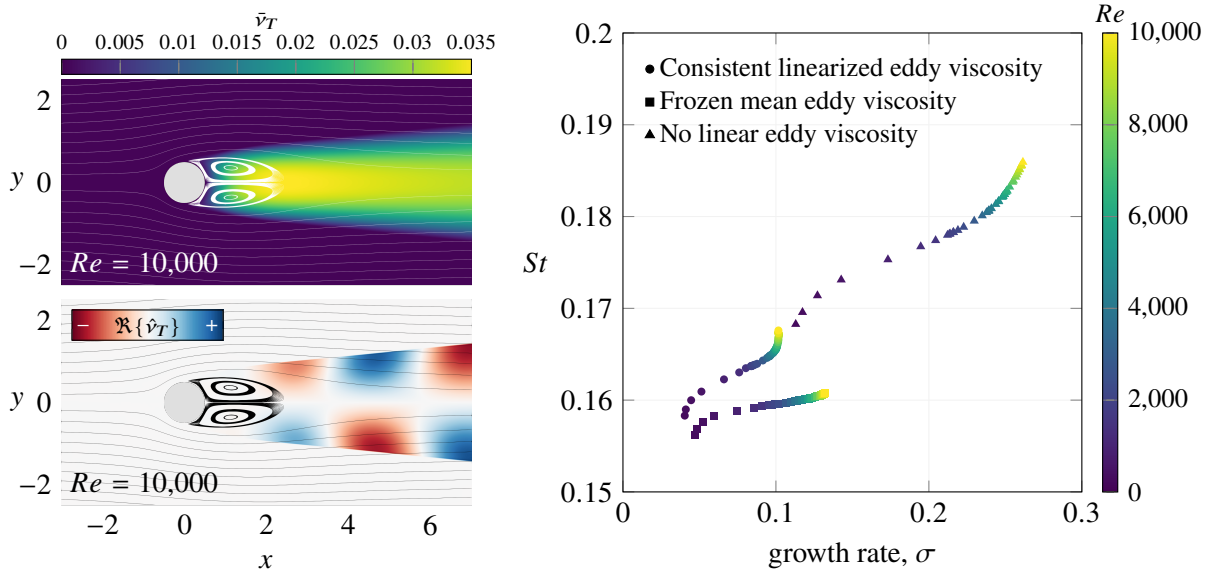


Figure 1: Visualizations of the mean eddy viscosity field $\bar{\nu}_T$ (top-left) and the real part of the eddy viscosity perturbation from the leading eigenmode $\Re\{\hat{\nu}_T\}$ (bottom-left) at $Re = 10,000$ for the RANS flow past a cylinder using the Spalart–Allmaras turbulence closure. Eigenspectra (right) are computed about the mean flow with (●) a fully consistent linearization of the RANS system, (■) a frozen mean eddy viscosity (with no viscosity perturbation), and (▲) a molecular viscosity only.

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
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Improving Physics-Informed Neural Network Inference for Turbulent Pollution Modelling Through Nonlinear Normalisation of Mean Flow Data

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Keywords: Machine Learning, Turbulence, Pollution, Normalisation.

Data-driven modelling has established itself as a dominant presence within the fluid dynamics community, particularly when considering turbulent flows. Physics-informed neural networks (PINNs) offer a complementary approach to address the problem of turbulence alongside traditional methods such as variational data assimilation and resolvent analysis [1]. Despite recent advances in PINN research, a persistent limitation of network parameter bias remains due to extreme variation in the magnitudes of the physical fields of interest. This often results in unreliable training cycles and the failure to capture important flow features in regions of strong turbulence. When turbulent flows containing passive scalars are considered, the issue is exacerbated due to the extremely small values associated with scalar concentrations, which are juxtaposed with strong turbulent mixing fields [2].

Through nondimensionalisation of the governing equations [3], as well as careful linear and nonlinear normalisation of the training data, we demonstrate that PINNs can be used as a tool for inferring turbulent fields/statistics from mean flow data, eliminating the requirement for large time-resolved datasets. Nonlinear normalisation is applied to a PINN trained using DES data of a turbulent wall-mounted cube flow with upstream passive scalar emission. We show that the normalisation procedure assists the PINN in inferring turbulent mixing fields, which can be decomposed into individual Reynolds stresses/turbulent scalar fluxes. The ability to infer turbulent scalar fluxes from mean-flow data may influence future urban pollution modelling strategies with additional refinement to the PINN methodology.

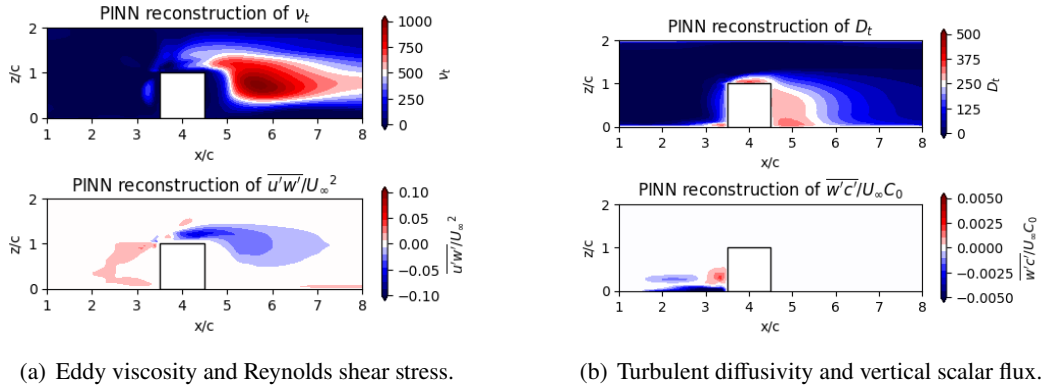


Figure 1: PINN reconstructions of turbulent fields and associated stresses/fluxes.

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An adjoint-based Bayesian approach to address non-parametric uncertainties in Reynolds-Averaged Navier-Stokes modeling

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Keywords: turbulence modeling, Bayesian inference, data assimilation, uncertainty quantification

Turbulence modeling is an essential tool to obtain affordable predictions of complex flows. In particular, Reynolds-Averaged Navier-Stokes (RANS) modeling may be considered to obtain mean-flow predictions at low computational cost. The thus obtained fixed points of the RANS equations may then be exploited in mean-flow-based linear analyses to characterize the development of coherent flow structures. However, deficiencies in RANS modeling may hinder the potentialities of such an approach, motivating the consideration of data-assimilation techniques to enhance the fidelity of RANS predictions [1]. In the present work, we develop an adjoint-based Bayesian approach [2–4] that not only provides improved mean-flow predictions from limited data, but also quantifies the associated uncertainties. The present approach is designed to rigorously deal with non-parametric modeling deficiencies, namely to infer spatially-dependent corrective terms, and relies on a high-order adjoint technique to accurately predict posterior statistics. This framework is in particular applied to the turbulent flow in a converging-diverging channel [5] where pointwise velocity data are employed to improve a RANS-based mean-flow prediction and evaluate the remaining reconstruction errors.

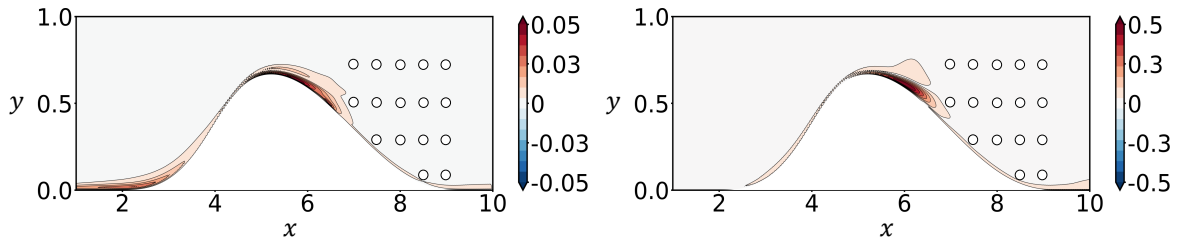


Figure 1: Left: predicted standard deviation in the reconstructed mean streamwise velocity based on pointwise velocity data at the locations marked by white dots; right: actual remaining reconstruction errors with respect to full DNS data.

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation

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Detecting non-stationary dynamics in supersonic twin jets by modal decomposition of high-speed schlieren images

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Keywords: twin jets, screech, OVMD, SPOD, schlieren.

Turbulent jets are known to support different modes of oscillation in the form of large-scale coherent structures. In practice, depending on the operation conditions, multiple modes can either co-exist, or the system can switch back and forth between different modes. When a twin jet configuration is considered, the dynamics can become even more complex as new forms of jet-to-jet mode coupling can occur. In this work, the modes of oscillation sustained by supersonic round twin jets are investigated using high-speed schlieren visualizations and two different data-driven modal decomposition techniques: SPOD informed with momentum potential theory [1] and orthogonalized variational mode decomposition (OVMD) [2, 3]. This is done with the purpose of extracting coherent information about the statistically-stationary dynamics of the system but also about transient events that can shed light into the mechanisms of mode switching.

A common example is screech mode staging. Although presenting a well-defined frequency due to their tonal nature, screech modes are not unique. For the studied configuration, the first mode staging occurs for $M_j \approx 1.3$. Modal decompositions for $M_j = 1.28$ reveal a single screech mode with constant amplitude over time, corresponding to symmetrically coupled toroidal oscillations consistent with screech stage A. However, for $M_j = 1.3$ (see figure 1), the oscillations are dominated by a coupled varicose flapping of the jets corresponding to stage B, followed by a second, weaker screech tone corresponding once again to stage A. The amplitude envelope of these modes presents a low-frequency beating, active only for some time intervals, and the system is found to alternate between a coupled oscillation of both jets and independent oscillations.

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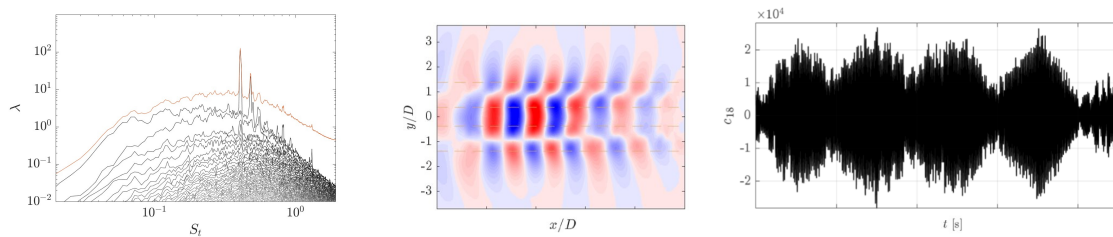


Figure 1: Results for $M_j = 1.3$: SPOD spectrum (left); varicose flapping mode associated with the dominant screech tone ($St = 0.405$) obtained via OVMD (center) and its temporal coefficient (right).

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Control-then-Reduce approach to optimal control using Dynamical Low-Rank Approximation.

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Keywords: Linear optimal control, Reduced-order modelling, Dynamic Low-Rank Approximation.

The Linear Quadratic Regulator (LQR) is a classic benchmark for model-based state-feedback control for continuous-time dynamical systems represented by Linear Time-Invariant (LTI) models including the system dynamics A , actuators B to apply the control law and sensors C to measure the partial system state. Central to both LQR and Kalman filtering is the solution of matrix-valued Algebraic Riccati equations of the general form

$$A^T P + PA - PB^T R^{-1} B P + Q = 0, \quad (1)$$

where $(\cdot)^T$ denotes transposition, R is the control cost and Q is the state cost. While the theory of optimal control is well established, the application of optimal control to very high-dimensional problems such as those encountered in fluid mechanics is a persistent problem as the full Riccati-type matrix equations that need to be solved for the computation of the controller gains are intractable. However, in many cases the solutions to the Riccati equations are of low rank and there are essentially two alternatives to take advantage of this fact. The first, *Reduce-then-Design*, consists of first constructing a reduced-order model for the system dynamics, either directly using the matrix representation or using a low-rank data-driven approaches, and then constructing a controller using standard tools for the small-scale Riccati equations of the reduced problem. The second approach, *Design-then-Reduce*, consists in taking advantage of the solution structure to directly approximate the low-rank algebraic Riccati equations to obtain the low-rank controller.

In this work, staying within the *Design-then-Reduce* framework, we take a different route towards a reduced controller considering the differential Riccati equation

$$\dot{P} = A^T P + PA - PB^T R^{-1} B P + Q, \quad (2)$$

which, for a stabilizable and detectable system, converges to a unique steady state P_∞ which is the solution of (1). We do not iterate P directly, but instead use a version of Dynamical Low-Rank Approximation [1], which allows the efficient time-integration of a low-rank SVD-like representation of the time-dependent matrix solution. We employ an operator-splitting technique [2] in order to integrate the approximation scheme into existing stand-alone integrators for the system dynamics. The toolchain is first developed and tested on the Ginzburg-Landau model equation using the in-house package `LightKrylov` [3] for the numerical linear algebra. Finally, the tools are linked to `Nek5000` [4], a high-order spectral-element solver for the incompressible Navier-Stokes equations, to compare the efficacy, accuracy and scalability of the computation of the low-rank controller for high-dimensional flow problems using the standard benchmark case of two-dimensional cylinder flow.

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Some observations of the Leading Edge Vortex

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Keywords: Leading Edge Vortex, active flow control, absolute instability, global instability.

Leading-edge vortices (LEVs) are integral to the aerodynamics of thin delta and lambda wings. These vortices are locally defined by the ratio between angular and linear momentum which in turn depends on many wing design parameters and the wing's attitude. It is a highly three-dimensional flow that is difficult to define mathematically. The current research attempts to control these vortices by disturbing the balance between these momenta on a cranked λ -wing ($\Lambda_{LE} = 60^\circ/30^\circ$) that has a flat suction surface, and investigated at $\alpha = 10^\circ$ using stereo-PIV (Fig. 1a). A single small jet located near the leading-edge crank altered the vorticity distribution within the main LEV and changed the nature of the interaction between two LEVs downstream of the crank (Fig. 1b-d). By doing so, it created a pitching moment with its sign dependent on the jet's orientation relative to the free stream, thus providing control over the wing without moving any control surface [1]. Cross-flow velocity profiles within the primary vortex measured upstream of the crank (broken black line) were fitted by a hyperbolic tangent velocity profile, $U(y, R) = 1 + R \tanh(y/2)$, such as was used in Ref. [2]. Here, U is scaled by the non-dimensionalized average velocity (U_{avg}) and y by the momentum thickness (Fig. 1g and h) suggesting that the reverse flow values create a flow that is absolutely unstable. The flow along the axis of the LEV core may add or subtract from the circulation at a given cross section depending on its direction relative to the free stream thus making the instability global. It is hoped that a detailed description of the mean flow in the LEV will provide a predictive tool of its stability and enable an optimal control of the flow field and the airplane.

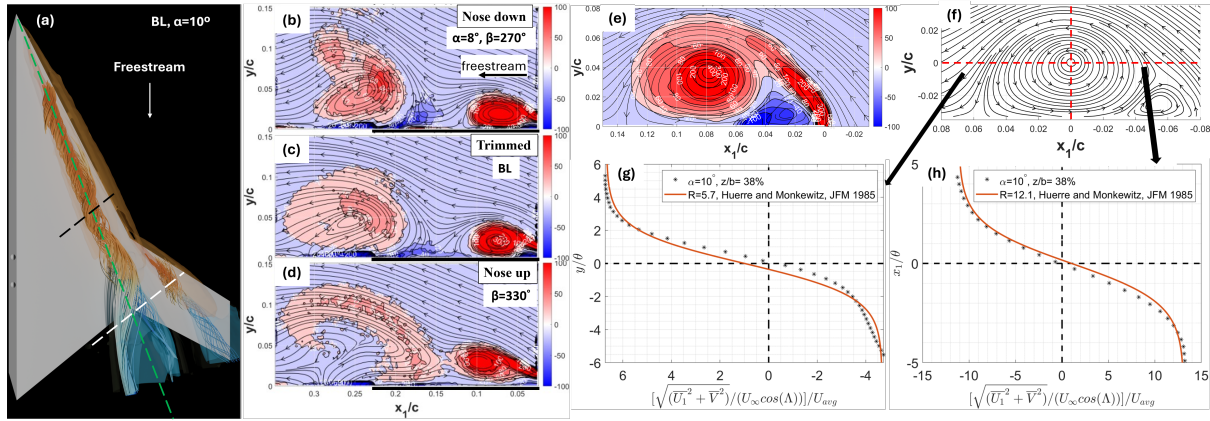


Figure 1: (a) 3D reconstruction of PIV results on λ -wing at $\alpha = 10^\circ$ with streamlines highlighting the LEV core for baseline; $\Omega_{z1}c/U_\infty \cos \Lambda$ at $z/b=0.6$ (broken white line), $\alpha = 8^\circ$ (b) actuation at $\beta = 270^\circ$, (c) baseline, (d) actuation at $\beta = 330^\circ$ [1]; Ensemble averaged contours at $z/b=0.38$ (broken black line), $\alpha = 8^\circ$ of (e) $\Omega_{z1}c/U_\infty \cos \Lambda$, (f) in-plane streamlines; Velocity profile in (g) y -direction, and (h) x_1 -direction [3].

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MEAN FIELD RESOLVENT ANALYSIS BASED MODELING FOR THE FLAME TRANSFER FUNCTION

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Keywords: Resolvent analysis, flame transfer function, large eddy simulation, thermoacoustic instability, combustion dynamics

Accurate Flame Transfer Function(FTF) prediction for Thermoacoustic instability analysis in gas turbine combustors remains a critical challenge. In recent years, several research groups have explored the use of Resolvent analysis (RA) of the linearized low Mach number equations of reacting flow to determine its response to imposed forcing in the linear limit. A mass consumption rate model is introduced to model the coherent fluctuating heat release rate. Flow forcing and response modes that optimally capture the global heat release response are determined by including linearized chemical source terms in the linearized operator (active approach) and also by leaving them out (passive approach). Our recent study [1] of a $Re = 1500$ turbulent premixed methane-air jet flame ($\phi = 0.8$), showed good prediction of FTF phase when using both active and passive approaches. The gain of the FTF was predicted well by the passive approach across the entire range of forcing frequencies. The active approach however, showed poor predictions.

We will extend our prior study as follows. FTF predictions from RA using both approaches will be recomputed for a turbulent premixed methane-air round jet flame at $\phi = 0.8$ and an unburnt gas temperature of 800 K, and Reynolds number $Re \approx 8000$. Harmonically forced LES will be used to determine the benchmark FTF characteristics for this flame. The time averaged mean field will be determined from an unforced flame LES. We will extend the heat release model based on Arrhenius expressions introduced in Chauhan *et al.* [1] to include additional features that can incorporate spatially varying turbulence intensity. The aim of this study is to explore the impact of Re on the RA method and explore further the reasons for good agreement observed with the passive approach. Indeed, it will be interesting to know whether the trends observed in Chauhan *et al* [1] translate to higher Re as well.

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Linear PSE modelling of wavepackets in installed jets**M. P. Avanci¹, Filipe R. do Amaral^{2,3}, J. C. Robinet¹, P. Jordan³, J. Huber⁴**¹ Arts et Métiers Institute of Technology, DynFluid Laboratory, Paris, France² Divisão de Aeronáutica, Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil³ Poitiers University, CNRS PPrime Institute, Poitiers, France⁴ Aeroacoustic sources, Airbus Operations SAS, Toulouse, France

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Keywords: Installed jets, Linear stability, PSE.

The interaction between a jet and a flap promotes unsteady flow behavior and acoustic disturbances that contribute to the overall aircraft noise profile [1, 2]. Wavepacket structures are closely linked to sound generation and propagation [3], and understanding their behavior is essential for the development of noise reduction strategies. This study investigates the effects on wavepacket evolution arising from the interaction between an subsonic compressible axisymmetric jet at Mach number $Ma = 0.4$ and a flat plate at zero angle of incidence, with the plate–jet distance r/D systematically varied. For a flow governed by the compressible Navier–Stokes equations, instability development is analyzed using a three-dimensional parabolized stability equations (3D-PSE) framework, which accounts for axial non-parallel effects and is initialized using a two-dimensional (y, z) local stability analysis. Perturbations are computed about a mean flow obtained from parametric RANS simulations, starting from an isolated jet configuration and progressively introducing the flat plate closer to the jet centerline. Figure 1 illustrates the mean flow field with plate interaction at some representative streamwise location x/D . Figure 2 presents a comparison of pressure wavepackets between an isolated jet and a jet–plate configuration with a plate distance of $r/D = 0.6$, considering the x – y plane and the axisymmetric azimuthal mode. These results will also be compared with experiments conducted at the Pprime Institute where PSE perturbations will be compared with SPOD modes from the experiments. These results will show that a linear superposition of PSE perturbations allows us to recover the SPOD leading mode. The authors acknowledge support of Airbus and the Pprime Institute.

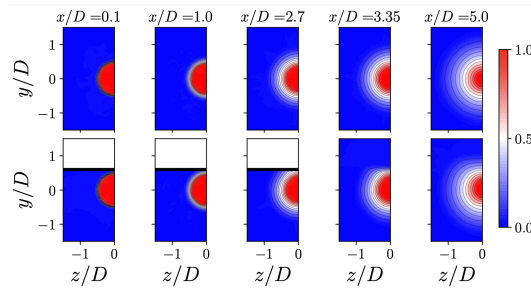


Figure 1: Streamwise component of the mean flow. Top row: isolated jet. Bottom row installed jet with $r/D = 0.6$

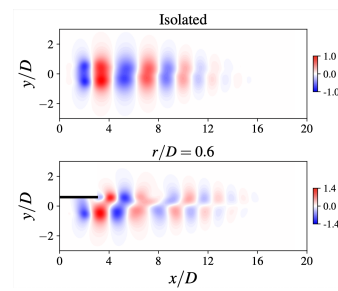


Figure 2: Real part of the pressure field on the $(y-x)$ plane for $St = 0.2$.

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Dual-Time SPOD for experimental identification of spatio-temporal patterns**M. Navarro-González¹, B. Yeung², O. T. Schmidt², E. García-Portugués³, M. Raiola¹**¹ Department of Aerospace Engineering, Universidad Carlos III de Madrid, Leganés, Spain² Department of Mechanical and Aerospace Engineering, University of California San Diego, La Jolla, USA³ Department of Statistics, Universidad Carlos III de Madrid, Leganés, Spain

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Keywords: Modal decomposition, data-driven methods, reduced order modelling

The Spectral Proper Orthogonal Decomposition (SPOD) is a powerful technique for identifying spatio-temporal coherent structures. In conventional implementations, SPOD computes, from a temporal series $q(\mathbf{x}, t)$, a spectrum of eigenvalues $\sigma_i(f)$ and spatial modes $\psi_i(\mathbf{x}, f)$ which are optimal in representing the spatial variance of the oscillations occurring at a fixed frequency [1]. Equation (1) summarizes the conventional SPOD algorithm for a time-resolved signal $q(\mathbf{x}, t)$:

$$S_{\text{SPOD}}(\mathbf{x}, \mathbf{x}', f) = \mathbb{E}[\mathcal{F}\{q(\mathbf{x}, t)\}\mathcal{F}\{q(\mathbf{x}', t)\}^*] \rightarrow [\sigma_{i,\text{SPOD}}, \psi_{i,\text{SPOD}}] = \text{eigs}(S_{\text{SPOD}}). \quad (1)$$

When computed from a measured time series, however, SPOD can provide spectral information up to the Nyquist frequency of the measurement system. In this work we propose a novel algorithm which exploits the statistical stationarity assumption of SPOD to obtain spectra that go beyond the Nyquist frequency of a single measurement system exploiting the dual-time sampling, i.e. sampling temporally underresolved time series staggered in time [2]. The resulting algorithm, dubbed *dual-time SPOD* (DT-SPOD), allows identifying spatio-temporal patterns without needing temporally resolved time series. DT-SPOD enables SPOD for measurements of high-speed flows when sampling frequency is too low for the application of conventional SPOD. Equation (2) summarizes the DT-SPOD algorithm implementation from a set of staggered measurements $q(\mathbf{x}, t)$ and $q(\mathbf{x}, t + \tau)$:

$$C(\mathbf{x}, \mathbf{x}', \tau) = \mathbb{E}[q(\mathbf{x}, t)q(\mathbf{x}', t + \tau)^*] \rightarrow S_{\text{DT}}(\mathbf{x}, \mathbf{x}', f) = \mathcal{F}\{C(\mathbf{x}, \mathbf{x}', \tau)\} \rightarrow [\sigma_{i,\text{DT}}, \psi_{i,\text{DT}}] = \text{eigs}(S_{\text{DT}}). \quad (2)$$

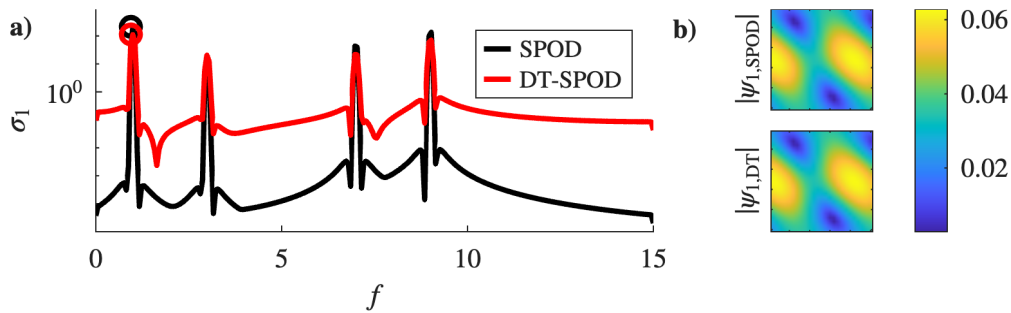


Figure 1: **a)** Comparison of the spectra of a nonlinear signal obtained by both methods. **b)** First SPOD mode of the frequency highlighted on (a) as described by conventional SPOD (top) and DT-SPOD (bottom).

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Space-time resolved coherent structures of LEVs on a 6-axis robotic flapper**Y. Goodwin¹, G. Rigas¹, J. Morrison¹**¹ Department of Aeronautics, Imperial College London, U.K.

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Keywords: Leading edge vortex, turbulent wake, space-time POD.

Leading-edge vortices (LEVs) are a key mechanism for delaying stall in flapping flight, preventing flow separation at high angles of attack and producing lift beyond typical fixed-wing performance. At high Reynolds numbers, LEVs break down into incoherent states, complicating their characterisation and limiting strategies for kinematic control [1]. Using a 6-axis robotic platform, we study pitching–translating figure-of-eight kinematics of a flat plate in fast forward flight at $Re = 15,000$. Time-resolved 2D2C-PIV at the half-span captures 118 periodic ensembles, resolving timescales from $10^{-3} - 10^2$ s and enabling multiscale analysis. Space-time proper orthogonal decomposition (ST-POD) [2, 3] extracts dominant spatio-temporal modes and deviations from the periodic mean. During LEV attachment, low-order modes capture shear-layer flapping and Kelvin–Helmholtz rollers governing cycle-to-cycle variability in LEV reattachment and topology. Following LEV burst, the energetic hierarchy is dominated by the higher-order modes, specifically a travelling-wave mode pair associated with turbulent wake formation and vortex shedding. This decomposition separates phase-locked coherent structures from cycle-specific instabilities, informing when active control may be required to sustain lift-enhancing attachment.

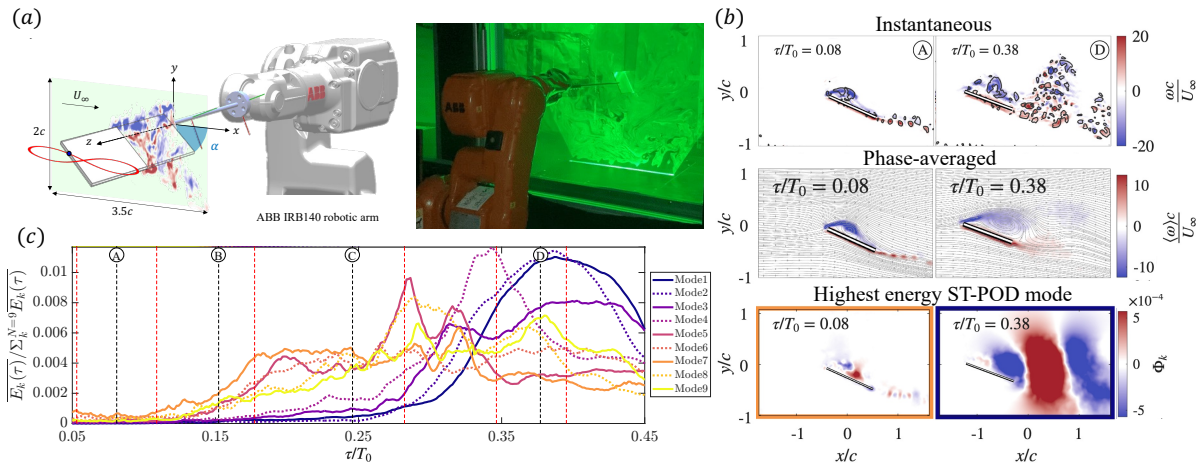


Figure 1: (a) Schematic of the measurement plane and coordinate system of the flapping wing, and photograph of the robot with the PIV laser sheet in the wind tunnel. (b) The instantaneous and phase-averaged vorticity during formation of a coherent LEV (A) and turbulent wake (D), with the highest energy ST-POD mode at each phase. (c) The energy variation of the first nine ST-POD modes over the first half of the stroke, normalised such that each has unit total energy over this window, showing competing dominance over the half-stroke.

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
Berlin, Germany 1–3 July 2026

Efficient and interpretable mean flow data assimilation of porous plates

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Keywords: Variational method, discrete adjoint, turbulent flows, RANS

Variational data assimilation has been applied to reconstruct time-averaged turbulent flows that are governed by the incompressible Reynolds-averaged Navier-Stokes (RANS) equations. The principle is to minimize a cost function, which penalizes the difference between high-fidelity reference measurements and the RANS solution, by tuning a design variable in the RANS equations. The choice of design variable, which can range from an unknown momentum source term to uncertain boundary conditions, plays a role on the quality of the reconstructed flow [1]. While tuning a momentum source term offers the greatest flexibility, it often involves a high number of design variables and may lack physical interpretability. Furthermore, current methods lack the ability to localize design variables based on physics or specific regions of interest.

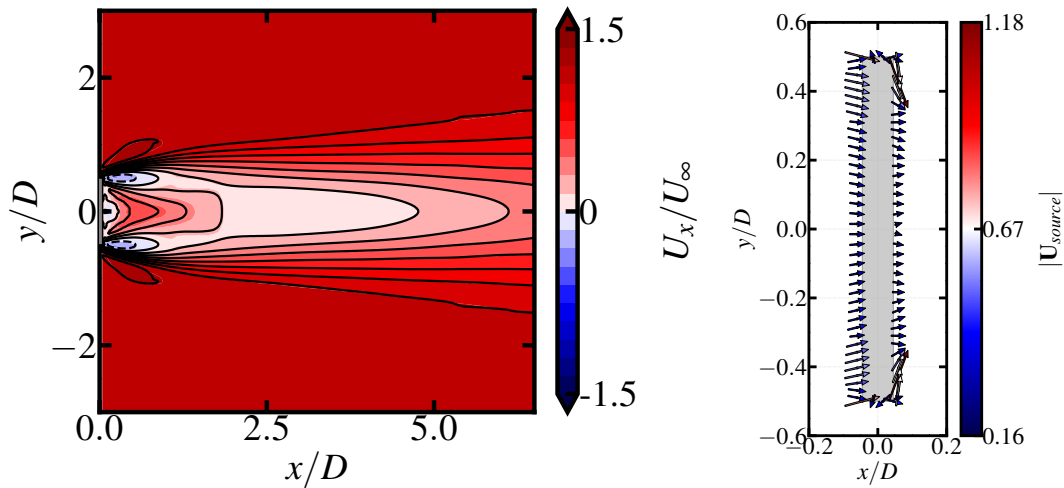


Figure 1: (Left) Mean streamwise velocity field in the wake of the porous plate with porosity $\beta = 0.25$ (ratio of open to total area) at $Re_H = 35000$ based on plate height H (Right) Optimized mean velocity magnitude on the face centers of the plate.

Building on our previous work [2], we present a mean-flow data assimilation framework for porous plates. A design variable is introduced within the boundary conditions to allow for streamwise and wall-normal velocity on a traditionally no-slip surface. By doing so, we are able to transform a solid plate into an “equivalent” porous plate. Our approach is demonstrated by assimilating planar particle image velocimetry (PIV) data from the wake of a flow past porous plates at 90° incidence. The assimilation achieves excellent convergence with the measured mean velocity field, as seen in Fig. 1 (left panel). By optimizing the distribution of mass sources and sinks on the plate surface (Fig. 1 right panel), the assimilation provides access to the mean pressure field, which is subsequently used to calculate Darcy and Forchheimer coefficients via control volume analysis. These optimized distributions offer a pathway toward developing models for porous flows.

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Strongly and weakly nonlinear dynamics of three-dimensional coherent structures in different flow regions of a round jet

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Keywords: Nonlinear dynamics, hydrodynamic instability theory, streaky structures

Due to the similarities in the appearances and dynamical behaviours, the dynamics of coherent structures (CS) in a turbulent flow can be described by the instability modes supported by the time-averaged mean-flow profile. A jet is inviscidly unstable due to the presence of the (generalised) inflectional point. For a nearly neutral mode, there is a critical level $r = r_c$ where the flow velocity is equal to the phase velocity, around which a thin non-equilibrium critical layer is introduced to regularise the singularity of the linear inviscid governing equation, and more importantly to account for the dominant nonlinear effects for different flow regions. The strong non-parallelism and the contribution from fine-scale turbulent fluctuations in a turbulent flow are also considered. For a three-dimensional (incompressible) CS, the singularity is only associated with the relative magnitude of the three-dimensionality and the non-equilibrium, where the former is measured by $\beta = (|m|/r_c)$ with the azimuthal wavenumber $m \in \mathbb{Z}$, and the latter is measured by the linear growth rate $\gamma \ll 1$. As in the very-near-nozzle region with $O(\beta) \leq O(\gamma)$, the three-dimensionality of a 3D fundamental CS is so weak that it can be neglected in the linear theory. The evolution and modulation of its amplitude are governed by the strongly nonlinear dynamical system (by adding an equation for the azimuthal velocity to the coupled equations in [1]), where the ring-mode CS ($m = 0$) and helical-mode CS with finite $m \neq 0$ can interact with each other. The finite-order harmonics with different m are all excited near the neutral position. It admits that the theory can describe the roll-up of CS (Figure 1a). As in $O(\gamma) \ll O(\beta) \leq O(\gamma^{1/2})$, the three-dimensionality works as a ‘correction’ to the two-dimensional mode in the linear theory, and the multiple ring–helical-mode CS also interact with each other but following a weakly nonlinear manner ([2]), where the nonlinearity contributes to the dynamical system via the mean-flow distortion only. As in the developed region with $O(\gamma^{1/2}) \ll O(\beta) \leq O(1)$, the three-dimensionality directly affects the linear dynamics, and the weakly nonlinear interaction only appears between the modes with opposite m through the mean-flow distortion and the first harmonic ([3]). All the theories formulate the generation and evolution of the streaky structures represented by the streamwise vortices (Figure 1b), which are important components of significant CS with low frequencies in jets.

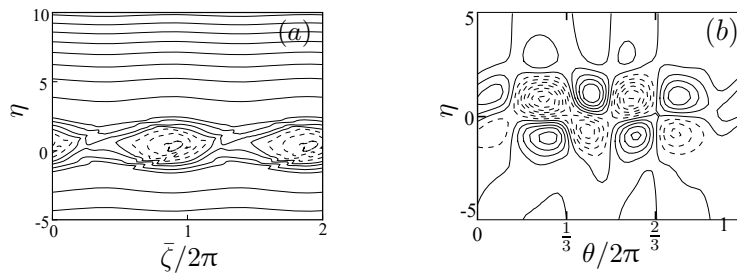


Figure 1: Contours of (a) azimuthal vortices and (b) streamwise vortices on a jet, which characterise the large-scale vortical structures and the streaky structures, respectively.

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Vortex breakdown of a swirling jet

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Keywords: swirling jet dynamics, vortex breakdown, Hopf bifurcation, transcritical bifurcation

In Francis-type turbines, the draft-tube swirl can generate a prominent helical coherent structure known as the vortex rope. Here, we analyze this phenomenon by viewing the rope as an unstable manifestation of vortex breakdown, focusing on a simplified laminar configuration. The study uses the axisymmetric draft-tube geometry introduced in [1], and imposes an inlet profile based on the corresponding experimental measurements. For no-slip walls, the helical mode is found to emerge supercritically from the axisymmetric solution. In contrast, when wall friction is omitted, a large axial recirculation bubble develops and a subcritical branch appears for operating conditions representative of turbine partial load, implying possible hysteresis. The computed dynamics show a repeatable sequence: formation of an axial recirculation bubble followed by its collapse as a helical vortex rope develops around its edge (illustrated by snapshots in Fig. 1). When parameters are shifted toward rated operation, the steady branches undergo an unfolding via a transcritical bifurcation, in a manner consistent with the pitchfork-unfolding picture discussed for swirling jets in [2]. Importantly, this transition is obtained at finite Reynolds number, complementing earlier studies where transcritical bifurcation in swirling jets was identified only in the inviscid limit [3].

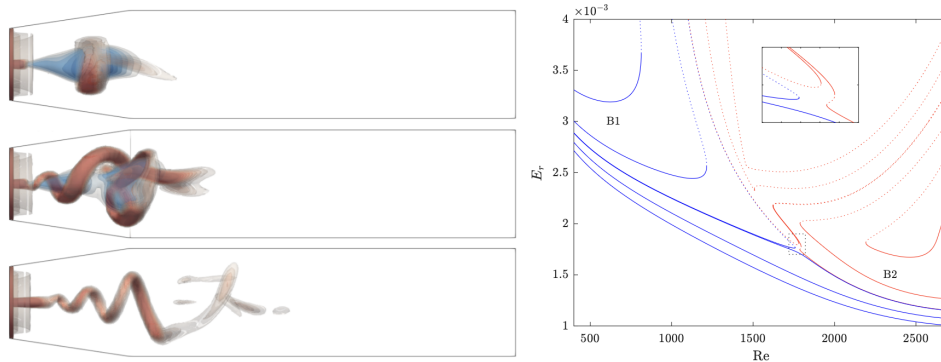


Figure 1: Left: snapshots of the recirculation bubble formation (negative axial velocity shown in blue isosurface) and its destruction due to formation of a helical vortex rope (visualised with positive Q -criterion isosurfaces in red). Right: collision of two families of branches of steady solutions plotted for a series of turbine operating points leading to a transcritical bifurcation, zoom on which is shown in the inset. Stability to axisymmetric modes is marked with solid (stable) and dotted (unstable) lines.

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Wavepackets eduction in turbulent jets using Hilbert POD

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Keywords: Data-drive methods, Modal analysis, Reduced order modelling, Jet noise.

Wavepackets are coherent features in turbulent jets, behaving as waves advected in the flow direction, which are considered to be a fundamental piece in the noise emission. The aeroacoustics community devoted considerable efforts in educing and modelling these features and their impact on the noise. In this work we apply the Hilbert POD (HPOD), a complex-valued extension of the standard POD, to extract advecting wave features from an LES database of a turbulent subsonic jet [1]. The HPOD is computed as the POD of the analytic representation of the real-valued flow field $\mathbf{u}(\mathbf{x}, t)$, obtained by summing to it an imaginary part equal to its Hilbert transform $\mathcal{H}[\mathbf{u}]$, resulting in the complex-valued decomposition

$$\mathbf{u}(\mathbf{x}, t) + i\mathcal{H}[\mathbf{u}](\mathbf{x}, t) = \sum_m \sigma^{(m)} \psi^{(m)}(t) \phi^{(m)}(\mathbf{x}) = \sum_m \sigma^{(m)} \Psi^{(m)}(t) \Phi^{(m)}(\mathbf{x}) e^{i(\omega(t)t + k(x)x)}.$$

The decomposition delivers real-valued singular values σ and complex-valued temporal (ψ) and spatial (ϕ) patterns, which can be interpreted as phasors with instantaneous/local amplitudes (Ψ and Φ) and frequency/wavenumber (ω and k). For travelling features with a wave velocity $c = \omega/k$, the Hilbert transform can be performed either in the temporal or advection direction [2]. Representative spatial and temporal patterns are reported in Fig. 1. These patterns are used to extract the most relevant features of the wavepackets and estimate their acoustic footprint.

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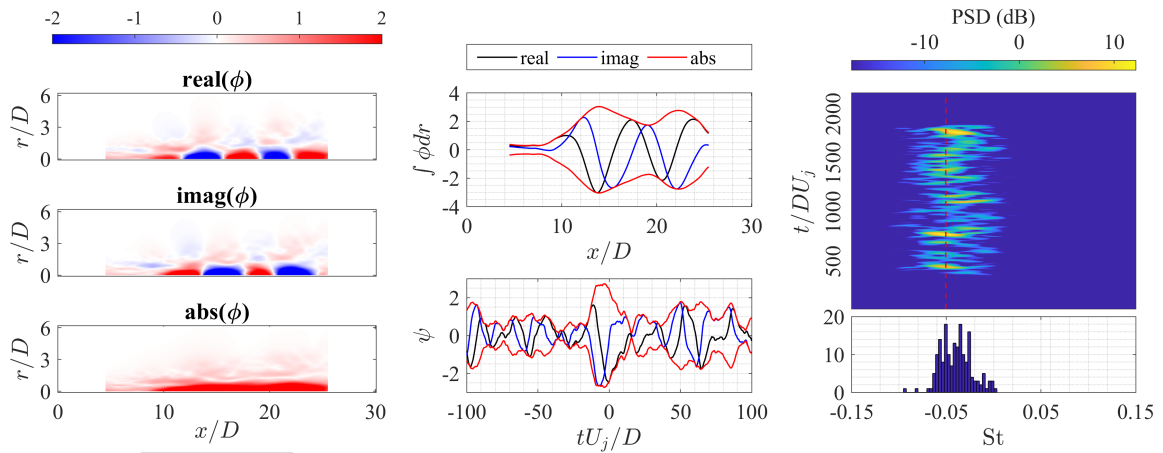


Figure 1: Representative HPOD mode: (left) complex-valued spatial pattern (streamwise component); (center) radial integral of the spatial pattern and temporal pattern; (right) spectrogram of the temporal pattern.

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On the analysis of vortex and particles dynamics in a square microfluidic T-junction**M. Chiatto¹, L. de Luca¹, H.A. Stone², F. Grasso³**¹ Department of Industrial Engineering, University of Naples “Federico II”, Naples, 80125, Italy² Department of Mechanical and Aerospace Engineering, Princeton University, Princeton 08544, New Jersey, USA³ DynFluid Laboratory, CNAM-Arts et Metiers Paris Tech, Paris 75013, France*Corresponding author: M. Chiatto (matteo.chiatto@unina.it)***Keywords:** Data-driven modal decomposition, Microfluidics, Particle/fluid flows.

Branching flows are common in pipeline networks and biological systems, where geometric bifurcations generate coherent vortical structures that strongly influence transport and control processes. In a square cross-section T-junction, the curvature of streamlines produces a dominant vortex pair that undergoes qualitative changes as the Reynolds number increases, including vortex breakdown and a Hopf bifurcation leading to a helical breathing mode (Vigolo et al. [1], Chen et al. [2]). This work investigates how such coherent structures govern particle trapping in the Reynolds number range $300 \leq Re \leq 570$. Single-phase numerical simulations of the base flow are combined with Lagrangian particle tracking through integration of the particle force balance equation. Particle dynamics are characterized in terms of Stokes number (St) and density ratio (ρ), which control viscous and buoyancy effects, respectively. At $Re = 500$ the flow exhibits a steady vortex pair associated with axisymmetric breakdown, leading to transient particle accumulation. At $Re = 570$ a Hopf bifurcation induces a periodic corkscrewing and breathing of the primary vortex, resulting in injection-time-dependent particle trajectories and sustained oscillations of the trapping region. Modal analysis associates the observed oscillations with the breathing mode of the vortex pair. The dominant frequency is interpreted as an edge-tone mechanism, linked to vortex shedding at the recirculation bubble and its interaction with the outlet boundary.

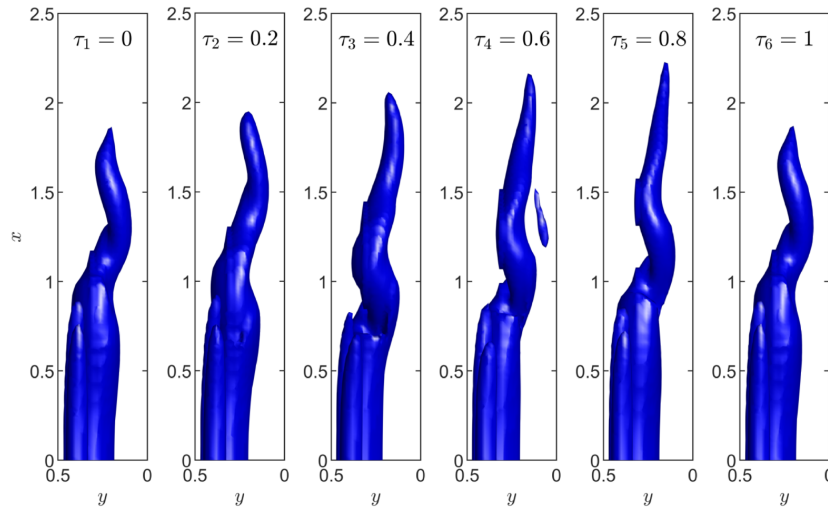


Figure 1: Time evolution of the flow at $Re = 570$ at various dimensionless times (τ_n) in the breathing period. The blue surface is a Q-criterion isosurface $Q = 25$.

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Dynamic response of the turbulent boundary layer to an unsteady boundary condition**A. Schulz¹, M. Hartmann², and D. Ronneberger³**¹ HTW Berlin, Berlin, Germany² Volkswagen AG, Wolfsburg, Germany³ Retired, formerly Professor at Drittes Physikalisches Institut, Georg-August-Universität Göttingen*Corresponding author: A. Schulz (anita.schulz@htw-berlin.de)*

Keywords: turbulent boundary layer, unsteady/acoustic boundary condition, impulse response function, burst frequency modulation, spatio-temporal dynamics of Reynolds-stresses.

We employ Direct Numerical Simulations (DNS) to investigate a fully turbulent plane channel flow where the rigid channel walls oscillate time-harmonically in the streamwise direction within the wall plane. The velocity amplitude of the wall oscillation is kept small relative to the mean flow velocity, ensuring the study remains within the linear regime—distinct from most research focused on the drag reduction effect. We focus on the dynamic response of the near-wall turbulence and its coherent structures to a sudden perturbation of their equilibrium, induced by a delta pulse of the streamwise wall velocity. To this end, impulse responses of all velocity correlations—specifically turbulent shear and normal stresses—are evaluated from frequency response functions derived from DNS data across 20 wall oscillation frequencies. Figure 1 (left) depicts the impulse response of the modulated turbulent shear stress (normalized by its temporal average) in the spatio-temporal domain. The peak at $y^+, t^+ \rightarrow 0$ originates from the wall-velocity pulse and represents a wave packet traveling away from the wall at finite speed, characterized by spatial decay and broadening. The spatio-temporal trajectories of the impulse response maxima (Figure 1, right) reveal two distinct wave propagation mechanisms: First, the initial wave packet propagates away from the wall. Subsequently, after a characteristic time of $T^+ = 160$, the entire buffer layer responds quasi-simultaneously, emitting a secondary wave packet back towards the wall. A detailed analysis demonstrates that the propagation mechanisms of these two "waves" are fundamentally different and independent. Moreover, we interpret the secondary explosive Reynolds-stress response as a modulation of large-scale coherent vortex bursts. Specifically, it reflects an intensified generation and evolution of these structures during the deceleration phase of the wall pulse.

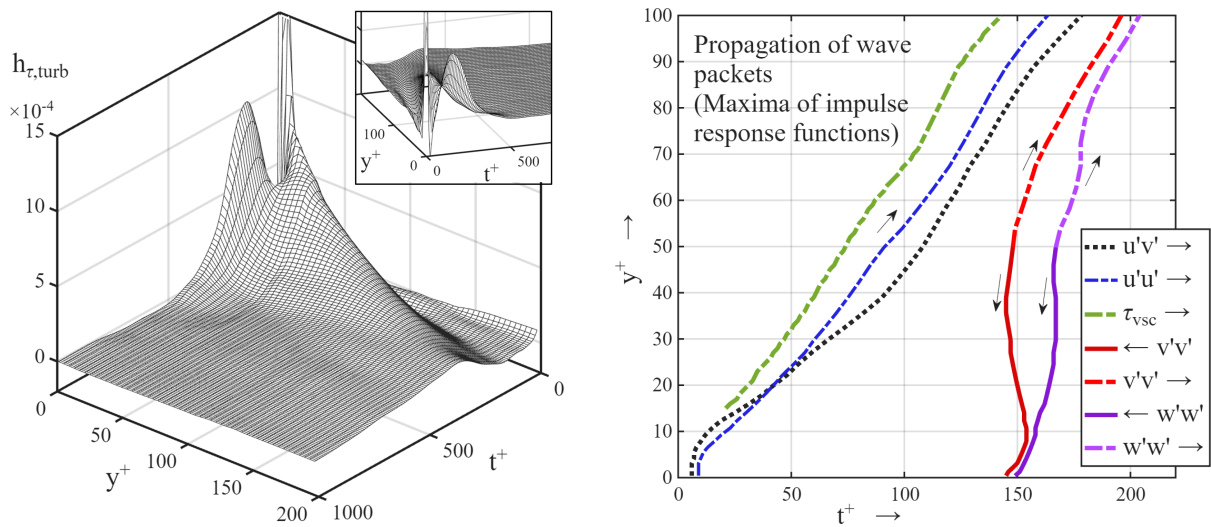


Figure 1: (Left) Impulse response of the modulated turbulent shear stress, normalized by its temporal average. (Right) Spatio-temporal trajectories of the response maxima for the turbulent shear and normal stress components. Arrows indicate the wave propagation direction: away from the wall ($\rightarrow$) and towards the wall ($\leftarrow$).

Coherent structures in multirotor hover flight**E. Pratschke¹, C. C. Wolf², O. T. Schmidt¹**¹ University of California San Diego, USA² German Aerospace Center (DLR), Germany*Corresponding author: O.T. Schmidt (oschmidt@ucsd.edu)***Keywords:** Vortex merging, multirotor, subharmonic, synchronization.

Assimilated experimental velocity data of a hovering quadcopter captured via Shake-The-Box Lagrangian particle tracking [1] are analyzed with modal decomposition methods. Energetic coherent structures are extracted via Spectral Proper Orthogonal Decomposition (SPOD) and assigned to different frequency bands and rotors. The most energetic mode in the low-frequency band f_a below the rotor frequency band f_b eludes explanation via either fundamental rotor dynamics or band-to-band triadic interactions. We hypothesize that the role of this structure is a global synchronization mode, representing an intermittent vortex merging process dominated by nonlinear interactions between the wakes of the individual rotors.

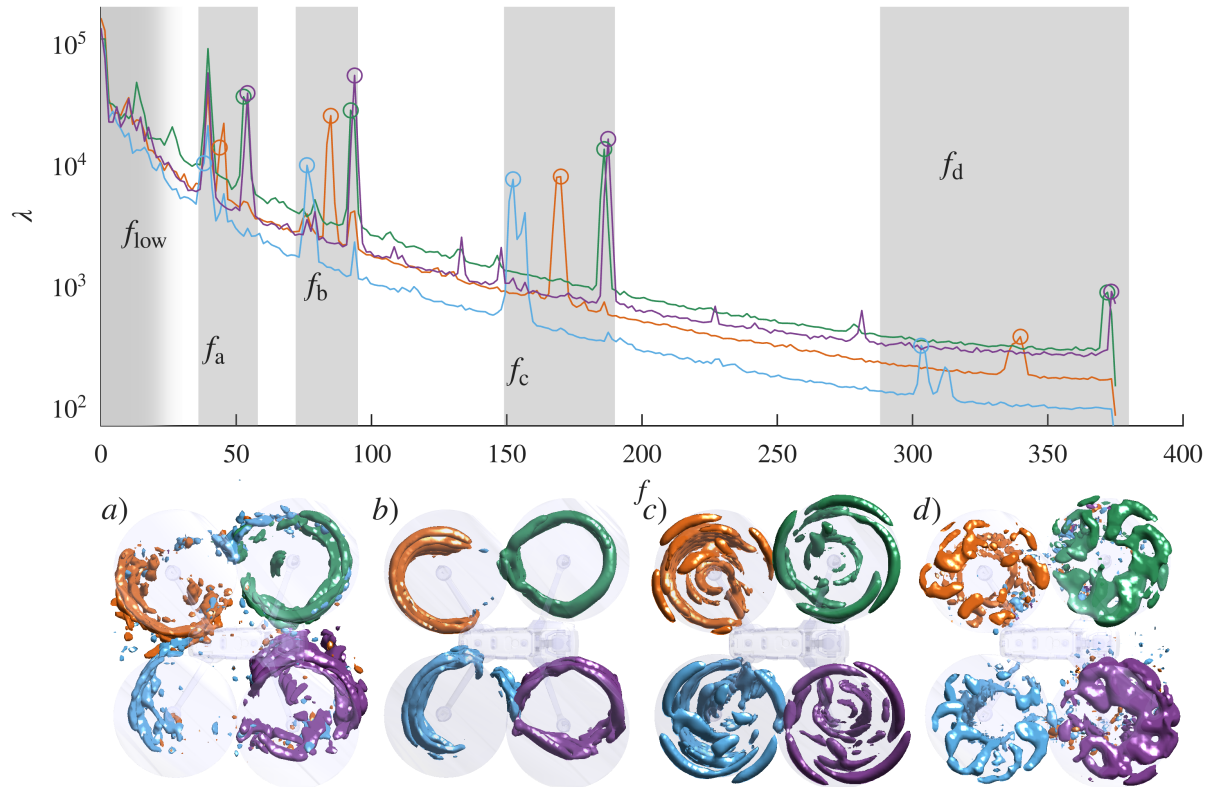


Figure 1: SPOD eigenvalue spectrum (top) and Q-criterion iso surfaces of selected modes (bottom). Frequency bands f_b , f_c and f_d are associated with rotor-, blade-passing- and harmonic frequencies, respectively.

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Resolvent Analysis of Assimilated Mean Flow for Capturing Airfoil's Tonal Fluctuations**R. Peron^{1,2}, M. Smith¹, V. Mons³, J. Leontini¹, O. Marquet^{2,3}**¹ Department of Mechanical and Product Design Engineering, Swinburne University of Technology, Hawthorn, VIC3122, Australia² DAAA, ONERA, Université Paris Saclay F-92190 Meudon, France³ DAAA, ONERA, Institut Polytechnique de Paris F-92190 Meudon, France*Corresponding author: R. Peron (romain.peron@mines-albi.fr)***Keywords:** Tonal fluctuations, Resolvent analysis, Data assimilation

We investigate tonal fluctuations in the incompressible flow around a NACA0012 airfoil at Reynolds number $Re = 5 \times 10^4$ and $\alpha = 2^\circ$ within the RANS modelling framework. Classical turbulence models are known to inadequately predict the mean flow velocity about which coherent structures are reconstructed using linear analyses. To address this limitation, a corrective forcing field $\bar{\mathbf{f}}$ is inferred through adjoint-based data-assimilation [1]. In contrast to the turbulence-model correction strategy adopted in [2], the present approach introduces the correction directly into the momentum equations, thereby ensuring a closer agreement with DNS mean velocity data. The principal novelty of this work lies in the a posteriori Boussinesq-like decomposition of the inferred correction, $\bar{\mathbf{f}} = 2\nabla \cdot [\bar{\nu}_t^a \mathbf{S}(\mathbf{u}_b)] + \bar{\mathbf{f}}^r$, where $\bar{\nu}_t^a$ is a mean eddy-viscosity field subsequently added to the modelled eddy-viscosity in the resolvent analysis. The influence of this augmented eddy-viscosity on the reconstruction of coherent structures is assessed by comparing resolvent modes with SPOD modes extracted from DNS snapshots. As evidenced by the spectrum shown in Fig. 1(a), the inclusion of $\bar{\nu}_t^a$ enhances the alignment of high-energy resolvent modes with their SPOD counterparts, but degrades it for lower-energy modes at higher frequencies. Figures 1(b) and 1(c) further demonstrate the excellent correspondence between the dominant SPOD modes and the associated resolvent modes computed with the augmented eddy viscosity field. Finally, the impact of incorporating perturbations of the eddy viscosity within the resolvent operator will be examined and discussed.

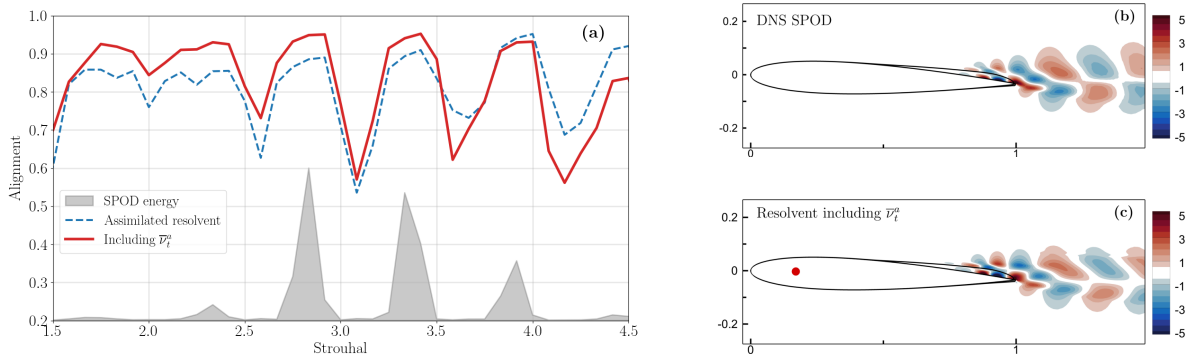


Figure 1: (Left) Alignment between SPOD modes and resolvent modes computed with (red line) and without (blue line) the added eddy-viscosity $\bar{\nu}_t^a$ as a function of the frequency St . The scaled SPOD energy spectrum is illustrated by the shaded region. (Right) Streamwise velocity component of the (top) SPOD and (bottom) resolvent modes around the assimilated mean-flow at frequency $St = 2.8$.

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Exceptional points in flutter and Vortex-Induced-Vibrations

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Keywords: Linear stability, Fluid-Structure-Interaction, Exceptional points, Non-Hermitian dynamics.

The linear stability analysis of fluid-structure interaction (FSI) systems, governed by inherently non-Hermitian operators, can exhibit spectral singularities known as exceptional points (EPs). This study is the first to demonstrate the existence and topological consequences of EPs in FSI across three canonical aeroelastic configurations: vortex-induced vibration of a spring-mounted cylinder, flutter of a thin plate, and transonic flutter of an OAT15A airfoil, sketched in fig. 1. A unified numerical framework is employed, coupling the compressible Navier–Stokes equations with structural dynamics. Stability is analysed via a characteristic equation constructed from fluid transfer functions, efficiently interpolated into the complex plane using the Loewner framework. Results reveal second-order EPs (EP₂) where two eigenmodes coalesce, leading to characteristic eigenvalue veering and mode-swapping phenomena governed by a half-integer winding number. In the transonic case, the interaction of three modes (fluid/buffet, pitching, heaving) is organised by a third-order EP (EP₃), a codimension-four singularity where three eigenvalues and eigenvectors coalesce. A partial unfolding of this degeneracy is represented in fig. 2. These findings establish EPs as fundamental features in FSI, providing a novel topological perspective on stability transitions, with implications for predicting and controlling phenomena like flutter and the transonic dip.

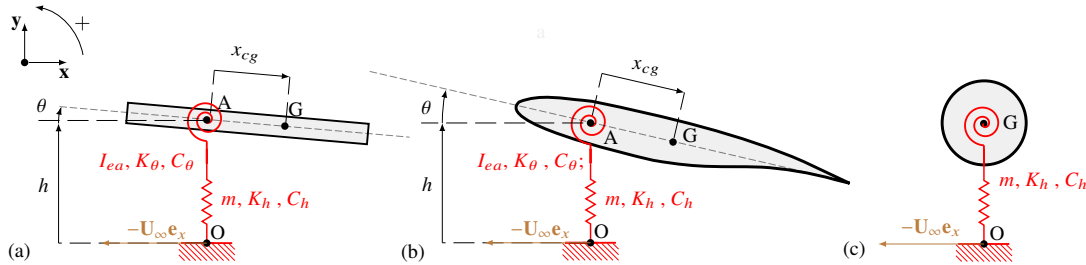


Figure 1: Diagram of the three aeroelastic configurations (a) Two-degrees of freedom spring-mounted plate. (b) Two degrees of freedom OAT15a airfoil. (c) Spring-mounted cylinder.

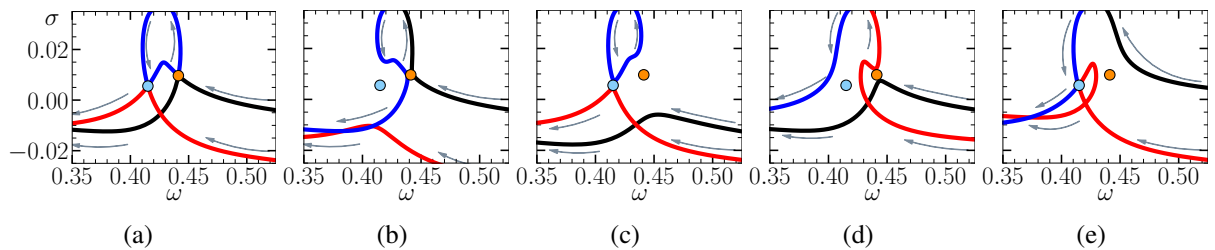


Figure 2: Veering phenomenon in the case of the transonic flutter. Tracking of the three leading eigenvalues: black line (pitching mode), red line (heaving mode) and blue line (fluid mode) around two exceptional points represented by two circle markers (blue and orange). Subfigure (a) is computed for $\zeta_h = 0.04273$, $\zeta_\theta = 0.0159$. Subfigures (b-e) are computed for damping parameters $\zeta_h = 0.04273 + r \cos(\theta)$, $\zeta_\theta = 0.0159 + r \sin(\theta)$ for $r = 0.0159$ and $\theta = 0$ for (b), $\theta = \pi/2$ for (c), $\theta = \pi$ for (d) and $\theta = 3\pi/2$ for (e). The grey arrows indicate the the direction of increasing U^* .



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Adjoint-accelerated Bayesian inference of two-equation turbulence models from noisy Flow-MRI data

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Keywords: Physics-informed machine learning, data assimilation, complex geometries

4D Flow-MRI is a noninvasive medical imaging technique used in the assessment of cardiovascular diseases, such as aortic stenosis and coarctation. These pathologies are known to induce turbulent flow patterns characterised by sub-voxel length- and time-scales of motion. Such turbulent structures cannot be captured directly due to the limited spatiotemporal resolution and low signal-to-noise ratios of Flow-MRI. It is possible, however, to measure the first-order turbulent statistics from the level of signal attenuation in Flow-MRI images. In this study, we use adjoint-accelerated Bayesian inference to jointly reconstruct turbulent flow fields and learn the parameters of well-established two-equation closure models. We formulate and solve an inverse RANS problem that assimilates noisy, experimental measurements of the time-averaged velocity and turbulent kinetic energy fields. The proposed framework is tested on a flow of Newtonian fluid through the Food and Drug Administration’s (FDA) benchmark nozzle at a Reynolds number of 6,500. The results are compared with data assimilations into algebraic and one-equation models (see figure 1). We show that the inferred closure models successfully reconstruct the confined turbulent jet without overfitting. We also obtain uncertainty bounds on the model predictions and the parameters. Our method can further provide accurate estimates of key haemodynamic biomarkers, such as wall shear stress and pressure loss, which are difficult or impossible to measure otherwise. The results demonstrate the effectiveness of Bayesian methods in patient-specific cardiovascular modelling and mark an important step towards improving the fidelity of existing RANS models.

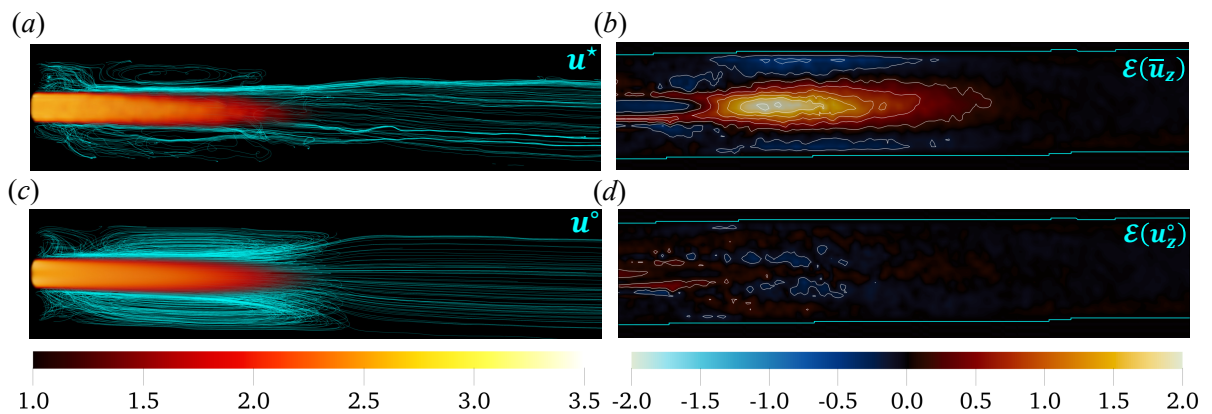


Figure 1: Noisy Flow-MRI data, $\mathbf{u}^*$ (figure 1a), and RANS model reconstruction, $\mathbf{u}^o$ (figure 1c), for the turbulent flow through the FDA benchmark nozzle. The RANS equations are closed by solving a transport equation for the turbulent kinetic energy. Figures 1a and 1c show velocity streamlines in cyan color and velocity magnitude in red color. The prior model-data discrepancy, $\mathcal{E}(\bar{u}_z)$, and the posterior model-data discrepancy, $\mathcal{E}(u_z^o)$, are displayed in figures 1b and 1d respectively.



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Interaction between thermoacoustic and hydrodynamic instabilities in a bluff-body wake inside a channel

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Keywords: Thermoacoustic instability, Rijke tube, bluff-body wake, weakly nonlinear analysis

Combustion instability is driven by multi-physics phenomena arising from the interplay of hydrodynamic, thermal, chemical, and acoustic processes. While these mechanisms are often studied in isolation, this work presents a unified linear and weakly nonlinear analysis of a simple yet representative setup to explore the coupling of thermoacoustic and hydrodynamic instability modes. We exclude from this configuration, for the time being, the aspect of chemical reaction.

We consider **compressible flow around a heated bluff body within a narrow channel**, a setup that harbours two classic instability archetypes: the hydrodynamic shear instability of bluff-body wakes (traditionally incompressible) and the thermoacoustic instability of the non-reacting Rijke tube. The flow configuration mirrors earlier work [1], where chemical reactions were included but acoustic effects were neglected, offering a complementary perspective.

Through linear stability analysis, we map neutral curves for distinct eigenmodes in a parameter space defined by the Reynolds number Re and bluff-body temperature T_w . These modes are driven by either hydrodynamic mechanisms (antisymmetric, wake-dominated) or thermoacoustic interactions (symmetric, Rijke-type). At the intersection of neutral curves, a *double Hopf point* emerges, serving as the focal point for our weakly nonlinear analysis. By expanding around the double Hopf point, we characterize the modal interactions and discuss their critical role in both the onset of instability and the fully nonlinear oscillatory dynamics. The coupling of hydrodynamic and thermoacoustic eigenmodes is found to give rise to a limit torus, combining symmetric and antisymmetric components, interacting through higher-order amplitude terms (illustrated in figure 1).

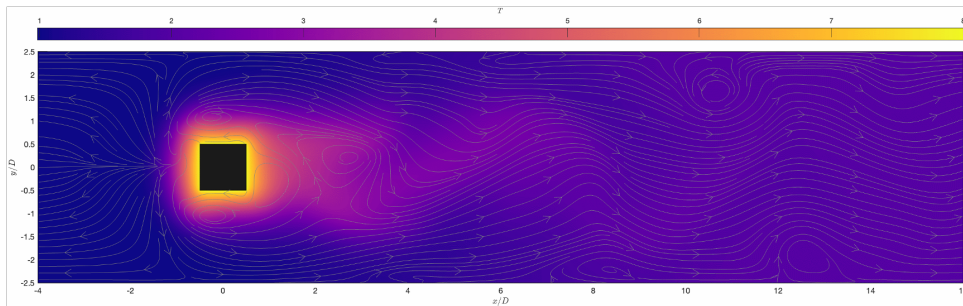


Figure 1: Temperature snapshot in the limit torus, from DNS at $Re = 80$ and $T_w = 8T_\infty$.

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Vortex instabilities leading to turbulence in slender delta wings

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Keywords: Delta Wings, Vortex Instabilities, Modal Decomposition

While the flow above a highly-swept delta wing is characterized by a pair of steady counter-rotating leading edge vortices (LEVs), the downstream wake undergoes a series of bifurcations at Reynolds numbers (Re) relevant to micro air vehicles (MAV) [1, 2]. Using incompressible direct numerical simulation with multi-level adaptive mesh refinement [3] and an immersed boundary method [4], we simulate the flow past a delta wing with 70° sweep at increasing Re and angles of attack (α). At $\alpha = 35^\circ$, the flow transitions to an asymmetric shedding at Re = 2,000, with vortex breakdown occurring upstream of the trailing edge by Re = 4,000. At $\alpha = 20^\circ$, the wake stays largely steady, until Re = 6,000 when symmetric shedding of the tip vortex occurs.

To characterize the transitional regime at Re = 10,000, we apply the normality-based triple decomposition of the velocity gradient tensor (VGT), partitioning the local fluid motion into normal straining, pure shearing, and rigid-body rotation components [5, 6]. This allows us to distinguish between instabilities originating in the vortex core, characterized by rigid rotation, and those driven by shear-layer instabilities, dominated by pure shearing. By combining this decomposition with proper orthogonal decomposition (POD), we seek to map the complex wake at Re = 10,000 onto the underlying bifurcations present at lower Re. Our results indicate that this transition is primarily driven by the breakdown of the shear layer, which ultimately disrupts the rotational core. By isolating the dominant components of the VGT decomposition, we establish a framework for identifying the topological triggers that drive the onset of wake turbulence in MAV flight regimes.

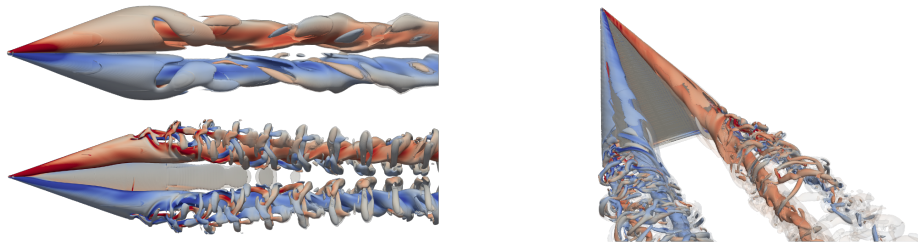


Figure 1: Q-Criterion isosurfaces colored by streamwise vorticity: (left, top) Re = 2,000, $\alpha = 35^\circ$; (left, bottom) Re = 6,000, $\alpha = 20^\circ$; (right) Re = 10,000, $\alpha = 20^\circ$.

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
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Global linear stability and resolvent analyses of over-expanded nozzle

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Keywords: Linear stability, global resolvent, over-expanded nozzle.

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. This study proposes to investigate the linear stability and transfer function to a harmonic or stochastic forcing through the calculation of the global resolvent in a URANS framework. A parametric study of a TIC (Truncated Ideal Nozzle) nozzle on the nozzle pressure ratio (NPR) covering a very wide range of regimes from over-expanded to under-expanded will be presented ($NPR \in [5; 20]$), giving a unified view of the low-frequency dynamics and the resulting acoustic radiation. One of the objectives of this study is to understand the origin of the asymmetric low frequencies that cause significant lateral forces on the nozzle. After calculating the various fixed points of the URANS equations (Fig. 1 for $NPR = 9$) for the studied NPR range, it will then be shown that there are weakly stable 3-D modes (see 2 for $NPR = 9$ and $m = 1$) that can be forced and destabilized by stochastic fluctuations related to turbulence. Results will be compared with the data from C. Tarsia Morisco's thesis [1] and experimental results [2] to assess the impact of different turbulence models on the stability limits.

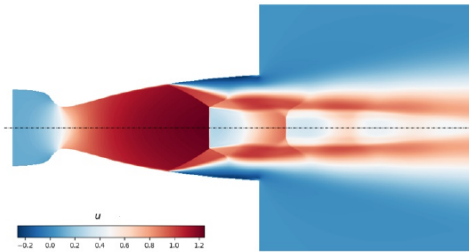


Figure 1: Streamwise mean velocity field for $NPR = 9$

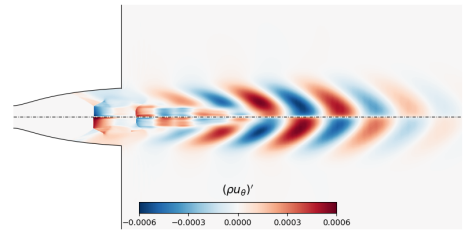


Figure 2: Streamwise velocity perturbation field of the helicoidal ($m = 1$) mode

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On the Meandering of Convective Rolls in Turbulent Channel Flow over Streamwise Ridges

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Keywords: Turbulent Mixed Convection, Surface Heterogeneity, Convective Flow Organization

This work examines how streamwise-aligned ridges affect the emergence and behavior of convective rolls in turbulent channel flow. Direct numerical simulations (DNS) are performed based on the Navier-Stokes equations under the Boussinesq approximation. Convective rolls are streamwise-elongated large-scale structures characteristic of mixed convection, arising when shear and buoyancy forces contribute comparably to heat and mass transfer, and manifesting as counter-rotating vortices in the channel cross-section (figure 1 (a)). Building on a recent study [1], which systematically explored how ridges reorganize mixed convection flows, two key findings were established: ridges can substantially shift the transition between convection regimes as a function of the bulk Richardson number Ri_b , and they can trigger a slow lateral meandering of the convective rolls (figure 1 (b)) - a phenomenon absent over smooth walls. This meandering is observed at $Ri_b = 1$ for spanwise ridge spacings S comparable to the natural spanwise wavelength of the rolls, such as $S = 4\delta$ and $S = 8\delta$, where δ denotes the half-channel height. The underlying hypothesis is that ridges promote the formation of up- and downdrafts at preferred spanwise locations. Under a symmetric ridge arrangement, however, up- and downdrafts are simultaneously promoted at opposing ridges, causing them to counteract one another and producing the observed meandering. To test this, asymmetric configurations — such as removing ridges from the upper wall — are examined. As shown in figure 1, a single bottom-wall ridge at $S = 8\delta$ pins the updraft to a fixed spanwise position, whereas the symmetric case retains the meandering behavior. Further investigations, including staggered ridge arrangements designed to probe whether ridges can modify the natural spanwise wavelength of convective rolls, will be presented at the conference. These results contribute to a deeper understanding of convective roll formation and the potential of structured surfaces to control their dynamics and associated transfer properties.

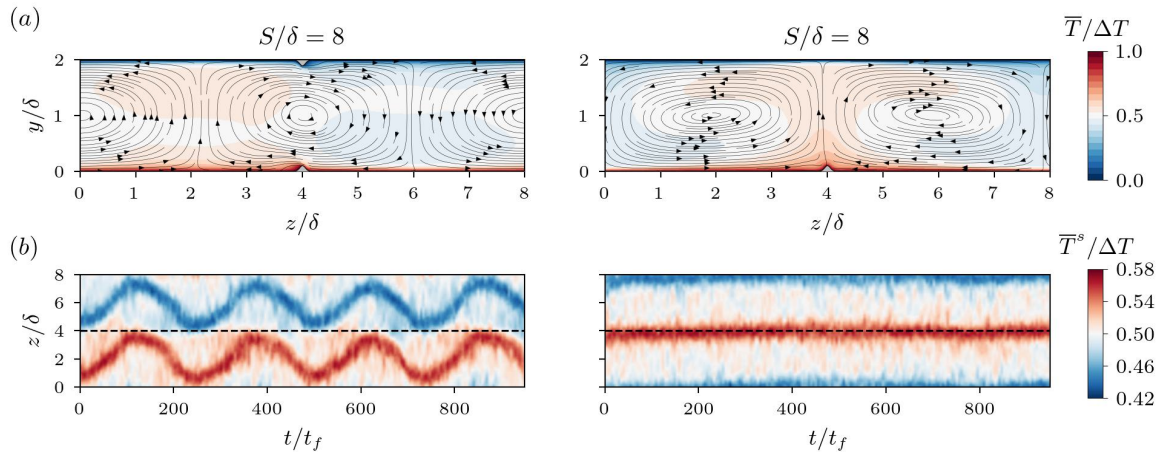


Figure 1: Mean temperature in the channel cross-section in (a) and short-time and streamwise averaged temperature over time and spanwise position at channel centre ($y = \delta$) in (b) for two different ridge arrangements. Left column shows the arrangement with ridges at the bottom and top wall, while the right column depicts the arrangement with ridges at the bottom wall. In (b) the black dashed line indicates the spanwise position of the ridges.

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EUROMECH Colloquium 668: Coherent Structures in Multiphysics Flows—Modelling, Control and Interpretation
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Wake interactions between porous discs: linear nowcasting and forecasting from sparse experimental data

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Keywords: Turbulent wake interactions, PIV, space-time ePOD

We report an experimental study of wake interactions between three porous discs in tandem. The discs (adapted from Bourhis and Buxton [1]) are mounted in-line with streamwise separation $L = 4.5D$, where $D = 0.1$ m, at Reynolds number $Re = U_\infty D/\nu = 3.33 \times 10^4$ (Fig. 1a). Time-resolved particle image velocimetry (PIV) is acquired simultaneously to six-component force measurements at the 2nd ($x = 0$) and 3rd ($x = 4.5$) disc mounts. The PIV is recorded at 250 Hz for and synchronised force-balance data are sampled at 2.5 kHz. The downstream discs operate in a turbulence-intensified, mean-deficit inflow, which leads to mean drag reduction and an increased unsteady aerodynamic loading. We investigate how much information about the wake movement can be recovered from measurements of these unsteady aerodynamic loadings. To this end, we employ extended proper orthogonal decomposition [2], where the forces alongside 4 virtual velocity probes (Fig. 1a) serve as the observation data (decomposed via POD), and the PIV time-series (snapshot shown in Fig. 1b) as the secondary signal, projected onto the POD time coefficients to yield the extended modes. The reconstruction accuracy can be improved significantly by retaining a short history of past observations, which transforms the space-only POD to space-time POD. The result of this approach is shown in Figure 1c. As a further step, we include future PIV snapshots in the computation of the extended modes, yielding space-time extended modes, which can be used for short-time forecasting of the velocity field, as in [3]. These methods might be applicable to inform sensor placement in the planning of control experiments, or online, as an observation transformation for data-driven approaches like reinforcement learning.

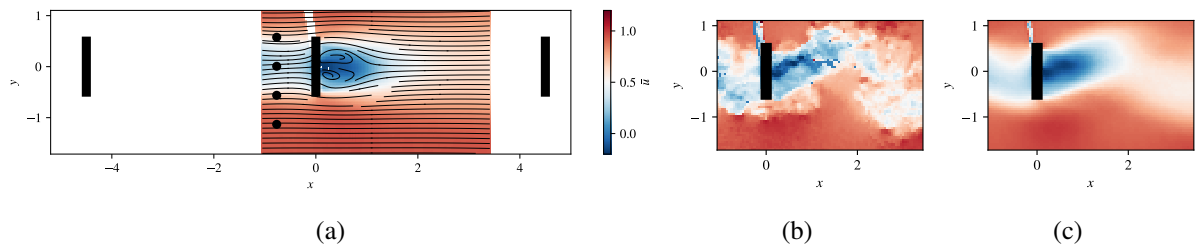


Figure 1: Three porous discs in tandem ($L/D = 4.5$, $Re = 3.33 \times 10^4$). (a) Experimental configuration including velocity mean field and positions of virtual velocity probes. (b) Instantaneous streamwise velocity $u(t)$. (c) Reconstructed velocity field $u(t)$. Same colorbar used in all sub-figures.

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Influence of uniform blowing on turbulent boundary layers: POD analysis of large scale structures**G. Hasanuzzaman¹ and Ch. Egbers¹**¹ Department of Aeodynamics and Fluid Mechanics, Brandenburg University of Technology, Germany*Corresponding author: G. Hasanuzzaman (gazihasanuzzaman.me@live.com)***Keywords:** Turbulent Boundary Layer, Particle Image Velocimetry, Flow control, Friction drag.

Most aerodynamic systems operate in the turbulent regime, where skin-friction drag constitutes nearly half of the total drag. Although geometric streamlining reduces pressure drag, friction drag remains a dominant contributor to fuel consumption and operating costs. Therefore, understanding and manipulating near-wall turbulence dynamics is essential for efficient drag-reduction strategies.

In the present study, uniform blowing through a porous surface is applied as an active flow-control technique to modify turbulent boundary layer (TBL) structures. The focus is placed on the interaction between wall-normal mass flux and large-scale coherent motions. Experiments were conducted using Stereo Particle Image Velocimetry (SPIV) over a shear Reynolds number range $0.4 \times 10^3 \leq Re_\tau \leq 5.6 \times 10^3$. Measurements were performed in two wind tunnel facilities at Brandenburg University of Technology and the University of Lille. Detailed descriptions of the blowing implementation and instrumentation are reported in [1]. Figure 1(a) shows the effects of wall-normal blowing at $Re_\theta \approx 7500$. Figure (left) presents an instantaneous velocity field, with color contours for streamwise velocity and vectors for in-plane components, revealing elongated low- and high-speed streaks and strong spanwise modulation. Compared to smooth-wall cases, blowing enhances outer-layer activity, promotes larger coherent motions, and redistributes turbulent energy away from the near-wall region. Figure 1 (right) displays pre-multiplied energy spectra at $y^+ \approx 25$, showing increased energy with higher blowing rates ($F = 0\% - 6\%$), particularly at intermediate and large scales, while the inertial subrange roughly follows $k^{-5/3}$. The spectral shift toward lower wavenumbers indicates strengthened outer-layer structures and altered interscale energy transfer, consistent with instantaneous flow observations and modified production and transport in the logarithmic region.

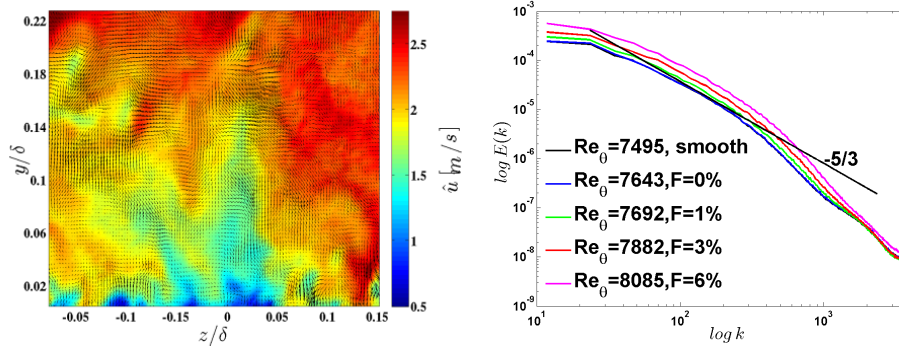


Figure 1: (left) Instantaneous velocity field with uniform blowing, (right) Pre-multiplied energy spectra at $y^+ \approx 25$ for different blowing rates. The inertial subrange scaling ($k^{-5/3}$) is indicated in vertical direction. [1]

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Multimodal Learning for Fluid Flows: Joint Representation and Bidirectional Inference from Heterogeneous Measurements

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Keywords: multimodal learning, invertible neural networks, flow estimation, wall-bounded turbulence.

Heterogeneous flow measurements provide rich and complementary information for probing complex fluid dynamics. Yet, many existing methods either treat each modality separately or learn a one-way mapping, leaving complementary information underexploited and hindering a more comprehensive characterization of flow physics. In this work, we propose a multimodal joint representation and modeling framework designed to systematically integrate heterogeneous observations and support downstream tasks such as flow sensing and reconstruction. Specifically, we adopt an encoder–decoder architecture for each modality and couple the latent representations through an Invertible Neural Network (INN) [1, INN], which provides an exact inverse mapping and thus enables a bijective cross-modal transform. All components are trained end-to-end using both forward and inverse cross-modal reconstruction losses; the INN is thereby jointly regularized through bidirectional supervision, enabling the framework to learn a more well-posed and consistent cross-modal correspondence. The proposed framework is evaluated on a turbulent channel flow at $Re_\tau = 200$, considering two modalities: the three-component velocity fields (u, v, w) at $y^+ = 15$ and the wall quantities $(\tau_{w,x}, p_w, \tau_{w,z})$. The INN parametrizes the forward transform $f : \mathcal{Z}_u \rightarrow \mathcal{Z}_\tau$ together with its exact inverse $f^{-1} : \mathcal{Z}_\tau \rightarrow \mathcal{Z}_u$. The proposed method robustly extracts shared cross-modal information, enabling consistent bidirectional flow estimation, i.e. reconstructing velocity fields from wall measurements for flow sensing and inferring wall shear stress from velocity fields toward wall-stress modeling. The relative cross-modal estimation errors of the fluctuating components in the testset are 3.7%, 6.7%, and 7.6% for (u, v, w) , and 3.7%, 14.5%, and 9.3% for $(\tau_{w,x}, p_w, \tau_{w,z})$, respectively. Moreover, this framework can be extended to partially paired settings (e.g., sparse or asynchronous measurements) by incorporating self-reconstruction and cycle consistency objectives, underscoring its potential for practical applications.

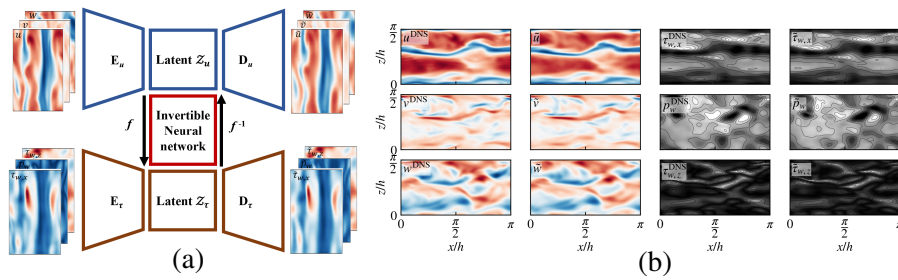


Figure 1: Overview of the proposed approach: (a) schematic illustration of the framework; (b) example snapshots of bidirectional cross-modal estimation.

Acknowledgments

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Event-Driven Flow Reconstruction via Physics-Informed Spiking Neural Networks

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Keywords: Spiking Neural Networks, Neuromorphic sensing, Convolutional Neural Networks.

Deep Learning has significantly advanced fluid mechanics, yet the computational cost of state-of-the-art architectures continues to grow. Spiking Neural Networks (SNNs), often referred to as the third generation of neural networks [1], have emerged as an energy-efficient alternative by encoding information as binary, event-driven spike trains, enabling ultra-fast and low-power computation on neuromorphic hardware. However, binary encoding introduces information loss and challenges in training, and despite recent progress in classification tasks [2], applications in fluid mechanics remain limited. In this work, we propose a physics-informed hybrid SNN framework for flow field reconstruction from binary spike trains. Velocity fluctuations from DNS of the fluidic pinball are encoded via rate coding with ON/OFF polarity channels $[u^+, u^-, v^+, v^-]$. A convolutional Leaky-Integrate-and-Fire (LIF) encoder compresses temporal flow features into a three-channel latent representation, decoded by a Convolutional Neural Network (CNN) whose output layer is a learned depthwise spatial filter. Divergence-free and vorticity penalties enforce physical consistency during training. The method achieves 11% relative reconstruction error at $Re = 150$, outperforming an equivalent CNN with identical architecture and binary inputs by 8%, confirming that LIF temporal integration produces more physically consistent fields from sparse spike data. The model generalises to the unseen $Re = 120$ with 17% error without any finetuning. The final contribution will compare fully spiking and hybrid neuromorphic approaches to identify the most promising strategy for fluid mechanics applications.

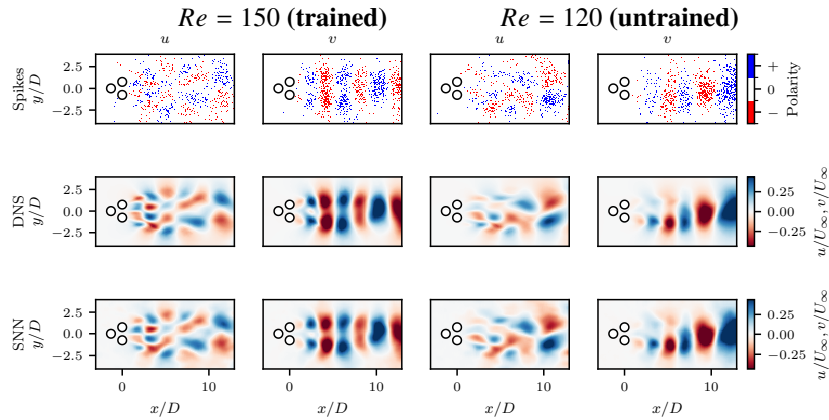


Figure 1: Example of reconstructed snapshots: left $Re = 150$ (trained), right $Re = 120$ (untrained). First row: input spikes for u and v ; second row: reference DNS data; third row: SNN reconstructions.

Acknowledgments

This work was supported by the project SPANDRELS (SParse AND paRsimonious Event-based fLow Sensing), which has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101171280 (ERC-2024-COG). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

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Resolvent Analysis and Spectral Proper Orthogonal Decomposition of rotating turbulent channel flows

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Keywords: Coherent Structures, Resolvent Analysis, Rotating Channel Flow, Wall-bounded Turbulence

Resolvent analysis has emerged as a powerful theoretical framework for modeling coherent structures in turbulent flows by identifying the most amplified linear responses to nonlinear forcing. This study extends its application to rotating turbulent half-channel flows at a high friction Reynolds number ($Re_\tau \approx 5200$ based on the friction velocity in the nonrotating case), where Coriolis force fundamentally alters the momentum balance. We evaluate the fidelity of the resolvent operator in predicting the dominant Large-Scale Motions (LSM) by comparing its leading response modes against Spectral Proper Orthogonal Decomposition (SPOD) extracted from a Wall-Modeled Large-Eddy Simulation (WMLES). The simulation is performed such that the final mean velocity is approximately aligned with the x -direction of the code. The linear operator is constructed using the mean velocity profiles obtained directly from the WMLES and augmented with an eddy-viscosity profile. Crucially, this eddy-viscosity model is scaled by the final friction Reynolds number to capture the rotation-induced reduction in turbulence. The results demonstrate a good agreement between the resolvent and SPOD modes across different rotation rates, confirming that this enhanced resolvent framework can reliably capture the topology and scaling of energy-containing structures in high-Reynolds-number rotating flows.

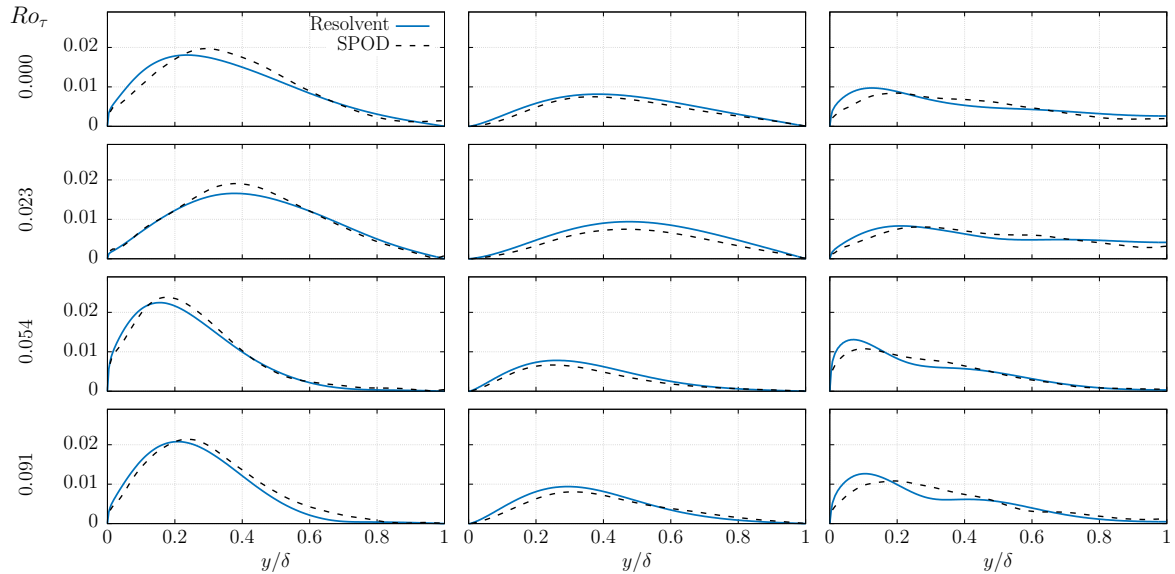


Figure 1: Comparison between the resolvent and SPOD for the first mode of the streamwise (left), wall-normal (middle), and spanwise (right) velocity components for the large-scale structures with wavelengths $(\lambda_x/\delta, \lambda_z/\delta, \lambda_t u_\tau/\delta) = (3.14, 1.05, 0.13)$. Results are shown for rotation numbers $Ro_\tau = 0.000, 0.023, 0.054$, and 0.091 (from top to bottom).

**Spectral Proper Orthogonal Decomposition of a turbulent channel flow from a coarse
Wall-Modeled Large-Eddy Simulation****Mateus P. Ribeiro¹, Matheus T. de Araújo², Leandro F. de Souza¹, André Cavalieri³,
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Spectral Proper Orthogonal Decomposition (SPOD) extracts spatially coherent structures evolving at specific frequencies, providing a rigorous way to separate energetic modes from complex multiscale turbulence and serving as an empirical benchmark to validate theoretical frameworks like Resolvent Analysis. This study assesses the fidelity of SPOD modes from a coarse Wall-Modeled Large-Eddy Simulation (WMLES) of a turbulent half-channel flow at $Re_\tau = u_\tau \delta / \nu \approx 950$ against Direct Numerical Simulation (DNS). Despite significant grid coarsening and boundary condition errors, WMLES accurately captures the main characteristics of the most energetic structures across various large-scale wavelengths. These results confirm that WMLES is a reliable, computationally efficient tool for investigating coherent structures at higher Reynolds numbers where DNS is prohibitive.

Table 1: Computational parameters (δ denotes the half-channel height).

	Re_τ	Domain ($L_x \times L_y \times L_z$)	Grid ($N_x \times N_y \times N_z$)
Ying et al. [1] (DNS)	934	$(4\pi \times 2 \times \pi)\delta$ (full channel)	$1536 \times 385 \times 768$
Present work (WMLES)	950	$(4\pi \times 1 \times 2\pi)\delta$ (half-channel)	$64 \times 64 \times 64$

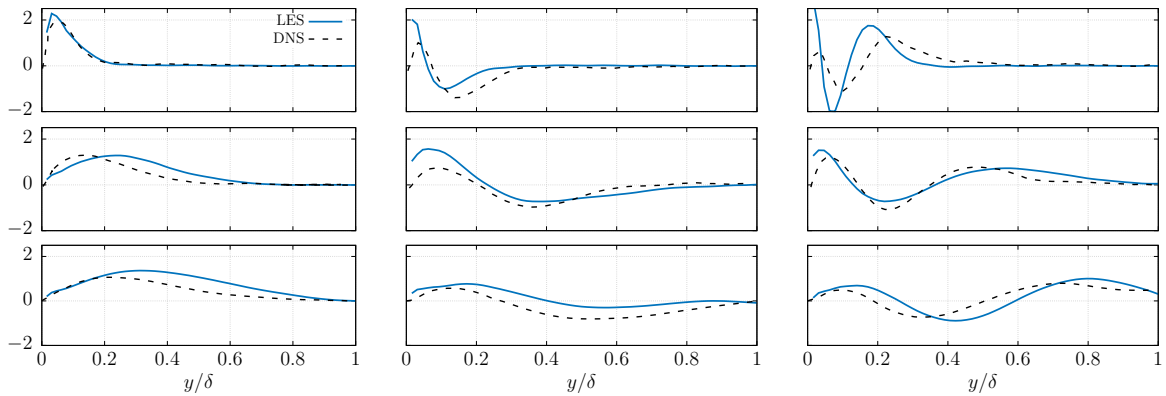


Figure 1: Comparison of the first (left), second (middle) and third (right) modes of the streamwise velocity component for the large-scale structures with wavelengths $(\lambda_x/\delta, \lambda_z/\delta, \lambda_t u_\tau/\delta) = (1, 0.2, 0.06)$ (top), $(2, 0.4, 0.11)$ (middle) and $(4, 0.8, 0.23)$ (bottom).

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Identification and reconstruction of high-frequency fluctuations evolving on a low-frequency base-flow

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Keywords: Quasi-steady approximation, Spectral POD, Resolvent analysis.

Oftentimes, turbulent flows exhibit a high-frequency component evolving on top of a strong low-frequency base-flow. In such cases, the base-flow motion may strongly influence the spatial-temporal features of the high-frequency component. A typical example of such behavior is the flow around bluff bodies, for which the high-frequency components, exemplified by Kelvin–Helmholtz structures associated with thin shear layers, depend on the phase of the low-frequency vortex-shedding base-flow. In figure 1 (a) we present this phenomenon for the case of the square-cylinder flow, at Reynolds number 22000, showing four different (and equi-spaced) phases.

If the low-frequency component is periodic, a general Harmonic-Resolvent [1] and a Cyclostationary-SPOD [2] analyses can be employed to model the high-frequency component and to identify it from data. In fact, those analyses do not require such frequency separation. This generality comes at a computational cost of dealing with extended-size matrices, accounting for the harmonics.

In this work, we exploit the frequency separation, using the Quasi-Steady approximation. We will assume that the high-frequency fluctuations have their cycle at almost the same phase of the low-frequency component, allowing us to formulate a simplified, phase-dependent, resolvent and SPOD analyses. In figure 1 (b) and (c), we provide some results on the resolvent and SPOD analyses, respectively, for the bluff-body case, presented in (a), at the same phases. We believe that, in addition to their computational simplicity (those analyses have both the same costs of classical resolvent and SPOD, for each phase), the present analyses may be more general than the previous ones, as they do not explicitly require a periodicity of the base-flow. This work was based on the author's previous paper [3].

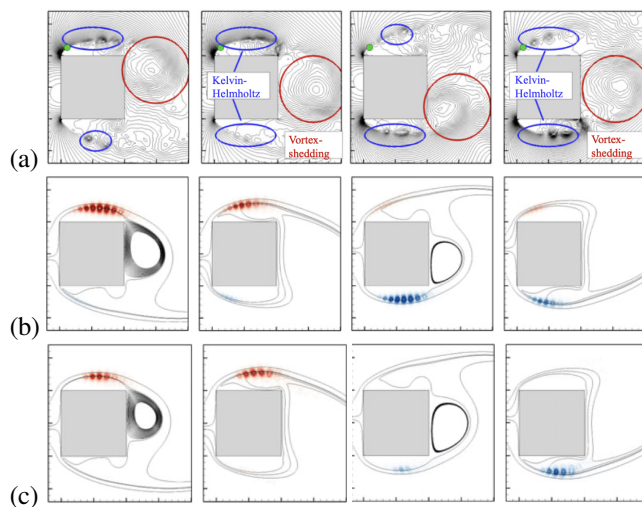


Figure 1: (a) Kelvin-Helmholtz modes evolving on Vortex-Shedding on a square-cylinder-flow, (b) resolvent and (c) SPOD analyses results.

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Flow oscillators vs. amplifiers in thermoacoustic instabilities – a global weakly nonlinear approach

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Keywords: Weakly nonlinear analysis, hydro-thermoacoustic mode interaction

The response of flames to acoustic perturbations impacts the thermoacoustic stability of combustion devices. Since technical relevant flames are often acoustically compact, shorter wavelength hydrodynamic structures are crucial intermediaries to disturb the flame. These hydrodynamic structures may either originate from autonomous oscillators in the flow at a set frequency, or are the result of convective amplification over a range of frequencies. Mitigation strategies of thermoacoustic instabilities may then differ depending on how the flow contributes, e.g., de-tuning of oscillators or alteration of shear distributions for amplifiers. While direct transient simulations include the interaction between flow and flame, the flow's role as oscillator or amplifier often remains obscured. On the other hand, the linear limit of the reactive flow equations allows to identify individual modes, but prohibits the possibility of mode interaction. We aim to bridge this gap using a weakly nonlinear expansion of the compressible and reactive Navier-Stokes equations. We investigate the canonical configuration of a ducted flame placed downstream of a cylinder. Reynolds number, length and acoustic terminations of the duct are tuned such that the wake and thermoacoustic mode become simultaneously unstable. The resulting slow dynamics are expressed on the centre-manifold of the corresponding double Hopf bifurcation by means of a multiple time-scales approach. Since the corresponding normal form is computed from first principles, we can attribute flow regions and specific nonlinearities to the mode coupling. Finally, either the thermoacoustic or wake mode are suppressed by taking the limit of zero Mach number or enforcing symmetry of the wake, respectively. Doing so, the impact of mode coupling on the resulting thermoacoustic instability is isolated and qualitative differences between thermoacoustic instabilities where the flow contributes as oscillator or amplifier are assessed.

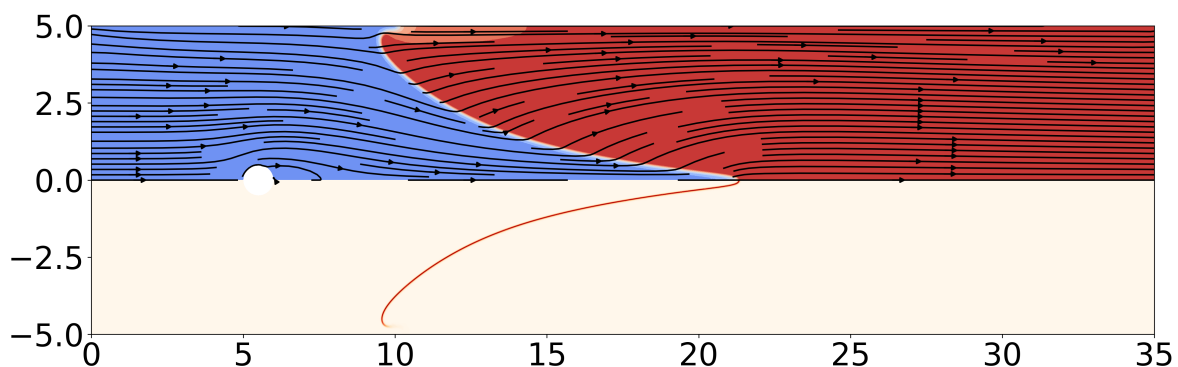


Figure 1: Base flow of ducted flame downstream of a cylinder: Temperature field with streamlines (top) and heat release field (bottom).



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Modeling of Reaction Dynamics in a Turbulent Hydrogen-Air Slot Flame Using Resolvent Analysis

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Keywords: Resolvent Analysis; Turbulent Flame; Spectral Proper Orthogonal Decomposition; Direct Numerical Simulation.

Understanding coherent structures in turbulent reacting flows is essential for predicting combustion dynamics and enabling flow control. Resolvent analysis (RA) has proven effective for identifying dominant amplification mechanisms in turbulent flames. Previous studies [1] applied RA to circular methane–air jet flames using a passive flame approach that neglects reaction-rate fluctuations. More recently, active-flame formulations incorporating linearized reaction-rate models were introduced to account for flow–chemistry coupling [2, 3]. While successful for methane–air jet flames, their applicability to hydrogen combustion remains unclear due to thermodynamic effects that strongly influence hydrogen–air flame dynamics. Here, we assess whether an active-flame resolvent framework can capture the dominant coherent structures in a turbulent lean hydrogen–air slot flame.

Direct Numerical Simulation (DNS) data of a piloted turbulent hydrogen–air slot flame are analyzed using Spectral Proper Orthogonal Decomposition (SPOD) to extract dominant coherent structures and characteristic frequencies. The DNS corresponds to a lean premixed flame with equivalence ratio $\Phi = 0.4$ and Reynolds number $Re = 5500$. SPOD reveals pronounced energetic structures in the range 300–1000 Hz, with anti-symmetric fluctuations dominating heat-release dynamics and exhibiting clear low-rank behavior. Furthermore, we observe distinct peaks in the SPOD spectrum of heat release, which we attribute to intrinsic flame instabilities.

Resolvent analysis is performed by linearizing the governing equations around the DNS mean flow. Chemical reactions are modeled through an active-flame approach. Comparison with SPOD shows good agreement in both spectral amplification and spatial mode shapes, reproducing the dominant velocity, progress-variable, and heat-release structures across the energetic frequency band. The optimal forcing is located outside the turbulent flame brush in the surrounding free stream, in contrast to non-reacting jets where forcing typically peaks in the nozzle shear layer [4].

Overall, the results show that thermodynamic effects in hydrogen flames do not fundamentally hinder the application of active-flame resolvent frameworks developed for methane–air configurations. However, discrepancies in the predicted reaction-rate structures indicate that refinements of the linearized reaction closure are required, supporting further development of resolvent-based models for hydrogen combustion.

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Recent progress on data-driven resolvent analysis

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Keywords: Data-driven methods, resolvent analysis, mean-field-based modelling.

Resolvent analysis is a rigorous framework to identify linear energy amplification mechanisms in non-normal dynamical systems that has been extensively used to predict, control, and understand the dynamics of laminar and turbulent flows [1–4]. However, for flows involving complex geometries and/or multiple physics, this analysis becomes implementation-heavy and computationally expensive, thus requiring the use of specialized codes that are typically only available in academic environments [5, 6]. Data-driven resolvent analysis (DDRA) is an alternative approach that allows computing resolvent modes and gains directly from time-resolved measurement data, and without requiring the governing equations [7], as shown schematically in figure 1. In this talk, we discuss the main limitations of the original DDRA formulation and review our recent research efforts to extend its capabilities. More specifically, we present the progress in addressing three challenges that are key to improve the usefulness of the method; dealing with nonlinearity, partially observed dynamics, and multiphysics systems. From our results, we identify promising opportunities for future research aiming at enabling physics learning from large datasets of industrially relevant turbulent flows.

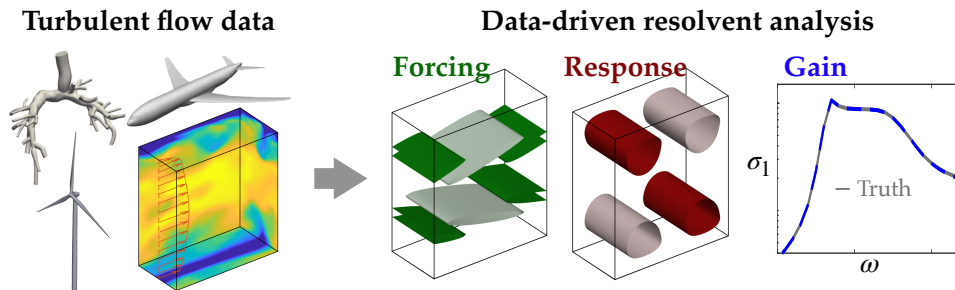


Figure 1: Data-driven resolvent analysis extracts physical insight from turbulent flow data.

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Lifecycle Statistics of Cavitating Structures

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Keywords: cavitaiton; vortex-ring; life-cycle statistics; collapse.

Cavitation vortex structures provide an example of coherent flow features shaped by the interaction of hydrodynamic instabilities and phase-change effects. In the upcoming presentation, we investigate the evolution of repeatedly generated cavitating structures in a cyclic vortex-ring configuration using high-speed imaging. Rather than focusing on a purely phase-averaged description, the analysis is formulated in an event-based manner to account for the fact that individual cavitation clouds may emerge, convect, deform, and break up with significant cycle-to-cycle variability.

The analysis combines image segmentation and object-based tracking to identify individual cavitating structures and to estimate key lifecycle statistics, including lifetime, transport distance, and breakup location. This provides a compact, physically interpretable description of the cloud evolution from formation to fragmentation and is intended to assess to what extent recurring patterns can be separated from cycle-to-cycle variability. The study is conceived as an exploratory step toward a data-driven characterization of coherent structures in multiphysical unsteady flows, with particular emphasis on the statistical structure of transport and breakup events.

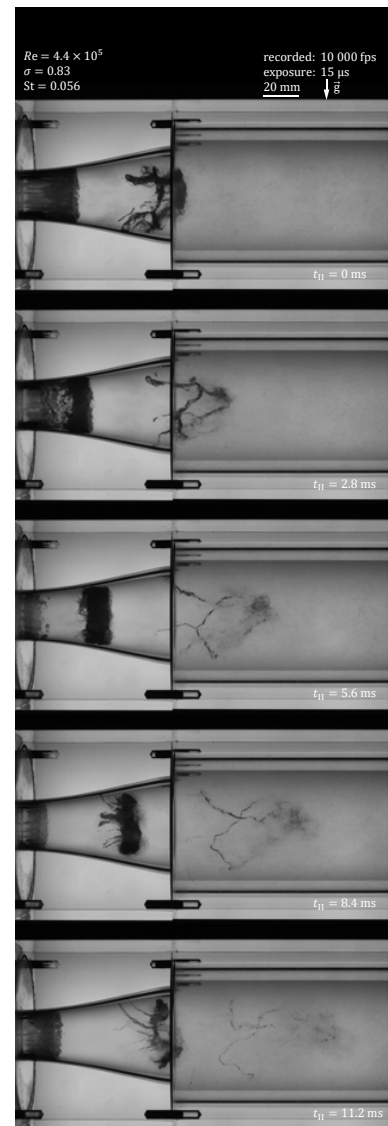


Image series of cavitating vortex-rings. One exemplary cycle from generation in the throat section (left) to the collapse in the plenum (right).

Effects of flexibility in airfoil self noise**Eduardo Martini¹, Pedro K. de Azevedo¹, Marios-Ioannis Spiropoulos¹, Nicolas Alfarez², Peter Jordan¹**¹ DFTC-2AT, Institut Pprime, CNRS – Université de Poitiers – ISAE-ENSMA, UPR 3346, 11 Boulevard Marie et Pierre Curie, Poitiers, 86073, Vienne, France² DynFluid, Conservatoire National des Arts et Métiers, Paris, France

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Keywords: Aeroacoustics, Fluid-Structure Interaction, Direct Numerical Simulation

Trailing-edge noise is a significant source of aerodynamic noise, particularly in applications such as wind turbines, aircraft wings, and propellers. This noise is generated by the interaction of turbulent flow structures with the trailing edge of an airfoil, which scatters turbulent energy into the acoustic field [1].

Different strategies have been studied to mitigate this phenomenon, such as bio-inspired geometrical modifications (e.g., serrations) or porous materials [2–4].

The use of structural flexibility has also been explored as a noise reduction approach, and it has been shown to act directly on the mechanism of sound generation, decreasing the acoustic scattering of the near-field pressure into the acoustic field.

In this work, the impact of trailing-edge flexibility on the aeroacoustics of a NACA-0012 airfoil is investigated. As an initial study, we focus on the problem of a whistling airfoil. A fluid-structure interaction solver, which solves the flow dynamics explicitly and the structural dynamics implicitly, is used to continuously map the transition between a rigid and a flexible airfoil. In particular, we explore whether trailing-edge flexibility can be used to reduce the scattered noise or suppress the feedback loop that leads to tonal noise. Figure 1 shows preliminary results for the airfoil at a Reynolds number of $Re = 10^5$ and an angle of attack of $\alpha = 3^\circ$. In it, the formation of self-sustained vortical structures and the associated acoustic footprint c :

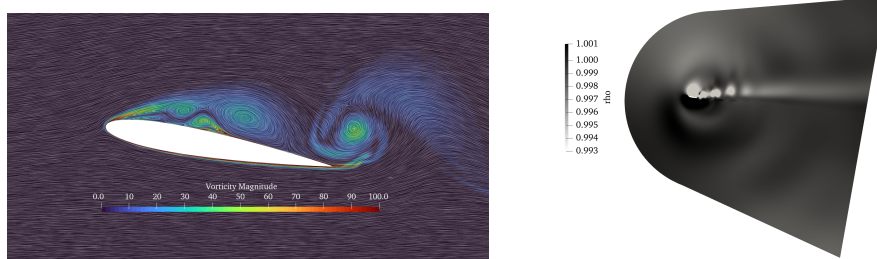


Figure 1: Vorticity (left) and density (right) fields for a NACA-0012 airfoil.

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Jet-edge interaction tones: a stochastically forced Stuart–Landau Oscillator?

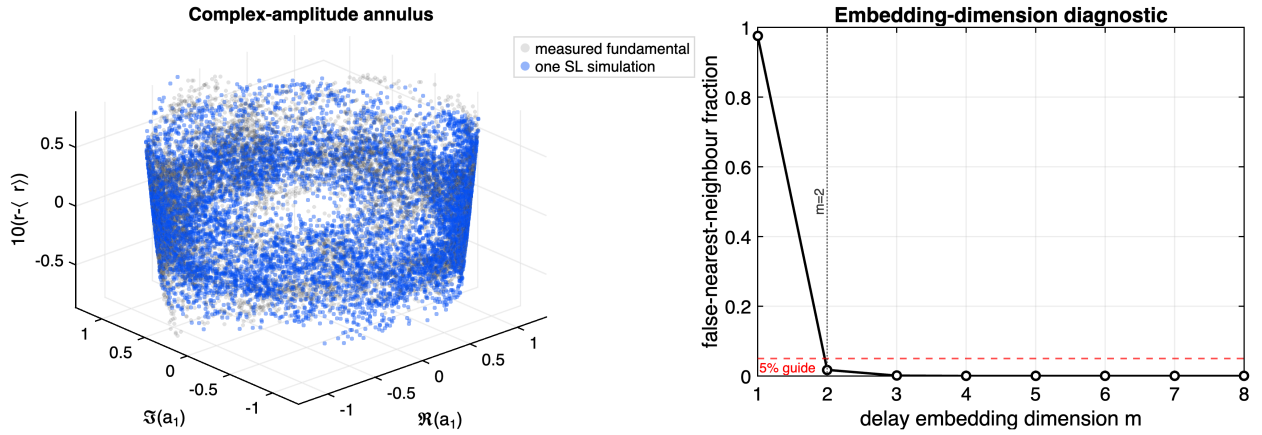
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Abstract. The interaction between a turbulent jet and an edge produces strong tonal components embedded in a broadband turbulent background. The question addressed here is whether such a jet–edge interaction tone can be interpreted as the signature of a low-dimensional oscillator. We take the cautious viewpoint: the full signal is not expected to be a clean deterministic attractor, but it may contain a low-dimensional oscillator backbone continuously perturbed by turbulent forcing.

We analyse one scalar time series for a reference case at Mach $M_j = 0.82$. The spectrum contains a dominant fundamental, $f_1 \simeq 2.99$ kHz, and a coherent harmonic ladder. Complex demodulation about f_1 gives a slowly varying complex amplitude $a_1(t) = r(t) \exp[i\theta(t)]$. The measured state forms a noisy annulus, and a stochastic Stuart–Landau reduced-order model (ROM) fitted to the same amplitude occupies a similar annular state. A false-nearest-neighbour diagnostic applied to a filtered fundamental delay embedding falls below the 5% guide by $m = 2$, giving a first indication that the fundamental oscillator coordinate is low-dimensional.



The stochastic model is tested through finite-time conditional moments of the measured radius. The conditional mean radial velocity has the cubic restoring form expected from a Stuart–Landau normal form,

$$dr = (\mu r - \beta r^3) dt + \sqrt{2D_r(r)} dW_r,$$

and gives a stable operating radius r_0 . Harmonic bicoherence and phase-locking show that the higher tones are not independent oscillators: they behave largely as nonlinear observations of the fundamental. Their amplitudes, however, are more strongly contaminated by broadband turbulence, so including weak harmonics increases the apparent dimension. This is interpreted as an observation-layer effect rather than as evidence against a low-dimensional oscillator core.

A first generative check uses the fitted radial drift together with a calibrated state-dependent diffusion $D_r(r)$. For $M_j = 0.82$, the generated ensemble reproduces the measured mean radius, radial variance, and amplitude probability density with useful accuracy: the measured and generated radial standard deviations are approximately 0.0260 and 0.0262, and the amplitude-PDF overlap is about 0.94. The main remaining mismatch is temporal: the generated radial decorrelation is slightly too slow. This suggests that the next model refinement should target coloured or slowly varying turbulent forcing, radial–phase noise coupling, and a more explicit noisy harmonic observation map.

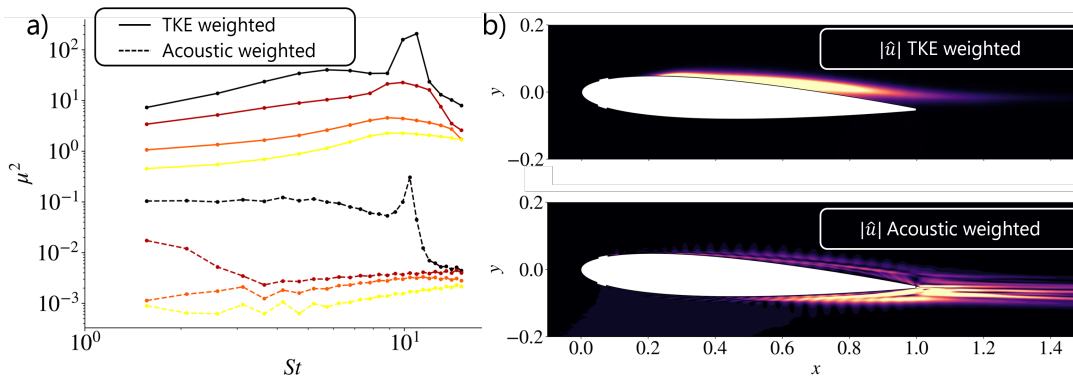
The results suggest the possibility of a synchronizable stochastic ROM: a Stuart–Landau oscillator core, calibrated process noise, and noisy nonlinear harmonic observations. We will next test whether this description survives across Mach number, especially through the observed change of dominant global mode between $M_j = 0.82$ and $M_j = 0.87$. If the carrier frequency, drift coefficients, diffusion scale, and observation map vary coherently through this transition, the method could provide a quantitative bridge between qualitative dynamical-systems diagnostics and physics-based modelling of turbulent jet–edge oscillators.

Keywords: jet–edge interaction; turbulent oscillator; Stuart–Landau model; nonlinear system identification; stochastic reduced-order model.

A low-order model of the coherent structures driving airfoil broadband trailing-edge noise**S. Demange¹, Z. Yuan², A. Hanifi², A. Cavalieri³, K. Oberleithner¹**¹ Laboratory for Flow Instability and Dynamics, Technische Universität Berlin, 10623 Berlin, Germany² FLOW, Department of Engineering Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden³ Divisão de Engenharia Aeronáutica, Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil*Corresponding author: S. Demange (s.demange@tu-berlin.de)***Keywords:** Airfoil aeroacoustics, resolvent, low-order modelling.

Broadband trailing-edge (TE) noise is a major contributor to airfoil acoustic emissions in clean inflow conditions and remains a limiting factor for wind-energy systems and aircraft. TE noise originates from the scattering of turbulent boundary-layer fluctuations at the TE. While numerous models provide quantitative predictions, identifying the coherent flow structures most relevant to noise generation remains an open question. For tonal TE noise associated with transitional boundary layers, the dominant sound-producing mechanisms can be related directly to global modes of the linearized Navier–Stokes equations [1]. In fully turbulent boundary layers, however, the broadband nature of the flow complicates a low-order description. We investigate whether a reduced set of coherent structures can still capture the sound-generating dynamics. We employ resolvent analysis about the mean flow from a large-eddy simulation of a NACA0012 airfoil at fully turbulent conditions. Alongside a conventional turbulent-kinetic-energy (TKE) norm, we consider an acoustic-output weighting inspired by recent developments for turbulent jets [2].

Figure 1 compares gain spectra and leading response modes from both formulations. The acoustic-weighted resolvent exhibits substantially more low-rank dynamics than the TKE-weighted formulation, particularly at low frequencies, suggesting that only a limited subset of energetic structures contributes efficiently to sound generation. While the leading modes remain qualitatively similar at low frequencies, substantial differences emerge at higher frequencies, indicating distinct mechanisms selected by the two formulations. Both formulations additionally reveal an amplification peak around $St \approx 10$. The associated response mode is localized within the recirculation downstream of the TE. Since no corresponding feature is observed in data-driven decompositions of the LES snapshots, this resonance may reflect limitations of the underlying mean-flow model and its closure assumptions. Ongoing work investigates the role of eddy diffusivity through RANS data-assimilation modelling.

Figure 1: (Gains from the TKE- and acoustic-weighted formulations (a) and leading mode shapes at $St = 15$ (b))**References**

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Linear amplification mechanisms in axisymmetric stenotic flows: from LES to MRI data

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Keywords: Resolvent analysis, Stenosis, Coherent structures, Transitional flow

This study investigates the capability of resolvent analysis (RA) to model transitional and turbulent dynamics in an axisymmetric smooth stenosis. We aim at explaining the amplification mechanisms derived from the mean field using a physics-based model. We analyze two mean flows sharing the same geometry. A three-dimensional transitional large-eddy simulation (LES) generates the first mean flow, enabling the computation of spectral proper orthogonal decomposition (SPOD) modes for validation. Here, a steady laminar jet emerging from the contraction forms a shear layer highly susceptible to convective amplification and subsequent turbulent breakdown. *In vitro* four-dimensional phase-contrast magnetic resonance imaging (4D flow MRI) measurements, enhanced through data assimilation, provide the second experimental mean flow. For both cases, time- and azimuthal-averaging yield an axisymmetric velocity field, while assimilating the Reynolds-averaged Navier-Stokes equations produces a frozen eddy viscosity field. Global Linear Stability Analysis reveals an unstable stationary mode ($m = 1$) associated with the recirculation bubble's breathing motion, alongside a damped global vortex shedding mode ($St = 0.5, m = 0$) that matches the resonance observed in the SPOD spectrum. Resolvent analysis confirms the dominance of the stationary mode at low frequencies and identifies a shear-layer convective instability at intermediate frequencies. Within this regime, the optimal resolvent response mode demonstrates high gain separation and strong alignment with the leading SPOD mode. Furthermore, pseudospectral analysis confirms that broadband amplification arises primarily from the non-normal interaction of multiple eigenmodes rather than from a modal instability. The forcing SPOD modes are very structured at the resonance harmonic frequencies, which explains why the resolvent does not capture the resonance mechanism. Ultimately, linear mechanisms effectively capture complex transitional post-stenotic dynamics, providing physically interpretable insights into the underlying flow physics.

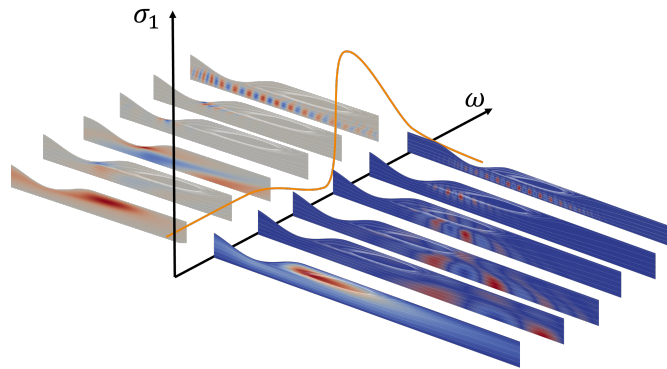


Figure 1: Illustration of the resolvent forcing/response pairs along with the resolvent gains, for axisymmetric fluctuations at different frequencies.