Coherent structures in aeroacoustics

ERCOFTAC SIG 39 Symposium

10^{th} - 12^{th} June, Rome, Italy

Contents

About

Objectives

The Ercoftac SIG 39 Symposium, *Coherent Structures in Aeroacoustics*, will gather experts to discuss recent progress in the identification, understanding and modelling of coherent structures in turbulent flow. The symposium objective will be to debate on the role played by coherent structures in aeroacoustics and identify perspectives for future research.

Chairpersons

Peter Jordan,
Institut Pprime,
CNRS · Université de Poitiers · ISAE-ENSMA,
Poitiers, France.

Matteo Mancinelli,
Dept. Civil Eng., Computer Science & Aeronautics,
Università Roma Tre,
Rome, Italy.

Scientific committee

Dan Bodony Christophe Bogey Roberto Camussi Damiano Casalino

André Cavalieri Tim Colonius Daniel Edgington-Mitchell Flavio Giannetti

Lutz Lesshafft Stephane Moreau Kilian Oberleithner Dani Rodriguez

Michel Roger Oliver Schmidt Christophe Schram Aaron Towne William Wolf

Abstract submission

A 200 word abstract should be submitted to ercoftacaeroacoustics@gmail.com by March 29th 2024.

The venue

The symposium will be held in the lecture hall of the Department of Civil, Computer Science and Aeronautical Technologies Engineering of Università degli Studi Roma Tre.

Context and motivation

Coherent structures, first observed in turbulent shear flow in the 1960s, motivate the search for simplified models that would clarify the mechanisms by which turbulence is sustained. In the past twenty years, thanks to advances in numerical simulation, modelling and experimental diagnostics, our understanding of coherent structures in turbulent shear flow has progressed considerably and promising new modelling paradigms are emerging [5].

Aeroacoustics applications involve a variety of flow regimes, many of which are turbulent. An aircraft at take-off or approach generates wakes, boundary layers, free shear-layers, trailing edge flow, resonant flow, turbulence that sheds from, impinges on and grazes all manner of surfaces... In many of these regimes, there is evidence for the existence and aeroacoustic importance of coherent structures; in others, the role they play remains to be clarified.

Aeroacoustic modelling frameworks rely on input from a turbulent field, in the form of direct space-time data in hybrid approaches, via the statistics that inform sound-source models in acoustic analogies. Simplified models of turbulent flow are therefore of interest for aeroacoustics, on account of the low-cost prediction methodologies they would enable and the opportunities they provide for understanding mechanisms. These points have been highlighted in recent reviews on trailing-edge noise [4], on jet noise [3, 1] and on resonant flows [2].

Research in aeroacoustics is increasingly supported by an abundant availability of data. Modern experimental measurement techniques, along with new computational and data-storage architectures, make possible the generation, storage and mining of Big Data. And this has led to a flourishing of new data-processing algorithms and methodologies. Among these, modal decomposition techniques, particularly well-suited to the identification of coherent structures in turbulence, are finding broad application [6, 7].

The goal of the symposium is to bring together members of the scientific community for a three-day event involving presentations on, and discussion of, coherent structures, their role in aeroacoustics, and the perspectives they invite for future developments.

The event will comprise oral presentations and round-table discussions. Social events will include 3 lunches, wine-tasting and a symposium dinner at the beach on the final night.

Bibliography

[1] A. V.G. Cavalieri, P. Jordan, and L. Lesshafft. Wave-packet models for jet dynamics and sound radiation. *Applied Mechanics Reviews*, 71(2), 2019.

[2] D. Edgington-Mitchell. Aeroacoustic resonance and self-excitation in screeching and impinging supersonic jets–a review. *International Journal of Aeroacoustics*, 18(2-3):118–188, 2019.

[3] P. Jordan and T. Colonius. Wave packets and turbulent jet noise. *Annual Review of Fluid Mechanics*, 45(1), 2013.

[4] S. Lee, L. Ayton, F. Bertagnolio, S. Moreau, T. P. Chong, and P. Joseph. Turbulent boundary layer trailing-edge noise: Theory, computation, experiment, and application. *Progress in Aerospace Sciences*, 126:100737, 2021.

[5] B.J. McKeon. The engine behind (wall) turbulence: perspectives on scale interactions. *Journal of Fluid Mechanics, Perspectives*, 817, 2017.

[6] K. Taira, S. L. Brunton, S.T.M. Dawson, C.W. Rowley, T. Colonius, B. J. McKeon, O. T. Schmidt, S. Gordeyev, V. Theofilis, and L. S. Ukeiley. Modal analysis of fluid flows: An overview. *Aiaa Journal*, 55(12):4013–4041, 2017.

[7] A. Towne, O. T. Schmidt, and T. Colonius. Spectral proper orthogonal decomposition and its relationship to dynamic mode decomposition and resolvent analysis. *Journal of Fluid Mechanics*, 847:821–867, 2018.

Timetable

Monday, 10^{th} of June

Sala Conferenze, Dept. Civil, Computer Science and Aeronautical Engineering, Via Vito Volterra, 62, 00154 Roma

8:30–9:15		**Registration**	
9:15–9:30		**Welcome**	
Session 1		**Jets I**	
9:30–10:00		**E. Eichberger**	Local resolvent bases for modelling jet turbulence and acoustic radiation
10:00–10:30		**B. Hasparyk**	Resolvent modelling of jet noise
10:30–11:00		**J. Von Saldern**	On the role of eddy viscosity modelling in jet flow resolvent analysis
11:00–11:30		**Coffee**	
Session 2		**Jets II**	
11:30–12:00		**P. Nogueira**	The flapping mode in screeching jets
12:00–12:30		**M. Samimy**	The role of coherent structures in the acoustics of supersonic jets
12:30–13:00		**T. Golliard**	Coherent structures and aeroacoustics of a swirling supersonic jet exhausting an aerospike nozzle
13:00–14:30		**Lunch**	
Session 3		**Flow-structure interaction I**	
14:30–15:00		**M. Spiropoulos**	Wake-airfoil interaction noise
15:00–15:30		**S. Moreau**	Coherent structures in turbomachines and their noise signature
15:30–16:00		**C. Tinney**	The XX-Topos form of the Gappy POD using Vold-Kalman filters for structure reconstruction using reduced sensor sets
16:00–16:30		**Coffee**	
16:30–17:30		**Roundtable 1: Coherent structures and aeroacoustic modelling: implications and perspectives?**	
18:00–. . .		**Wine tasting. . .**	

Tuesday, 11th of June

Sala Conferenze, Dept. Civil, Computer Science and Aeronautical Engineering, Via Vito Volterra, 62, 00154 Roma

Session 4	**Jets III**		
9:00–9:30		**D. Rodriguez**	On the identification of acoustically relevant large-scale structures for subsonic jets using correlation techniques in the time domain
9:30–10:00		**L. Heidt**	Coherent structures in forced turbulent jets
10:00–10:30		**G. Tissot**	Coherence decay in turbulent jets by stochastic modelling under location uncertainty
10:30–11:00		**A. Bongarzone**	Mean resolvent analysis of a hot axisymmetric jet
11:00–11:30	**Coffee**		
Session 5	**Jets IV**		
11:30–12:00		**S. Mazharmanesh**	Mean flow modification in screeching jets
12:00–12:30		**A. Nekkanti**	Input-output response to non-linear interactions in a turbulent jet
12:30–13:00		**R. Sainia**	How important are azimuthal mode interactions for jet noise?
13:00–14:30	**Lunch**		
Session 6	**Flow-structure interaction II**		
14:30–15:00		**M. Ali**	Impact of turbulent inflow on acoustics of a propellor operating at low Reynolds number
15:00–15:30		**M. Wang**	Coherent structures and turbulence ingestion noise
15:30–16:00		**M. Stavropoulos**	Non-linear analysis and modelling of jet-edge interaction tones
16:00–16:30		**M. Mancinelli**	Jet-plate installation effects on screeching tones
16:30–17:00	**Coffee**		
17:00–18:00	**Roundtable 2: Non-linear dynamic modelling of coherent structures for aeroacoustics. . . ?**		
19:00–. . .	**Freewheeling in Rome**		

Wednesday, 12th of June

Sala Conferenze, Dept. Civil, Computer Science and Aeronautical Engineering, Via Vito Volterra, 62, 00154 Roma

Session 7	**Jets V**		
9:00–9:30		**A. Towne**	Scalable resolvent and harmonic resolvent analysis with applications to complex jets
9:30–10:00		**I. Padilla-Montero**	Modelling wavepackets in supersonic twin jets and comparison against experimentally educed coherent structures
10:00–10:30		**M. Avanci**	Coherent structures in elliptical jets
10:30–11:00		**B. Yeung**	Modal energy balance analysis of plasma-actuated screeching twin-rectangular jets
11:00–11:30	**Coffee**		
Session 8	**Flow-structure interaction III**		
11:30–12:00		**K. L. Leung**	Influence of the spanwise flow dynamics onto the aerodynamic noise by bluff bodies: A computational study
12:00–12:30		**Z. Yuan**	Wavepackets driving trailing edge noise
12:30–13:00		**S. Demange**	Resolvent model of wavepackets driving trailing edge noise
13:00–14:30	**Lunch**		
Session 9	**Combustion & mode coupling**		
14:30–15:00		**T. Kaiser**	Turbulence closure in linearized analyses of non-uniform density flows
15:00–15:30		**L. Lesshafft**	Intrinsic thermo-acoustic instability in a laminar V-flame
15:30–16:00		**G. Khujadze**	Vortex-wave linear non-modal coupling versus wavepacket model for aerodynamic sound generation: a study of turbulent temporal shear layers
16:00–16:30	**Coffee**		
Session 10	**Control / noise reduction**		
16:30–17:00		**C. Leclercq**	Feedback control of resonator flows using linear tools: towards experiments
17:00–17:30		**S. R. Murthy**	Reducing jet noise from an underexpanded biconical nozzle
17:30–18:00		**D. Audiffred**	Control of turbulent jets and their sound
19:00–...	**Dinner at the beach**		

List of Abstracts – Talks

Monday 10th June

Session 1

Local resolvent bases for modelling jet turbulence and acoustic radiation

E. Eichberger, L. Heidt, T. Colonius

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Modes from global resolvent analyses have been shown to accurately model the frequencies and spatial structure of the dominant coherent structures in several turbulent flows. In many flows, the coherent structures differ in structure and frequency in different regions of the flow. For example, a turbulent jet has a spatial domain that includes the near nozzle flow, the annular shear layer, the end of the potential core, the fully-developed jet (with an increasingly thick shear layer), and the near and far acoustic fields. In order to model the spatially varying physics present in turbulent jets, resolvent-mode forcing models must be developed to predict the amplitude of the structures or other flow statistics, including the radiated noise. The present research aims to apply data-driven approaches to learn forcing coefficients from lower-order statistics available from Reynolds-averaged Navier-Stokes (RANS) predictions. We develop what we term as a localized resolvent basis that computes modes whose forcing and observation regions are broken down into a set of possibly overlapping spatial regions, while retaining the global definition of the flow state. This adds flexibility and robustness to the construction of global modes. Local resolvent analysis acts as a balance between global resolvent and pointwise descriptions like LES. We first demonstrate the utility of this technique by reconstructing the spectral proper orthogonal decomposition (SPOD) modes of an isothermal Mach 0.4 jet at $Re = 450,000$. The results showcase the flexibility localized resolvent modes provide in the construction of global SPOD, while using 10 or fewer total localized modes total across $St = [0.05, 1.00]$. Furthermore, we employ localized resolvent modes to reconstruct second-order statistics, comparing their performance with that of global modes. At low reconstruction error, it is shown that about twice as many global modes are needed to achieve comparable errors This work has been supported by the Office of Naval Research under grant N00014-23-1-2650 and the Federal Aviation Administration under grant 13-C-AJFE-UI.

Resolvent modelling of subsonic jet noise

***B. Hasparyk*[1]*, P. Jordan*[1]*, L. Lesshafft*[2]*, E. Pickering*[3]*, T. Colonius*[4]

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In the two-point formulation of resolvent analysis, jet noise can be cast as a linear input-output problem where the cross-spectral-density (CSD) matrix of the sound field is forced, via the resolvent operator, by the CSD of non-linear interactions. The forcing CSD is difficult to compute or measure, but its projection onto the resolvent input space can be identified from the CSD of the sound field. Pickering et al. [J. Acoust. Soc. Am. 150, 2421–2433 (2021)] showed, using data from a large-eddy simulation that a low-rank truncation of the identified forcing-projection matrix could be used to reconstruct the acoustic field of transonic and supersonic turbulent jets. We follow that study, performing two-point acoustic measurements of turbulent jets over a broad range of subsonic Mach numbers, identifying low-rank, forcing-projection matrices for the acoustically important azimuthal modes, and then providing an empirical model that captures their frequency and Mach-number dependence. The model captures downstream radiation to within 2dB.

On the role of eddy viscosity in jet flow resolvent analysis

***J.G.R. von Saldern*[1], *O.T. Schmidt*[2], *P. Jordan*[3], *K. Oberleithner*[1]**

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This talk delves into the intricate interplay between eddy viscosity modelling and Resolvent analysis. This is particularly crucial given the potential of Resolvent analysis in modelling large-scale coherent structures relevant for many aeroacoustics phenomena such as jet noise and trailing edge noise. We apply extended SPOD and Resolvent analysis to a jet flow at Re = 50,000. Our investigation highlights the pivotal role of the coherent component of the Reynolds stress tensor in modelling coherent structures. We demonstrate that this coherent component has a dissipative effect on the energy budget of dominant coherent structures, validating the utilization of the Boussinesq model with eddy viscosity. Furthermore, our findings reveal that the incorporation of mean field-consistent eddy viscosity, assimilated from RANS equations, effectively dissipates energy received by coherent structures from the mean field. Additionally, we challenge the common practice of using alignment measures to validate Resolvent with SPOD modes, emphasizing its qualitative nature and the necessity for a deeper understanding of the modes' underlying physics. Overall, this talk sheds light on the intricate relationship between eddy viscosity and Resolvent analysis, offering valuable insights for improving predictive capabilities in aeroacoustics applications and advancing our understanding of turbulent flow dynamics.

Session 2

The flapping mode in screeching jets

P. Nogueira, D. Edgington-Mitchell

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The flapping behaviour displayed by screeching round jets remains as one of its most puzzling features. The current understanding of the staging behaviour classifies B, C and D screech modes as helical/flapping modes, despite being all dominated by azimuthal wavenumber m = ±1. This work aims to shed light on the possible reasons for a flapping behaviour in these jets by analysing the different coherent structures present in the flow. The analysis will start with the study of the flow features using a large-eddy simulation of a Mj = 1.35 overexpanded jet, and the effect of interactions between coherent structures in the flow will be analysed using stability techniques. Preliminary results suggest that the development of m = 2 streaks tend to deform the mean flow and anchor the position of the flapping mode – this effect hinders the existence of pure helical modes in this flow.

The role of coherent structures in the acoustics of supersonic jets

M. Samimy

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It has been known since the 1960s that coherent structures (CS) exist in the shear layers of free jets and that the Kelvin-Helmholtz (K-H) instability is responsible for their existence. The broad peak at shallow polar angles in the far-field (FF) noise spectrum of the jets (subsonic to ideally-expanded low supersonic) is generated by the dynamics of CS, primarily around the end of the potential core. In off-design supersonic jets, interactions of CS with shock cells generate broadband shock associated noise with an amplitude and frequency that is dependent on the polar angle. The acoustic feedback from these interactions to the nozzle exit can also generate the tonal noise known as screech. When the convective velocity of CS becomes supersonic (e.g., in highly heated subsonic/supersonic jets or high supersonic), CS directly generate Mach waves, which add to the mixing noise at shallow polar angles. In addition, CS are responsible for the entrainment and bulk mixing in jets (i.e., in shaping of the mean flow). Breakdown of CS and the cascading processes in turbulent jets produce small scale structures, which generate omnidirectional noise. Thus, CS are responsible for all components of jet noise. Directly controlling CS by leveraging the K-H instability, has allowed us to explore and learn about these processes in various jet geometries, configurations and flow regimes and demonstrate the capability of the control to mitigate both near-field pressure fluctuations and FF acoustics.

Coherent structures and aeroacoustics of a swirling supersonic jet exhausting an aerospike nozzle

T. Golliard, M. Mihaescu

FLOW, Department of Engineering Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden

Large Eddy Simulations (LES) are deployed to simulate the supersonic flow of a swirling, cold aerospike nozzle jet. Three Swirl Numbers S = 0.10, 0.20, 0.30 are simulated and the flow results are compared with those of the baseline case without swirl. Spectral Proper Orthogonal Decomposition (SPOD) is applied in two and three dimensions to the flow data. Coupled with an analysis of the tonalities in the near-field, this approach allows to identify the flow mechanisms responsible for noise generation. The azimuthal jet modes detected by means of two-point cross-correlation is directly linked to the vortex shedding at a Strouhal number around St = 0.85 for all the swirling cases, resulting in a helical sound propagation in the upstream direction. Moreover, the SPOD energy spectra for the swirling cases exhibit less peaks compared to the baseline case, indicating a loss of coherence. As a consequence, mixing noise due to large vortical structures convected downstream is attenuated. Furthermore, no flapping motion of the shock-cell structure downstream of the aerospike bluff body is detected. This suggests that an additional swirling component leads to screech noise removal. Finally, the aeroacoustic signature is computed using the Ffowcs Williams- Hawkings equation (FWH). The obtained far-field spectra exhibit shock-associated noise and tonal components linked to the jet azimuthal modes as well as the oscillation modes of the annular shock-cell structure.

Session 3

Wake-airfoil interaction noise

M. Spiropoulos, F.R. do Amaral, F. Margnat, V. Valeau, P. Jordan

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Motivated by the problem of the sound generated by the interaction of a landing-gear wake with a deployed flap, we investigate the flow and sound fields generated by the interaction of a cylinder wake and a downstream airfoil orthogonally aligned with respect to the cylinder. Detailed experiments (stereo-PIV, acoustic measurements) have been conducted in an anechoic wind tunnel and the data post-processed using spectral proper orthogonal decomposition has been applied to develop low-rank representations of the flow field. The low-rank flow data is used to inform semi-empirical source models in the framework of Howe's vortex-sound theory. Sound propagation is modelled using compact Green's functions obtained using the source panel method. Finally, we employ the previous tools to derive a simplified model for the far-field acoustic pressure.

Coherent structures in turbomachines and their noise signature

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The flow in turbomachines is usually turbulent (high enough Reynolds number over a portion of the blade span), highly three dimensional and characterized by several secondary flow features. The latter involves several potentially large coherent structures developing at the blade foot (horseshoe and corner vortices), on the blade (leading-edge vortex or diagonal rollers in the transitional region) or at the blade tip (the complex vortex system usually involving the tip leakage vortex, the tip separation vortex and potentially several induced vortices). In turn these large coherent structures carrying a large amount of vorticity can not only generate losses but also yield acoustic waves by interaction with the rotating blade rows or stationary vanes of the turbomachine, or by vortex interactions similarly to what is observed in turbulent jets. The former has been more studied and models have been proposed and classified either as leading-edge noise models when it involves a blade-vortex interaction at the blade leading edge, or trailing-edge noise models when it involves the interaction of turbulent eddies with the blade trailing edge. The situation is more complex and less understood at the blade tip even though tip noise is the dominant noise particularly for low-speed rotating machines. Another challenge in the latter machines is the transition to turbulence, which involves Kelvin-Helmholtz instabilities and vortex pairing that can even yield typical noise signature above other noise sources.

The XX-Topos form of the Gappy POD using Vold-Kalman filters for structure reconstruction using reduced sensor sets

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The mathematical framework for the gappy-POD was first proposed by Everson and Sirovich (J. Opt. Soc. America, Vol. 12, 1995) as a means for reconstructing images from gappy sensor sets. Numerous applications of this technique to problems in fluid mechanics have since been published in the open literature but are mostly confined to only one of several plausible heterogeneous forms of the technique. Recently, Zhao-Dubuc and Tinney (AIAA Aviation Forum, 2024) outlined the mathematical recipe for all homogeneous and heterogeneous forms of the gappy-POD using conventional kernels; companion papers by these same authors outline the same frameworks in the context of harmonic-based kernels and with the inclusion of higher-order (quadratic) effects. In this presentation, the XX-topos form of the gappy-POD is described where structure in the opposing vector space are extracted using Vold-Kalman filters based on the technique of Stephens and Vold (J. Sound Vib., Vol. 333, 2014). A demonstration of this combination of analysis tools is then presented using spatially and temporally resolved measurements of the sound field generated by a notional eVTOL rotor in hover. The findings are evaluated for different collectives of the rotor hub to understand the effect of rotor inflow on the space-time structure of sound generated by hovering rotors.

Tuesday 11th June

Session 4

On the identification of acoustically-relevant large-scale structures for subsonic jets using correlation techniques in the time domain

***I. Padilla-Montero*[1], *D. Rodríguez*[1], *V. Jaunet*[2], *P. Jordan*[2]**

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The presence of wavepackets in high-speed jets has been widely confirmed experimentally over the last decades with the advent of time-resolved visualisation techniques and advanced statistical techniques as POD and SPOD. Models of the wavepackets in the frequency domain, either based on homogeneous linearised equations or on the leading SPOD modes, directly recover the acoustic radiation in supersonic jets. Conversely, while a correlation between the wavepackets and the directional noise component in subsonic jets clearly exists, how the former originates the latter is still unclear. Predicting the noise radiation based on linearised equations or SPOD modes, which is relatively straightforward for supersonic jets, requires of relatively involved formalisms incorporating 'jitter' in SPOD modes, or coupling SPOD with linear resolvent analysis. Possibly, a more direct relation between large-scale turbulent structures and the noise radiated by them can be established in the time domain. This work employs high-speed schlieren visualisations of single and twin round jets and applies both Doak's decomposition and a variant of POD recently named Permuted POD. Doak's decomposition is used to extract, from the schlieren images, a flow variable closely related to acoustic radiation. Permuted POD is based on a covariance matrix between the variable of interest at different streamwise coordinates and time. Combinations of these techniques are tested with the aim of identifying the large-scale noise-generating structures in the time domain.

Coherent structures in forced turbulent jets

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Harmonic forcing has been shown to reduce the noise produced by turbulent jets, where the forcing results in a strong deterministic tonal response and a modulation of the underlying stochastic turbulence. When forcing is strong enough to modulate the turbulence, the statistics become periodic functions of time (cyclostationary), and tools such as spectral proper orthogonal decomposition (SPOD) and resolvent analysis that rely on stationarity are not justified. We investigate the impact of the forcing on turbulent jets using recent extensions to SPOD and resolvent analysis, called cyclostationary SPOD (CS-SPOD) and harmonic resolvent analysis, which are suitable for analyzing flows with periodically varying statistics. We perform large-eddy simulations of forced turbulent jets using low-frequency $St_f = 0.3$ and high-frequency $St_f = 1.5$ forcing at various amplitudes. We investigate both the periodic (phase-averaged) response and how coherent structures are modified by forcing. Excellent agreement between the dominant coherent structures determined via CS-SPOD and those predicted by the linearized harmonic resolvent analysis are seen for all forced jets across all frequencies and dominant azimuthal mode numbers. Supported by ONR N00014-20-1-2311 and N00014-23-1-2650.

Coherence decay in turbulent jets by stochastic modelling under location uncertainty

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Coherent structures and wave-like solutions evolve within turbulent flows. Reduced-order models defined in the frequency domain, such as resolvent analysis, face a closure issue since the wavepackets interact with the (unresolved) turbulent field through non-linear interactions. The aim of the present study is to consider the impact of turbulence on wavepackets through stochastic modelling under location uncertainty. This framework considers the conservation of mass and momentum of fluid parcels submitted to a stochastic transport, representing here the effect of turbulence. By linearising the resulting generalised stochastic Navier–Stokes equations and expressing it in the Fourier domain, a stochastic linear model (SLM) is obtained. In turbulent subsonic jets, coherence decay has been understood in the literature to be a key quantity to predict acoustic noise emitted by wavepackets. Standard linear models usually fail to this particular task. We show in this presentation the ability of SLM to predict the two point coherence of the wavepackets in turbulent jets, and show its impact on acoustic emissions. In the proposed model, the stochastic noise parametrisation and the mean flow are obtained via the output of a RANS model, in order to develop a model-based strategy.

Mean resolvent analysis of a hot axisymmetric jet

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Resolvent analysis about a mean flow is commonly used to model input-output behaviour of open shear flows, including turbulent jets in the context of aeroacoustics (Jordan & Colonius, 2013). However, Karban et al. (2020) highlighted a fundamental ambiguity of this framework, magnified in the case of a hot supersonic jet. Indeed, discrepancies up to 40% in the resolvent gain were observed depending on the choice of formulation for the governing equations. Leclercq & Sipp (2023) later proposed to consider the mean resolvent operator, which predicts the mean response to forcing about a statistically steady flow. For periodic flows, the ambiguity noted by Karban et al. 2020 disappears since the poles of this operator are invariant with respect to changes in governing equation formulation. In this work, we propose a numerical method to approximate mean resolvent modes using resolvent modes about the mean flow. We also perform resolvent analysis using the mean Jacobian, which differs from the Jacobian about the mean flow for governing equations with a cubic nonlinearity. Results are presented for a hot axisymmetric jet displaying a regime of self-sustained oscillations (Lesshafft et al. 2006). This work is a stepping stone towards mean resolvent analysis of more realistic jet flows.

Session 5

Mean-flow modification in screeching jets

S. Mazharmanesh, P.A.S. Nogueira, J. Weightman, D. Edgington-Mitchell

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This study analyses the intermittency of coherent structures in screeching jets. Under consideration here are unheated elliptical and rectangular jets with an aspect ratio AR = 2.0 operating at the nozzle pressure ratios NPR = 2.0 to 5.0. From ultra-high-speed schlieren, multiple non-harmonic screech frequencies are identified in a single operating condition. Our results demonstrate that the mean flow experiences distortions due to the difference-self-interaction of the non-harmonic screech modes. The overall mean flow that encompasses all the distortions is utilized to identify shock-cell structures. A comparison of axial wavenumber spectra of the spatial modes shows that in the presence of multimodality, the guided jet mode (G-JM) is energized by triadic interactions between the Kelvin–Helmholtz (KH) wavepacket and the secondary peak (k_{s2}) in the axial wavenumber transform of the mean shock structure. Furthermore, the spatial mode at fr = 0.0 that represents modified mean flow is used to extract the zero-frequency shock wavenumber peak (k_{s0}). The interaction between the Kelvin–Helmholtz wavepacket with the zero-frequency peak is found to be responsible for closing the resonance loop of the dominant frequency when multiple screech modes are active. These findings pave the way for a better understanding of screech.

Input-output response to nonlinear interactions in a turbulent jet

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Quadratic nonlinear interactions arise from the convective term in the Navier-Stokes equations, resulting in a wide range of azimuthal and frequency triads. Bispectral mode decomposition (BMD) is a data-driven technique for extracting the flow structures involved in triadic interactions. As a counterpart to this empirical approach, here we present an operator-based approach that identifies the responses to specific azimuthal wavenumber and frequency triads. i.e., it extracts spatial flow structures generated from each quadratic nonlinear interaction. Using an input-output framework, we first compute the convective term for the interaction between azimuthal wavenumbers, m1 and m2, and frequencies, St1 and St2. Next, we construct the resolvent operator at the azimuthal wavenumber, m3 “ m1 ‘m2, and frequency St3 “ St1 ‘St2. Finally, the response mode is obtained by applying this resolvent operator to the quadratic convective term. We demonstrate this approach on a Mach 0.4 turbulent jet and further compare the response modes with those obtained from the BMD. aiding in the development of nonlinear models and spectral eddy viscosity for resolvent analysis. This method enables us to differentiate between the optimal linear response obtained from resolvent analysis and the response to the triadic interaction, aiding in the development of nonlinear models and spectral eddy viscosity for resolvent analysis.

How important are azimuthal mode interactions for jet noise?

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Analysis and modelling of round jets is facilitated by the expansion of fluctuations using an azimuthal Fourier-series. When the expansion is performed in terms of an equivalent source model, for instance in the framework of Lighthill's acoustic analogy (LAA), a direct connection can be established between azimuthal modes of source and sound. But the LAA source term is non-linear in the flow fluctuations, raising the question as to how important non-linear, flow-mode interactions are in determining a given azimuthal mode of the source. We explore this question via a signal-processing methodology applied to data from a high-fidelity numerical simulation. Lighthill's equivalent source term is constructed and analysed in two ways: (1) without azimuthal decomposition of the flow variables, in which case all mode interactions are included; (2) following azimuthal decomposition of the flow, considering limited numbers of azimuthal modes. In this way we aim to explore the azimuthal mode interactions that underpin the acoustically important source modes, $m = 0, \pm 1, \pm 2$.

Session 6

Impact of turbulent inflow on acoustics of a propeller operating at low Reynolds number

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Ingested turbulence affects propeller noise at frequencies higher than the 2nd Blade Passing Frequency (BPF). Amiet's model extension to rotating structures represents a useful tool to predict this phenomenon. However, comparison with experimental results revealed discrepancies between predicted and measured acoustoc spectra, particularly at high frequencies. A possible explanation for this discrepancy lies in turbulence distortion. The objective of this paper is to study numerically the interaction between a turbulent inflow and a propeller operating at low Reynolds number and the consequent impact on far-field acoustic spectrum. The final goal is to obtain a comprehensive description of the flow physics to improve, in future studies, Amiet's prediction model. Lattice Boltzmann Very Large Eddy Simulations with the commercial software 3DS PowerFLOW of a reference propeller, for which experimental data have been obtained at TU Delft University, are carried out. First, the characterization of grid generated turbulence in terms of turbulence intensity, integral length scale and Power Spectral Density (PSD) has been conducted without the propeller upstream and at the propeller plane. Then, the evolution of turbulence approaching the propeller plane and the leading edge of the propeller blade was analysed. Data have been sampled at several radial positions to evaluate the impact of the radial velocity. Spectral analysis of the fluctuating velocity components reveals the effects of streamtube contraction and leading edge induced distortio on the different turbulent scales and the redistribution of momentum among the velocity components. Unsteady pressure fluctuations are sampled on blade surface and used to feed the Ffowcs-Williams and Hawkings analogy to obtain the far-field acoustic spectrum.

Coherent structures and turbulence ingestion noise

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The interaction of a rotor with turbulent inflow is a significant source of noise in a variety of engineering devices. The spectral characteristics of the acoustic radiation is strongly influenced by the coherent structures in the flow ingested by the rotor. In this presentation we discuss a recent computational investigation of the noise produced by a five-bladed rotor ingesting a low-Machnumber turbulent boundary layer at the tail end of an axisymmetric body of revolution using largeeddy simulation and the Ffowcs Williams-Hawkings equation. Correlation and spectral analyses demonstrate rapid growth of turbulence structures in the decelerating tail-cone boundary layer, whose interaction with successive rotor blades generates correlated unsteady-loading dipole sources on adjacent blades at frequencies near multiples of the blade-passing frequency and halfway between them. The constructive and destructive interference among the correlated dipole radiation produces multiple peaks and valleys around the broadband sound pressure spectrum. These findings offer new insights into the physical mechanisms of the well-recognized haystacking phenomenon, and suggest that the term "haystack" does not provide an accurate characterization of the oscillatory spectral features of turbulence ingestion noise.

Non-linear analysis and modelling of jet-edge interaction tones

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Motivated by the problem of jet-flap interaction noise, we study the tones generated when a round subsonic jet grazes an edge. In Jordan et al. [Jnl. Fluid Mech. 853, 2018] jet-edge tones were shown to be largely underpinned by linear frequency selection mechanisms, but the effects of non-linearity were also observed. The objective of this study is to explore these non-linear phenomena. This presentation provides a first classification of the different tonal regimes observed in a parameter space defined by jet Mach number and radial edge position. The classification is enabled by a viewing of the data using three different statistical measures (power spectral density; bi-coherence; wavelet spectrogram) and allows a preliminary identification of the following regimes: broadband; linear frequency selection (LFS); LFS with non-linear interaction; non-linear frequency-selection (NLFS); non-linear mode competition (NLMC).

Jet-plate installation effects on screeching tones

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This study examines how a flat plate affects the generation of axisymmetric A1, A2, and asymmetric B and C screech modes. The plate is positioned parallel to the nozzle axis of an under-expanded supersonic jet. The plate is large enough in both stream-wise and span-wise directions to disregard edge effects. To assess the impact of the plate distance H on screech-tone generation, we conduct acoustic measurements in the far field of the jet under various flow conditions. Our findings reveal that when H is equal to or less than one nozzle diameter D, the presence of the plate significantly alters the typical behaviour of screech modes. Specifically, the plate reduces the range of jet Mach numbers for which A2 and C modes are supported. Additionally, when the jet-plate distance is smaller than 0.85 diameters, modes A2 and C disappear, while modes A1 and B extend into flow conditions for which the other two modes are typically dominant in the free-jet case. To enhance our comprehension of the phenomenon, we aim at elucidating the system's behaviour using parallel linear stability analysis. Specifically, we seek to assess the influence of the installation by investigating the sensitivity of local modes presumed to be responsible for the feedback mechanism generating the screech tones. This analysis will enable us to pinpoint areas where minor adjustments in the problem structure could lead to significant alterations in the feedback gain.

Wednesday 12th June

Session 7

Scalable resolvent and harmonic resolvent analysis with applications to complex jets

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Resolvent analysis of the Navier-Stokes equations has proven useful for understanding and modeling the dynamics of coherent structures in statistically stationary axisymmetric jets. However, the application of resolvent analysis to more complex jets with non-axisymmetric mean profiles and of harmonic resolvent analysis to jets with strong internal oscillations (such as screech) has been hindered by the poor cost scaling of standard methods used to compute resolvent modes. To overcome this challenge, we combine randomized singular value decomposition with an efficient time-stepping method that exploits the direct and adjoint time-domain equations underlying the resolvent system. This combination of methods overcomes the main computational bottlenecks of previous methods and yields an algorithm that scales linearly with problem size. Paired with a strategy to minimize the duration of the time stepping by removing unwanted transients and a steaming approach to minimize memory consumption, our algorithm drastically reduces CPU and memory costs for large systems. In addition to describing the algorithm, we will present results for three problems: a resolvent analysis of twin jets, a secondary resolvent analysis of a round jet with streaks, and a harmonic resolvent analysis of a screeching supersonic jet.

Modeling of wavepackets in supersonic twin jets and their comparison against experimentally-educed coherent structures

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Twin-jet engine configurations are common in the propulsion systems of modern aerospace applications. The noise pollution produced by these systems demands the creation of new technologies for its mitigation and control. Coherent structures are known to play a crucial role in the sound generation mechanisms of these systems, but their characterization and understanding is not yet complete, requiring the development of novel simplified models and data analysis techniques. This work presents, on one hand, a modeling strategy for wavepackets in perfectly-expanded twin jets, based on RANS mean flow calculations and PIV mean flow measurements combined with linear plane-marching parabolized stability equations. On the other hand, it also presents a datadriven approach to extract coherent structures from time-resolved experimental schlieren visualizations of the twin-jet system. The latter method is based on the spectral proper orthogonal decomposition technique, but in addition it is informed with the momentum potential theory of Doak, yielding coherent structures which are more interpretable and consistent with the known instability mechanisms of twin jets than those obtained with standard SPOD analyses of schlieren data. The obtained wavepackets are quantitatively compared against the educed coherent structures in order to validate their fidelity for the twin-jet configuration

Coherent structures in elliptical jets

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Jet flows, present in many natural or industrial systems, comprise coherent structures that motivate the search for simplified modelling frameworks that would promote understanding of the jet dynamics, and with respect to aircraft propulstion, the mechanisms of sound generation. Linear mean-field analysis is one such simplified model, and it has proved useful for the description of coherent structures in round turbulent jets. For non-axisymmetric jets, however, analysis and modelling of coherent structures is more complex. We address this issue by considering elliptical jets, which we explore by means of experiments and linear modelling. Velocity measurements are performed in an aspect-ratio-two elliptical jet using time-resolved stereo PIV. Coherent structures are educed from the data using a decomposition procedure that combines D_2 symmetry and SPOD. Three-dimensional locally parallel and parabolised stability equations (PSE) are used to model the coherent structures. Comparison of modelled and empirical structures is performed in two ways: using a similarity projection between empirical structure and PSE; and, for the locally parallel analysis, using bi-orthogonal projection. The analysis permits an identification and classification of coherent structures underpinned by convective instability.

Modal energy balance analysis of plasma-actuated screeching twin-rectangular jets

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We study the coherent structures responsible for spectral energy flow in a supersonic twin-rectangular jet. Large-eddy simulations (LES) of the jet are performed in the nominally ideally-expanded condition. Periodic forcing is applied at the nozzle lips through the use of localized arc filament plasma actuators (LAFPA), modeled as source terms in the energy equation. Twelve actuators fire in-phase with each other and at the frequency of the natural jet screech. The invariance of the nozzle geometry with respect to reflections about its major and minor axes and the strong coupling between the twin jet plumes permit the LES data to be decomposed into D2 symmetry components, with no loss of generality. Each component is perfectly symmetric or antisymmetric about the major, minor, or both axes. For discrete symmetries, e.g. D2, we derive a set of symmetry-balanced Navier-Stokes equations (NSE), which couple different symmetry components through the convective term. To examine symmetry-to-symmetry and frequency-to-frequency energy flow, we leverage a concurrently-developed, data-driven modal energy budget analysis, which seeks pairs of modes representing the acceleration and convective terms of the spectral NSE that are triadically consistent and optimally correlated with each other. We extend the analysis to the compressible regime. Modal energy flow in the twin jet via triadic interactions is identified and quantified.

Session 8

Influence of the spanwise flow dynamics onto the aerodynamic noise by bluff bodies: A computational study

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This study investigates the influence of the spanwise flow dynamics onto the aerodynamic noise emitted by either a cylinder in a flow or an airfoil at stall. To do so, compressible Large Eddy Simulations (LES) are carried out for each geometry, with various aspect ratios considered. The unsteady results are post-processed using specific techniques (e.g. Dynamic Mode Decomposition) to discriminate the dominant flow patterns and their corresponding noise signatures. Particular attention is given to the vortex dynamics occurring in the shear layer and wake regions, which exhibit distinct characteristics and are driven by specific mechanisms, namely Kelvin-Helmholtz and von Kármán instabilities. Their respective spanwise features and noise signatures are tentatively connected, this being done through coherence and cross-correlation analyses. The impact of the span onto the development of the large-scale coherent structures and their associated noise emissions is also explored.

Wavepackets driving trailing edge noise.

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The aim of present work is to investigate trailing-edge noise generation mechanisms to improve prediction tools and control strategies. We focus on a NACA 0012 aerofoil at 3 degrees angle of attack with zigzag tripping elements close to the leading edge to generate a turbulent boundary layer. A compressible implicit large eddy simulation (LES), using the open-source high-order numerical framework PyFR, is performed for collecting data for our analysis. For comparison, we use data from an experimental campaign performed in parallel at the facility in TU Berlin. The comparison of velocity and sound pressure statistics shows good agreement between simulations and experiments. Further, spectral proper orthogonal decomposition (SPOD) is applied to the LES dataset to investigate dominant feature of the turbulent boundary layer and its relation to sound radiation. SPOD analysis is applied to different spanwise wavenumbers in order to understand their contribution to noise generation. Leading SPOD modes for the first spanwise wavenumbers, which dominate acoustic radiation, are shown to correspond to wavepackets. The contribution of such coherent structures in the radiated sound field is examined, clarifying their contribution to trailing-edge noise for a wide range of frequencies.

Resolvent model of wavepackets driving trailing edge noise.

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We present a framework for investigating the underlying mechanisms of trailing edge noise for airfoils at low angles of attack. It is proposed that the relevant coherent structures for trailing-edge noise are wave packets with low spanwise wavenumbers in the turbulent boundary layer, consistent with the edge scattering condition derived from Lighthill's acoustic analogy. We demonstrate that relevant structures can be recovered from resolvent analysis of the turbulent mean flow, providing a physically based model of the acoustic sources. This approach applies modal reduction to the turbulent flow dynamics by extracting optimal structures from the linear operator, and is therefore particularly suitable for the development of low-order prediction tools and control strategies. The model's ability to recover the acoustic field is presented for a NACA0012 profile at two Reynolds numbers, featuring tonal and broadband noise respectively. Highly detailed large eddy simulations are used to obtain the mean flow, and an empirical decomposition of the snapshots is used to extract coherent structures from the databases to provide a comparison to the physics-based model. Results show that at frequencies of low rank flow dynamics, the leading resolvent mode accurately reproduces the directivity and sound power of the acoustic field radiated by the airfoil.

Session 9

Turbulence closure in linearized analyses of non-uniform density flows

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In recent years, the application of linearized flow analysis has expanded towards configurations involving turbulence and varying fluid density. Studies on such configurations focus for example on acoustic noise emissions of high Mach-number flows (and more generally aeroacoustics) and turbulent flames. This study investigates linearized turbulence closure in such flows. We demonstrate that in flows of non-uniform density, the linearization using the tripple decomposition leads to a significant closure problem in all linearized transport equations including the continuity equation. An analogous problem is well known from the Reynolds-Averaged Navier-Stokes and Large-Eddy Simulation frameworks, where the turbulence closure is significantly reduced by applying a Favre average for the temporal mean states. We show that the additional closure terms cannot be avoided by solely performing the linearization around the Favre mean state. Instead, additionally, the state variables must be decomposed using an adapted triple decomposition, which we derive based on first principles. Finally, we test our findings empirically against direct numerical simulations of a generic turbulent jet flame, which is subject to external acoustic forcing. The analysis reveals that ignoring the closure problem, a common practice in current state-of-the-art approaches, leads to non-negligible errors, which are avoided using the adapted decomposition techique.

Intrinsic thermo-acoustic instability in a laminar V-flame

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Flames exhibit rich unsteady dynamics that arise from the interplay of vortical, thermal, chemical and acoustic elements. We use linear analysis to investigate self-excited oscillations of an axisymmetric V-flame inside a laminar annular jet. Parameters are chosen so as to represent lean premixed methane–air reaction. The flame is anchored near the rim of the centerbody, forming an inverted cone that extends downstream into the free outer shear layer of the annular jet. The inner shear layer is mostly destroyed by the thermal expansion across the flame front, so that the vorticity in the steady state is concentrated in the outer shear layer. Consequently, reaction and vorticity dynamics are spatially separated, except near the flame tip, where both coalesce. The reacting flow equations are linearised around the steady state [Avdonin et al., Proc. Combust. Inst. 37(4), 5307–5314 (2019).], and axisymmetric global eigenmodes are computed. At sufficiently high Reynolds number, instability arises for a mode on an "arc branch", indicative of non-local pressure feedback. Eigenmodes on this arc branch are characterized by strong oscillations at the flame tip. The period time of the leading eigenmode frequency is found to match the advection time from the nozzle plane to the flame tip, along a streamline in the outer shear layer. A similar observation was made in experiments with forced V-flames [Durox et al., Proc. Combust. Inst. 30(2), 1717–1724 (2005).]. Our linear results suggest a non-local feedback mechanism, involving downstream-travelling vorticity waves that are amplified in the shear layer, and upstream-travelling pressure waves that are generated by unsteady reaction in the flame tip region. Nonlinear time-resolved simulation, however, reveals a subcritical onset of self-sustained oscillations, at Reynolds number values where the flame is linearly stable. In this regime, the flow settles into a limit-cycle, with a periodicity that does not match any linear eigenmodes of the base flow or the mean flow. Close to the critical Reynolds number for linear instability, the leading eigenmode frequency appears in the power density spectrum; periodicity of the self-sustained unsteadiness is lost at Reynolds numbers in the linearly unstable regime. It is concluded that nonlinear dynamics dominate the self-excited behavior in the investigated V-flame configuration.

Vortex-wave linear nonmodal coupling vs. wave-packet model for aerodynamic sound generation: A study of turbulent temporal shear layers

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It is generally accepted that in engineering shear flows acoustic waves are generated by wave-packets. However, our analytical and numerical comparative studies (on the example of compressible turbulent temporal mixing layer) show that, in reality, acoustic waves are generated by the vortex harmonics due to the mechanism induced by the shear flow nonnormality - the wave-packet only collects the generated acoustic wave harmonics by constructive interference, as the source of them are spatially and temporally coherent vortex harmonics of the wave-packet. So, we aim to establish the pivotal role of the linear non-modal dynamics of perturbations in the aerodynamic sound emission of turbulent temporal shear/mixing layers at the self-similar stage of evolution. This is achieved by comparing the results of direct numerical simulations (DNS) of the mixing layer to the linear non-modal analysis of the flow central/body part model - 3D homentropic, unbounded flow, $U_0(Ay, 0, 0)$, with shear rate, A. The non-modal analysis captures the only linear mechanism of acoustic wave generation - *the linear vortex-wave mode coupling induced by the non-modal dynamics of perturbations in shear flows*. The efficiency of this linear generation is uniquely determined by the mode-dependent Mach number, $\mathcal{M} = A\lambda_x/c_s$, related to the convective Mach number via $\mathcal{M} = M_c\lambda_x/\pi\Delta y$. Here, λ_x, c_s and Δy denote the streamwise wavelength, speed of sound and shear-layer width, respectively. DNS of compressible turbulent temporal mixing layers were performed for different convective Mach numbers (M_c = 0.3, 0.7, 1.4) and simulation boxes (L_x, L_y, L_z) for reliably identifying the essence of the origin of sound in the turbulent layer. The simulations clearly show the decisive role of the linear non-modal mechanism of sound generation in the flow. This novelty highlights the significance of $\mathcal{M}$ in the sound generation, thus ensuring maximum efficiency for harmonics with largest streamwise wavelength, $\lambda_x = L_x$. Accordingly, the aerodynamic sound efficiency is determined by M_cL_x rather than M_c. Overall, our analysis points to the inadequacy of employing the modal approach to describe compressible dynamic processes in the turbulent flow.

Session 10

Feedback control of resonator flows using linear tools: towards experiments

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The wake of a cylinder or the shear-layer over an open cavity are archetypes of resonator flows oscillating in a self-sustained fashion. The latter configuration is particularly relevant to military applications, but it is also an ideal test-bench to validate flow control methods in the lab. The aim is to suppress oscillations using a feedback loop between an actuator located at the leading-edge of the cavity and a sensor located further downstream. Self-sustained oscillations are the signature of strongly nonlinear autonomous dynamics, yet it is found numerically that full stabilization is achievable from the oscillating state, using linear tools only, without prior knowledge of the target base flow. After reviewing the heuristic method initially used in simulation, we will discuss some progress made towards its practical implementation and theoretical justification. In particular, we will present a fully data-driven version of the initial method based on the « mean transfer function » (MTF) rather than impractical linearization about a mean flow. The method is assessed numerically on the case of cylinder flow. We study key properties of the MTF, in particular its close connection to linearization about a mean flow. We then investigate the MTF system identification problem on two distinct cavity flow experiments performed at ONERA and LISN.

Reducing jet noise from an underexpanded biconical nozzle

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The intense noise radiated by jet aircraft exhaust nozzles causes structural vibration, fatigue, carrier deck personnel operational difficulties, and community environmental concerns. Prior work into the physics and control of jet noise have identified several important sound sources, including wavepackets, screech, Mach wave radiation, and broadband shock associated noise, to name a few. Reducing the loudest sources of jet noise, without sacrificing propulsive performance, has thus-far relied on intuition, parametric survey, or optimal control techniques. With the aim of developing a more general and robust method of jet noise reduction (JNR), we seek a physics-based JNR approach that is built upon a linear input-output analysis appropriate for mean flows with strong shocks. JNR strategies for an underexpanded jet issuing from a biconical nozzle are evaluated according to their impact on the gains of the most dominant output modes using structural sensitivity analysis and tested using large-eddy simulation. The effect of flow discontinuities on linear analysis, including the optimal forcing and response modes that arise from resolvents, is investigated.

Control of turbulent jets and their sound

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Axisymmetric coherent structures are known to underpin the peak sound radiation of turbulent jets. When the jet interacts with a nearby surface, such as the trailing edge of a wing, the same hydrodynamic structures are scattered into the acoustic field, increasing the emitted noise. In this context, two classes of flow-control problems are considered: the control of axisymmetric coherent structures in upstream region of the turbulent jet, and the control of installed jet noise based on axisymmetric hydrodynamic pressure readings. Control laws are designed using a Wiener-Hopf-based approach that ensures optimal, causal solutions when constructing the control kernels in frequency space. The control strategies target coherent-structures dynamics and sound-source mechanisms accessible to linear mean-field models. Results are compared with a wave-cancellation approach where causality is imposed via truncation of the estimation and control kernels, leading to suboptimal solutions. The controllers achieve attenuations of 60 % in the power spectral density of turbulent velocity fluctuations, and 7 dB in the installed jet noise.