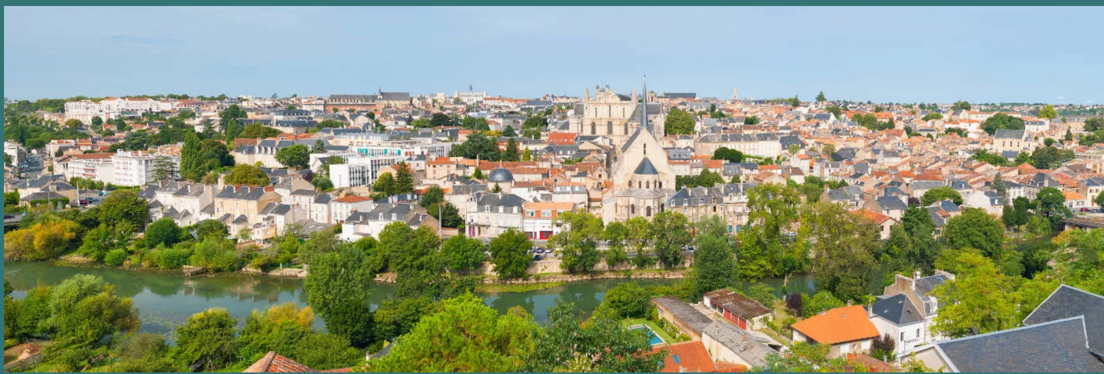
EUROPEAN MECHANICS SOCIETY

Euromech Colloquium 611

Jet Noise Modelling and Control 2021

29^{th} August - 1^{st} September, Poitiers, France



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About

Euromech Colloquium 611

The Euromech Colloquium 611, Jet Noise Modelling and Control 2021 will gather experts from the jet-noise community to discuss recent progress in understanding, modelling and control of turbulent jets and their sound.

Chairpersons

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

Lutz Lesshafft,
CNRS Research Scientist,
Laboratoire d'Hydrodynamique,
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Scientific committee

Franco Auteri André Cavalieri Tim Colonius Patrick Huerre
Kilian Oberleithner Thierry Poinsot Wolfgang Schroeder

Clean Sky 2 - H2020 - DARETOMODEL

The colloquium is supported by the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No. 785303 through the project DARETOMODEL. Within this project, physics-based aeroacoustics models are developed for the propulsive jets that will power next-generation civil aircraft equipped with Ultra-High-Bypass-Ratio (UHBR) turbofan engines. Researchers at the CNRS laboratories, Institut Pprime (Poitiers, France) and LadHyX (Palaiseau, France), and at the University of Cambridge, U.K., work collaboratively, combining computational, theoretical and experimental approaches for the elaboration of a modelling framework adapted to Industry needs.

Institut Pprime

Institut Pprime is a CNRS research laboratory specialised in the fields of Physics and Engineering Sciences. It is affiliated with the University of Poitiers and the engineering school ISAE-ENSMA. Research activities at the Institute cover a broad range of topics, from the physics and mechanics of materials and fluids to mechanical engineering and energetics. Privileged areas of application are in the fields of transportation and energy, with a particular emphasis on environmental issues.

University of Poitiers

The University of Poitiers, founded in 1431 by Pope Eugene IV and chartered by King Charles VII, is one of the oldest universities of Europe. It is a multidisciplinary university and with a student population of about 28000, it contributes to making of Poitiers the city with the highest student/inhabitant ratio in France. In the 16th century the university exerted strong local and national influences, begin second only to Paris, and among the students of that period are Jean-Louis Guez de Balzac, François Rabelais and René Descartes.

ISAE-ENSMA

ENSMA (*École Nationale Supérieure de Mécanique et d'Aérotechnique*) is one of 204 national engineering schools (*grandes écoles*). It was founded in 1948 from the former *Institut de Mécanique et d'Aérotechnique de Poitiers* (IMAP, which was a collaboration between the French Air Ministry, the University of Paris and the University of Poitiers). Teaching at ENSMA covers a broad range of scientific fields related to applications in aerospace, transportation and energetics. The school has an academic staff of about 300 and a student population of about 600.

Poitiers

Poitiers, today capital of the Vienne department, is situated in the west of France. It is a university town known for its rich history. Founded on the Roman base of Lemonum, it became the capital of a territory that included the current departments of Vienne, Deux-Sèvres and Vendée, and was a key city in the first urban networks of Gaul. In the 1st century it developed as an important political center and relay of the imperial administration. A bisphoric from the fourth century, it is home to the Saint-Croix Abbey, first abbey for women, founded by St. Radegonde in the sixth century. In the twelfth century, the city was known for its princes, its clergy and its schools. Eleanor of Aquitaine, queen consort of France and England and duchess of Aquitaine, first placed Poitiers in the royal domain of the Capetians, and then in the domain of the Plantagenets. The creation of the university in 1431 further affirmed the status of Poitiers as a regional capital. With its 29 parishes, its numerous religious establishments, its lawyers and the strong reputation of the University, it was a prestigious urban center. Poitiers is today a city with an immensely rich past, as attested to by the architecture and monuments of the city. Notre Dame La Grande, the Saint-Pierre cathedral with its Clicquot organ, the Saint-Jean Baptistry, the Salle des Pas Perdus of the Palais de Justice: the imprint of history is everywhere.

The venue

The colloquium will be held in the Salle du Conseil of Hôtel Pinet, 15 Rue de l'Hôtel Dieu, Poitiers. Hôtel Pinet, the building of which was completed in 1668 by Jean Pinet, the Receiver General of finances at that time, has previously been a residence of the King, a criminal court, a civil and military hospice and a seminary. It is today the headquarters of the presidency of the University of Poitiers.

Timetable

Sunday, 29th of August

Salon d'Honneur, Hôtel de Ville, Place Leclerc

19:00	**Welcome reception**
19:30	**Welcome address by Madame la Maire, Léanore Moncond'huy**
19:40	**Performance[1,2] by *L'Orchestre des Champs Elysées*[3]**

[1] *Sonates et Partitas* for violin by Jean Sébastien Bach
[2] Duo for violon and cello by Jean Sébastien Bach

[3] *L'Orchestre des Champs-Elysées* interprets, on period instruments, a repertoire spanning from Haydn to Debussy. The orchestra, created in 1991 following the initiative of Alain Durel, director of the *Théâtre des Champs-Elysées* and Philippe Herreweghe, was, for a number of years, in residence at the *Théâtre des Champs-Elysées* and the *Palais des Beaux-Arts de Bruxelles*. The orchestra has performed in concert halls worldwide: Musikverein, Vienna; Concertgebouw, Amsterdam; Barbican Center, London; the Philharmonics of Munich, Berlin and Cologne; Alte Oper, Francfort; Gewandhaus, Leipzig; Lincoln Center, New York; Parco della Musica, Rome; auditoria of Lucerne and Dijon. The orchestra has also performed in Japan, Korea, China and Australia. It is presently under the direction of Philippe Herreweghe, but other conductors are regularly invited for its direction, among whom, Daniel Harding, Christian Zacharias, Louis Langrée, Heinz Holliger, Christophe Coin and René Jacobs. The orchestra has an exclusive and privileged relationship with *Le Collegium Vocale Gent* with which it has recorded

The *Orchestre des Champs-Élysées*, today associated with the TAP (*Théâtre Auditorium de Poitiers*), and in residence in *Nouvelle Aquitaine*, is supported by the Ministry of Culture, by the *Nouvelle Aquitaine* region and by the town of Poitiers. It also receives support from its patrons via the *Cercle Des Amis de l'orchestre* and the business club, *Le Club Contre Champs*.

Monday, 30th of August

Salle du Conseil, Hôtel Pinet, 15 Rue d'Hôtel Dieu

8:00–9:00	**Registration**		
9:00–9:20	**Welcome remarks**		
Session 1	**Linear-mean-flow modelling and analysis I**		
9:20–9:40		**E. Pickering**	Eddy viscosity resolvent models of jet turbulence and radiated sound
9:40–10:00		**U. Karban**	Resolvent-based forcing identification and modelling
10:00–10:20		**L. Lesshafft**	The effect of streaks on the instability of jets
10:20–10:40		**M. Yudin**	The contribution of instability waves to the statistics of velocity field fluctuations of turbulent jets
10:40–11:00	**Coffee**		
Session 2	**Data analysis techniques**		
11:00–11:20		**A. Nekkanti**	Triadic nonlinear interactions and the acoustics of forced versus natural turbulent jets
11:20–11:40		**A. Markesteijn**	Spectral analysis of co-axial jets
11:40–12:00		**L. Heidt**	Application of resolvent analysis and SPOD to forced jets
12:00–12:20		**H. Jawahar**	Spectral and wavelet analysis of pure and installed jet flow with chevrons
12:20–14:00	**Lunch**		
Session 3	**Resonance I**		
14:00–14:20		**P. Nogueira**	Supersonic screech as an absolute instability
14:20–14:40		**P. Jordan**	A simplified model for long-range-resonant global instability
14:40–15:00		**F. Giannetti**	An insight into the non-local physical mechanisms of impinging jet instability
15:00–15:20		**M. Mancinelli**	Reflection of a Kelvin-Helmholtz wave incident on a shock
15:20–15:40	**Coffee**		
15:40–17:30	**Roundtable 1: How have streaks changed the jet-noise modelling paradigm?**		
19:00–...	**Evening activity: Freewheeling in downtown Poitiers**		

Tuesday, 31st of August

Salle du Conseil, Hôtel Pinet, 15 Rue d'Hôtel Dieu

Session 4	**Linear-mean-flow modelling and analysis II**		
9:00–9:20		**D. Rodriguez**	Wavepacket models for supersonic twin jets using 3D PSE
9:20–9:40		**M. Avanci**	Wavepacket modelling of elliptical jets
9:40–10:00		**M. Stavropoulos**	Vortex-sheet modelling of twin jets
10:00–10:20		**J.C. Robinet**	Global linear analysis of a hot jet issuing from a rocket nozzle
10:20–10:40	**Coffee**		
Session 5	**Control**		
10:40–11:00		**E. Martini**	Optimal resolvent-based control using the Wiener-Hopf approach
11:00–11:20		**I. Maia**	Estimation and control of forced turbulent jets
11:20–11:40		**V. Kopiev**	Active feedback control of instability waves in unexcited turbulent jets
11:40–12:00		**D. Bodony**	Reducing noise from single and twin supersonic jets using very-low-frequency control
12:00–14:00	**Lunch at *Le Roy des Ribauds***		
Session 6	**Resonance II**		
14:00–14:20		**C. Bogey**	Mach-number dependence of the acoustic tones near the nozzle of jets
14:20–14:40		**V. Jaunet**	Linear modelling of resonance in a rocket nozzle
14:40–15:00		**M. Varé**	Modelling of the acoustic radiation of high subsonic jets impinging on flat or perforated plates
15:00–15:20		**D. Fabre**	Explaining the whistling of a jet through a plate using impedance criteria and global stability analysis
15:20–15:40		**D. Edgington-Mitchell**	Wavepacket signatures in jet resonance
15:40–16:00	**Coffee**		
16:00–17:30	**Roundtable 2: Towards non-linear dynamic modelling of jets and their sound**		
19:00–...	**Evening activity: Dinner at *Château de Dissay***		

Wednesday, 1^{st} of September

Salle du Conseil, Hôtel Pinet, 15 Rue d'Hôtel Dieu

Session 7	**Reacting flows**		
9:00–9:20		**T. Kaiser**	Identification of axisymmetric coherent structures in a turbulent bunsen flame using resolvent analysis
9:20–9:40		**C. Wang**	Resolvent analysis of a premixed slot flame
9:40–10:00		**K. Oberleithner**	Identification and linear modelling of swirl fluctuations in swirl combustors
10:00–10:20		**C. Tam**	On the generation of entropy noise in a shock-containing nozzle of high-performance aircraft at afterburner
10:20–10:40	**Coffee**		
Session 8	**Jet-noise sources**		
10:40–11:00		**G. Faranosov**	Once again on the quadrupole nature of low-speed jet noise
11:00–11:20		**F. Amaral**	Resolvent-based estimation of jet-noise sources
11:20–11:40		**S. Chernyshev**	On the absence of shear-noise component in sound radiation of a turbulent jet
11:40–12:00		**M. Wong**	Wavepacket-based BBSAN sound-source modelling
12:00–12:20		**M. Z. Afsar**	Supersonic jet noise predictions - impact of using numerical optimization to determine the turbulence structure within a non-parallel flow based generalized acoustic analogy
12:20–14:00	**Lunch at *La Cuisine au Beurre***		
Session 9	**Simulation and modelling**		
14:00–14:20		**Q. Chevalier**	Reynolds-stress modelling for linear resolvent analysis
14:20–14:40		**A.V.G. Cavalieri**	Non-linear transition and turbulence dynamics of a model shear layer
14:40–15:00		**A. Towne**	An efficient algorithm for computing resolvent modes for three-dimensional jets
15:00–15:40		**V. Gryasev**	On the use of data- and physics-based approaches for jet-noise modelling
15:40–16:00		**G. Pont**	Installed jet-noise simulation in an industrial framework
16:00–16:20	**Coffee**		
16:20–17:30	**Free time for small group meetings**		
19:00–...	**Evening activity: *Churrasco*, 25 Rue René Descartes**		

List of Abstracts – Talks

Monday 30th August

Session 1

Eddy viscosity resolvent models of jet turbulence and radiated sound

***E. Pickering*[1,4], *A. Towne*[2], *P. Jordan*[3], *T. Colonius*[4]**

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[3] Institut Pprime, CNRS · Université de Poitiers · ISAE-ENSMA, 86962 Futuroscope Chasseneuil, France
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Resolvent modes computed using a linear eddy-viscosity model have demonstrated encouraging results for modeling coherent structures of turbulent jets when compared against their data-educed counterparts (i.e. spectral proper orthogonal decomposition) from high-fidelity large-eddy simulations. In this talk, we further discuss the effect, and subsequent implications, of a Reynolds-averaged Navier-Stokes (RANS)-derived eddy-viscosity model for resolvent analysis on both the near-field turbulence and the far-field acoustic structures of turbulent jets (Mach 0.4, 0.9, and 1.5). In both regions of the jet, we find the rank of reconstructing the second-order statistics is greatly reduced, requiring only a few modes (at each wavenumber and frequency) to represent 80% of the turbulent kinetic energy in the near-field or to within 2dB of observed noise levels in the far-field. Not only do we find improved reconstructions, but also that the associated resolvent projection coefficients have much weaker correlations between resolvent modes, perhaps permitting a white-noise forcing model. Finally, we investigate whether these coefficients may be inferred by matching first-order statistics found via RANS to predict quantities that are not directly available from RANS such as the near-field pressure fluctuations and far-field sound.

Resolvent-based forcing identification and modelling

U. Karban[1], ***B. Bugeat***[2], ***E. Martini***[1], ***A.V.G. Cavalieri***[3], ***L. Lesshafft***[4], ***A. Agarwal***[2], ***P. Jordan***[1]

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Resolvent analysis is proving to be a useful framework for the modelling, estimation and control of coherent structures in turbulent shear flow. The resolvent operator alone has been shown to provide a good qualitative description of organised structures observed in both wall-bounded and free turbulent flows. But for a more complete description of these structures (amplitudes, higher-order statistics,...) knowledge of the endogenous non-linear forcing term is required. While this can be extracted from high-fidelity numerical simulation data, it alone does not tell the entire story of how the observed structures arise. It is of interest to identify and model the piece of the forcing responsible for the observed structures. We outline a methodology, based on the correlation between forcing and response, that allows the active piece of the forcing to be identified. Applications to jets and channel flow will be discussed.

The effect of streaks on the instability of jets

C. Wang[1], ***L. Lesshafft***[1], ***A.V.G. Cavalieri***[2], ***P. Jordan***[3]

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[2] Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil
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Alongside the wavepackets that arise from Kelvin-Helmholtz instability, streaks represent a separate and important class of coherent perturbation structures in jets, which can also be described by linear analysis. Their role for instability dynamics and laminar-turbulent transition has been extensively studied in the context of wall-bounded shear flows, however, the very presence of streaks in free shear flows such as jets has seldom been recognised until recently. We now know that streaks are a prominent feature of jet turbulence, and that linear analysis predicts their dominant role at low Strouhal numbers. Their interplay with Kelvin-Helmholtz waves may even provide a self-sustaining mechanism for turbulence. We present a first linear instability analysis of parallel jet base flows, where the axisymmetry of the circular shear layer is broken by finite-amplitude streaks. The modified Kelvin-Helmholtz modes in such a nonlinearly perturbed base flow are characterised with regard to their growth rates and eigenfunctions. Sinuous streak structures are found to have a stabilising effect on the Kelvin-Helmholtz instability, whereas varicose streaks have a destabilising effect. To our disappointment, streaks in the base flow are not found to render the jet absolutely unstable.

The contribution of instability waves to the statistics of velocity field fluctuations of turbulent jets

M.A. Yudin, G.A. Faranosov, V.F. Kopiev, S.A. Chernyshev. Karban

TsAGI, Moscow Branch, Aeroacoustic Department, Russia

In various papers devoted to the statistics of hydrodynamic fields of a turbulent jet, attention is drawn to the intermittency effect – a significant difference of statistics from normal distribution, which is associated with the anomalously frequent occurrence of large deviations from the average values. In this paper, it is shown that in turbulent jet, the difference of statistics from normal distribution can be associated not only with rare intense events, but also with large-scale oscillations of the jet (instability waves), which must be taken into account for the correct interpretation of the small-scale fluctuations of hydrodynamic fields obtained in experiment or numerical simulation. The results of numerical simulation of a turbulent jet with a Mach number of 0.85 are used in this paper. It is shown, that the distribution of axial velocity in the initial region section of the jet differs from the normal one. The distinction appears in the regions close to the potential core boundary and close to the boundary of the jet itself. It turned out that this difference is associated with large-scale oscillations of the jet, which are instability waves with an azimuthal number n=1 (flapping modes). Such large-scale fluctuations result in the fact that the measurement point at different times actually falls either in the flow region with constant velocity or in the shear layer region. As a result, the inhomogeneity of the mean flow field will contribute to the statistics of the axial velocity fluctuations. The analysis of the axial velocity distribution on the axis of the jet behind the potential core was also carried out and the difference of velocity statistics from the normal one was also found, which can be explained by the same effect. The work has been partly supported by the Russian Science Foundation, project 21-71-30016.

Session 2

Triadic nonlinear interactions and the acoustics of forced versus natural turbulent jets

A. Nekkanti[1]***, O. Schmidt***[1]***, I. Maia***[2]***, P. Jordan***[2]***, L. Heidt***[3]***, T. Colonius***[3]

[1] University of California San Diego, La Jolla, CA USA
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[3] California Institute of Technology, Pasadena, CA USA

We explore the potential of bispectral mode decomposition (BMD) for physical discovery in jet flows. BMD is a modal decomposition that is tailored to the extraction of flow structures involved in triadic interactions. We address the question of how to identify and distinguish naturally occurring hydrodynamic instabilities and resonances from responses due to external forcing. In the context of laminar jets, we focus on the suppression of natural triadic interactions by external forcing. Even though the jet acoustics far away from the nozzle behave linearly, we expect to be able to identify the footprint of nonlinear triadic interactions occurring in the hydrodynamic near-field from phase-coupling in the acoustic far-field. Four large-eddy simulations (LES) of laminar and turbulent, and forced and unforced round jets at Re=50000 and Ma=0.4 are conducted and valsidated with the companion experiment at the Institut Pprime.

Spectral analysis of co-axial jets

A. Markesteijn, V. Gryasev, S. Karabasov

School of Engineering and Material Science, Queen Mary University of London, Mile End Road, London, E1 4NS, UK

Recently, the high-resolution CABARET Wall Modelled LES method was applied for flow and noise calculation of several coaxial jets corresponding to the conditions of the Coaxial Jet Noise project (CoJeN) [1]. In the present work, we will report results of the Fourier-Laplace and Spectral Proper Orthogonal Decomposition (SPOD) analyses of the same CoJeN jets following the work of Towne et al. for single stream jets [2]. SPOD is known to effectively compress the space-time resolved data whilst keeping the frequency-coherent content. One of the objectives of our work is, in addition to the commonly considered pressure fluctuations, to probe several alternative acoustic solution-sensitive variables such as the fluctuating Reynolds stress, which has been used in acoustic analogies for far-field noise modelling.

Application of resolvent analysis and SPOD to forced jets

L. Heidt[1], **T. Colonius**[1], **A. Nekkanti**[2], **O. Schmidt**[2], **I. Maia**[3], **P. Jordan**[3]

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Various actuation methods have been applied to turbulent jets for the purpose of mitigating jet noise. These methods have exhibited varying levels of success, with up to a 5dB reduction in overall sound pressure level noted in specific cases. However, a detailed understanding of the mechanisms by which forcing alters the turbulence and far-field sound is lacking. Existing literature suggests that periodic forcing has some benefits in terms of reducing far-field sound, but this is primarily associated with non-linear interactions resulting in a change to the turbulent mean flow of the jet. We investigate the effect of forcing by performing large-eddy simulations of turbulent axisymmetric jets subjected to periodic forcing at multiple frequencies and amplitudes. Spectral proper orthogonal decomposition is used to study the effect of the forcing on the linear spectrum. Low-frequency periodic forcing, $St_f = 0.3$, while producing highly energetic tonal structures and noise, has a limited effect upon the underlying turbulent spectrum of the jet and the most energetic modes. High levels of forcing, 1% of the jet velocity, are required to achieve a small change to the turbulent mean flow and a minor shift in the turbulent spectrum. The changes in the overall spectrum and the shift in the modes are predicted well via the resolvent analysis performed on the new turbulent mean flow. This shows that the turbulent spectrum stems from the turbulent mean flow and not via interactions between phase-locked structures and the natural turbulence. High-frequency periodic forcing, $St_f = 1.5$, is less effective at altering the mean flow field compared to the low-frequency forcing at the same amplitude, but results in a non-linear interaction associated with vortex pairing, amplifying the turbulence spectrum at $St \approx 0.75$.

Spectral and wavelet analysis of pure and installed jet flow with chevrons

H. K. Jawahar[1], **M. Azarpeyvand**[1], **A.P. Markesteijn**[2], **S. Karabasov**[2],

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We report results of the combined computational and experimental campaign aimed at the investigation of pertinent noise-related characteristics of several round and chevron jets issued from single stream nozzles of NASA SMC000 and SMC006-type. Both the isolated jets and the jets installed with a flat plate are considered. Flow simulations are performed using the high-resolution CABARET Wall Modelled LES solver accelerated on GPUs. Far-field acoustic spectra predictions are obtained with the Ffowcs Williams–Hawkings method using multiple penetrable control surfaces. The experimental part of the campaign is underway, and comparisons between the experiment and the LES solutions will be reported at the meeting. Following the work of Schmidt et al. (2018), all jet flows are analysed using Fourier-Laplace transform as well as Spectral Proper Orthogonal Decomposition (SPOD). Additionally, dynamic features of the considered jets are highlighted using the continuous wavelet analysis.

Session 3

Guided jet mode and screech in rectangular jets

A. Towne, R. Tolontan

University of Michigan, Ann Arbor, MI, USA

A mountain of recent evidence has established the key role of acoustic waves traveling within the core of round jets in closing the resonance loop leading to screech as well as other forms of tonal noise. The properties of these guided acoustic waves determine properties of these tonal noise components, for example the frequency and Mach number ranges over which they exist. In this presentation we investigate the properties of these waves and their role in screech in rectangular jets, a configuration for which they have not been previously characterized. Using a two-dimensional finite thickness model, we show that there exists a doubly infinite set of these waves, each categorized by its transverse order along the major and minor axis of the jet. The relative positioning of these waves in frequency-wavenumber space scales with the aspect ratio of the jet, and we explore the implication of this observation on the character of the waves available to the screech resonance loop as a function of Mach number and aspect ratio and on the asymmetries of the tonal signature of these waves observed outside of the jet. After establishing the properties of these waves, our longer term goal is to use these findings to develop a predictive screech tone model.

Supersonic screech as an absolute instability

***P. Nogueira*[1], *P. Jordan*[2], *V. Jaunet*[2], *A.V.G. Cavalieri*[3], *A. Towne*[4], *D. Edgington-Mitchell*[1]**

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In this work, we present a new formulation for the stability analysis of shock-containing jets. The flow is linearized around a spatially periodic mean, which leads to a system of partial differential equations with periodic coefficients. The equations are then solved using the Floquet ansatz, resulting in eigenvalues and eigenvectors that are directly comparable to the locally parallel case. The imposed periodicity of the system does not lead to substantial changes in the eigenvalues for small shock amplitudes, but the resulting eigenfunctions display a modulated behaviour, with peak wavenumbers connected to the flow periodicity. Further analysis of the spectrum led to the identification of saddle points between the Kelvin-Helmholtz mode and the discrete neutral upstream mode, characterising an absolute instability mechanism. Frequencies of the saddle points and mode shapes close to the saddle are in good agreement with previous experimental data, which strongly suggests that screech is actually the result of an absolute instability of the flow, in which the jet displays an oscillator behaviour.

A simplified model for long-range-resonant global instability

P. Jordan

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Fluid systems exhibit global instability when a synchronised energy exchange occurs between waves travelling in opposite directions such that the rate of energy extraction from the base-flow exceeds that associated with energy lost by the two waves over one period of the frequency of interest. The waves are mutually reinforced. They resonate. Wave synchronisation may occur in at least two different ways. Short-range synchronisation can occur in the absence of boundaries when the two waves have the same wavenumber and frequency; such is the mechanism underpinning instability in cold wakes and hot jets [Martini *et al.* (2019) JFM **Vol. 867**]. Another class of resonance is associated with long-range feedback, where two waves of similar frequency but different wavenumber become coupled due to energy exchange at reflection points separated by some distance. Such is the case for the global instability of cavity flows, impinging jets and jet-edge interaction. A global instability calculation (eigensolution of the linearised Navier-Stokes system) does not distinguish between these two, fundamentally different, mechanisms. For weakly non-parallel flows, local stability analysis proves to be a useful tool, both as a means by which to determine which of the two mechanisms underpin a given global instability, *and* as a basis for the construction of simplified resonance models that allow the global instability to be both predicted and understood. The talk will review simplified models suitable for the long-range-resonant scenario and that have been used to provide insight into jet-edge interactions [Jordan *et al.* (2018) JFM **Vol. 853**] and supersonic jet screech [Mancinelli *et al.* (2019) Exp. Fluids **60(22)**; (2020) **arXiv:2012.01342v1**]

An insight into the non-local physical mechanisms of impinging jet instability

***F. Giannetti*[1], *J. Sierra*[1,2], *V. Citro*[2], *P. Luchini*[1], *D. Fabre*[2]**

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It is well known that high subsonic jets directed normal to a wall are able to produce, under particular conditions, intense discrete frequency sound waves called impingement tones. This phenomenon has been studied by a number of investigators in the past and is generally accepted that such tones are generated by a non local feed- back loop among two kind of waves: a downstream-travelling wave, which is excited at the nozzle lip and propagates around the jet core position, and an upstream-travelling wave generated by the impingement of disturbances on the plate and propagates back- ward inside the jet core. The non-local constructive interaction of such waves gives rise to a self-sustained global in time instability, which in some circumstances, is able to radiate an intense acoustic field. In this work we analyse in details the characteristics of the global instability which drives the main characteristics of the flow field. In particular, a parametric global stability analysis will be performed by first calculating the unstable symmetric base ow and then by evaluating the leading eigenvalues and eigenvectors of the linearised compressible Navier-Stokes operator. The resulting spectra and the characteristics and nature of the associated leading unstable eigen- modes will be discussed. Further insight into the instability mechanism is gained by performing a weakly-nonparallel local stability analysis. The two component of the feedback mechanism, the forward convectively unstable hydrodynamic mode of Kelvin-Helmholtz type and the backward propagating waves of acoustic nature, will be precisely identified and the transmission and reection coecients of the waves will be locally extracted with the aid of an "adjoint projection" on the global eigenvector. The analysis will precisely unveil "the scattering region", i.e. the area where the exci- tation and the interaction of the local waves occur, providing important information on the resonant mechanism and the condition for sound radiation. The results will serve as a base for the possible identification of a quantitative "frequency selection criterion" and mode reconstruction procedure based on a local-type analysis.

A mode-matching approach for the evaluation of the reflection coefficient of a Kelvin-Helmholtz wave incident on a shock

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Resonances were shown to be the probable source of tonal noise in both subsonic and supersonic jets. For supersonic jets the tonal noise, known as screech, was previously explained via the feedback loop between a downstream-travelling Kelvin-Helmholtz (K-H) mode and an upstream-travelling acoustic wave generated by the interaction of the K-H mode with the shock-cell structure (Powell, 1953). Recently, it has been proposed that discrete, upstreamtravelling guided modes are responsible for the feed-back loop (Edgington-Mitchell et al., 2018). A simplified screech-tone prediction model based on this idea has been developed and validated by Mancinelli et al. (2019). In the simplest formulation of the screech-tone model, the spatial growth of the K-H mode is ignored, and a phase-matching criterion is sufficient to provide a reasonable prediction of screech-tone frequencies. In a more complete model (Mancinelli et al., 2020), where the spatial growth rates of the upstream- and downstream-travelling waves are included, knowledge of the reflection-coefficients in the jet exit plane and at the shock-cell location is required. It is this that motivates the study we here report. In this work we investigate the reflection and transmission of waves associated with the interaction between a Kelvin-Helmholtz wave and a normal shock in an under-expanded jet using a mode-matching approach. Both a vortex-sheet and a finite thickness shear-layer models are explored, quantifying the impact of the shear layer in the said reflection. This approach may open the possibility for more quantitative predictions for fluid-mechanics resonance phenomena.

Tuesday 31st August

Session 4

Wavepacket models for supersonic twin-jets using 3D parabolized stability equations

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An extension of the classic Parabolized Stability Equations to flows strongly dependent on the two cross-stream spatial directions and a milder dependence on the streamwise one is applied to modeling the large scale structures present on twin-jet configurations. The existence of these unsteady flow structures, usually referred to as wavepackets, has been demonstrated for both subsonic and supersonic round jets, as well as and their relation to the generation of the highly directional noise emitted in the aft direction. Wavepacket models can predict the main contribution to the turbulent-mixing noise emitted by supersonic jets, and also be used in more complex models for the prediction of shock-associated noise components. The present study considers twin-jet configurations with different separations at high Reynolds number and ideally-expanded exhaust supersonic conditions. The instability modes existing for the twin-jets mean flow, the interaction between the wavepackets and their associated noise is investigated for different jet separations.

Wavepacket modelling of elliptical jets

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The hydrodynamic instability analysis has been widely used for predictions of the acoustic field of a jet. The geometry of the jet nozzle is an important factor that can delay or accelerate the growth rate of the disturbances and in turn increase or decrease the sound field at the end. The present work discusses the development of a numerical code for a 3D-LPSE (Linear Parabolized Stability Equations) analysis applied to a jet with an elliptical-shaped nozzle. For the initialization of the method, the spatial stability analysis BiLocal EVP (Eigenvalue Problem) solutions was used in cylindrical coordinates with the typical spectral method for calculations. The code was implemented and extensively validated focusing on the case in the literature of a jet with an asymmetric flow profi

le. For the 3D-LPSE stability analysis the validations were focused on a contra-rotating vortex case. Finally, after using a numerical solution for the base flow of the elliptical jet, the linear 3D-LPSE was performed for different values of elliptical eccentricity. The results were also compared using the BiLocal EVP analysis for different points in the domain and the results show a good agreement between both methods.

Vortex-sheet modelling of twin jets

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Presented here is a vortex sheet formulation for a twin-jet system and the resulting dispersion relation for the setup. Through solving this relation key flow features, such as the Kelvin-Helmholtz (KH) and upstream-propagating neutral mode (K-), are illustrated along with their sensitivity to the jet spacing. For the K- modes this manifests as their existence region increasing with increasing spacing for solutions that are antisymmetric about the two jets, leading to changes in where screech can occur for this symmetry. Also considered is the method of classifying twin-jet solutions based on an equivalent single jet solution. At very low jet spacings a single azimuthal classification is misleading, as despite still being dominant, there is significant energy held in forms of other azimuthal orders.

Global stability analysis in over-expanded nozzles

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Shock wave-boundary layer interactions occurring in over-expanded rocket nozzles during start-up and shut-down are responsible are responsible for non-axisymmetric forces the socalled side-loads. The mechanisms underlying these are related to the unsteady dynamics of the shear layers side-loads from the separated point and the triple point interacting with the second Mach disk. The purpose of this talk is to better describe and better understand these mechanisms. For that, numerical simulations, using a hybrid approach (here DDES) of the turbulence, are realized on a TIC (Truncated Ideal Contoured) nozzle for a jet Mach of Mj = 2:09. These simulations will be supplemented by linear stability analyzes around a stationary solution of RANS and DDES approaches. These analyzes show that a possible origin of these side-loads is the existence of an unstable helical mode. These results will be compared to the experiments carried out in the same configurations by the Pprime Institute. In the present case, the nonlinear unsteady solution is obtained by solving the compressible URANS equations in a DDES approach. For stability analyzes, the base-flow is computed as the fixed point of RANS solution of the problem. After computing this solution, the Linearised Navier-Stokes Equations (LNSE) are solved about this solution. The solution of the deriving eigenvalue problem gives the spatial distribution, growth rate and circular frequency of the global modes.

Session 5

Optimal resolvent-based control using the Wiener-Hopf approach

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The design and implementation of optimal control laws to complex flows typically require simplified forcing modeling, which can reduce the control efficiency, and the construction of reduced-order models (ROMs), which can be cumbersome and expensive. We use the Wiener-Hopf formalism to circumvent these drawbacks. A matrix-free method is used to construct the Wiener-Hopf problems associated with optimal estimation and control, and a tailored approach is used to solve it. The resulting method allows optimal control to be obtained for large systems with high-rank forcing and targets, disturbed by spatio-temporal coloured forcing, as well as inexpensive actuator/sensor placement investigation when the targets/forcing are low rank. The method is particularly suited for the control of amplifier flows, for which optimal control is typically robust, and can be applied using only experimental data, allowing not only direct application to experiments, with considerable potential to existing improve wave-canceling strategies, but also when adjoint solvers are not available. Control of the linearized and non-linear flow around a backwards-facing step is investigated, showing that downstream of the step the flow is low-rank, but with a high-rank receptivity to upstream disturbances, pointing towards the need of multiple sensors and few actuators.

Estimation and control of forced turbulent jets

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Estimation and control of turbulent flow is a challenging problem with important practical and fundamental applications. In this work we perform reactive control of stochastic disturbances in forced turbulent jets based on destructive interference. The study is motivated by the success of recent studies in applying this type of control on instability waves in transitional boundary layers and free-shear flows. Linear convective mechanisms in the initial region of turbulent jets are explored in order to perform estimation and actuation based on linear transfer functions measured experimentally. The control law is produces an actuation signal which is updated in real time based on sensor measurements performed upstream, resulting in an inverse feedforward approach. Since turbulent jets have energy content spread in a number of azimuthal wavenumbers, we apply axisymmetric forcing at the nozzle lip in order to be able to perform control using a reduced number of sensors and actuators. The external forcing produces axisymmetric wavepackets which possess stochastic phases and amplitudes, akin to turbulent fluctuations found in unforced jets. We demonstrate the successful implementation of real-time reactive control of these disturbances, achieving order-of-magnitude attenuations of associated velocity fluctuations. Control is shown to reduce fluctuation levels over an extensive streamwise range. We also present perspectives on the use of nonlinear transfer functions based on the bispectrum in order to improve real-time estimation in turbulent jets.

Active feedback control of instability waves in unexcited turbulent jets

V. Kopiev, G. Faranosov, O. Bychkov, Vl. Kopiev, I. Moralev, P. Kazansky, A. Efimov

TsAGI, Moscow Branch, Aeroacoustic Department, Russia

The possibility of active closed-loop control of instability waves in unexcited subsonic turbulent jets is investigated theoretically and experimentally. The proposed control strategy consists in the narrowband sliding filtration of the original signal and the formation of a narrowband control action on the nozzle edge (where shear layer is most sensitive to the external action). The strategy is based on the linear principle of signal superposition: it is assumed that the total signal will be reduced in certain domain downstream from the edge if the control action generates instability waves so that they occur of the same amplitude and in the antiphase to the natural instability waves in this domain. To implement active suppression, it is necessary to predict the signal in a narrow frequency band for a time sufficient to ensure such interference. The control system realized in experiments includes near-field microphones in the area under control, plasma actuator at the nozzle edge, and data processing module. The closed-loop is organized in a feedback type scheme. It is demonstrated that one can choose the system settings so that near-field pressure pulsations associated with the instability waves can be attenuated there in a narrow frequency band. For the low-speed free jets the instability waves are not an effective sound generator. Thus, the effect of control is localized in the near field. However, direct acoustic effect of control can be observed in the far field for an installed jet. The work has been partly supported by the Russian Science Foundation, project 21-71-30016.

Reducing the noise from twin supersonic hot jets

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The intense jet noise radiated by closely-spaced, twin supersonic hot jets causes operational and health concerns for aircraft carrier operations and personnel. To acheive jet noise reduction (JNR), we develop and test a physics-based strategy that utilizes the resolvent framework to identify candidate flow control strategies that yield reductions in the output gains for a range of target Strouhal numbers. Explicit formulas that connect the change in the gains to the control parameters are derived and incorporated into an optimization procedure. Both unsteady actuation and mean flow modification approaches are devised. Uncontrolled and controlled twin supersonic hot jets are simulated using large-eddy simulation techniques to understand the impact the control has on the jet plume and on its radiated noise.

Session 6

Mach-number dependence of the acoustic tones near the nozzle of jets

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The properties of acoustic peaks in the near-nozzle region of jets are investigated for Mach numbers M between 0.50 and 2 using large-eddy simulations (Bogey, C., 2021, Acoustic tones in the near-nozzle region of jets: characteristics and variations between Mach numbers 0.5 and 2, J. Fluid Mech., to appear).The peaks are tonal for $M \geq 0.75$ and broaden for lower Mach numbers. They are associated with the azimuthal modes 0 to $nthetamax$, with $nthetamax = 8$ for $M = 0.75$ and to $nthetamax = 1$ for $M = 2$ for instance. Their frequencies do not appreciably vary with the nozzle-exit boundary-layer conditions and fall in the bands predicted for the upstream-propagating neutral subsonic, guided jet waves using a jet vortex-sheet model. Over the whole Mach number range, the peak intensities increase roughly as M^8 for $M \leq 1$ and as M^3 for $M \geq 1$, following the typical scaling laws of jet noise. The Mach number variations of the peak width and sharpness are explained by the eigenfunctions of the guided jet waves. Finally, the acoustic peaks are detectable in the jet far field for large angles relative to the flow direction. For $M = 0.90$, for example, they emerge in the pressure spectra for angles higher than 135 degrees.

Linear modelling of resonance in a rocket nozzle

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Resonances in jet flows, issued from truncated ideal contour (TIC)» nozzles, have been observed in a very narrow range of nozzle pressure ratio. Recent studies have shown that the associated non-axisymmetric pressure disturbances are sufficiently correlated in space and time to induce intense lateral forces that may cause structural damages or even flight control issues. At these regimes, the jet exhibits a large Mach disk, followed by an annular supersonic stream. The subsequent internal and external mixing layers have been shown to be of importance in the resonance mechanism. In the light of recent studies on screeching jets, we evaluate the possible mechanisms of resonance with the help of a simplified linear dynamical model of the flow, validated against available numerical and experimental data

Modelling of the acoustic radiation of high subsonic jets impinging on flat or perforated plates

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The acoustic radiation of four jets at a Mach number of 0.9 impinging on a plate is investigated using large-eddy simulations (LES) and an acoustic analogy based on the pressure fluctuations on the plate, in order to study the nature of the noise sources. For three jets, the plate is perforated by a hole of diameter $h = 2r0$, $3r0$ and $4.4r0$, centered on the jet axis, whereas for the fourth jet the plate is flat. In the LES, for all jets, a tonal acoustic radiation is observed, due to the establishment of an aeroacoustic feedback loop between the nozzle and the plate. The frequency of this radiation does not vary much with the hole diameter, but the tonal levels decrease as the hole diameter increases, by a few dB for $h \leq 3r0$ and by about $40dB$ for $h = 4.4r0$. The sound radiation is then evaluated using Curle's analogy. The pressure fields obtained are in good agreement with the LES results. In particular, the effects of the hole and its size are well reproduced. The acoustic spectra predicted using the analogy are close to those of the LES, suggesting that the noise sources on the plate are dominant compared to the noise generated by the flow turbulence.

Explaining the whistling of a jet through a plate using impedance criteria and global stability analysis

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We focus our attention on the fluid flow through a circular hole in a thick plate. The spatio-temporal evolution of the perturbation state is described by the linearised Navier-Stokes equations that are able to correctly predict the non-linear impedance even in cases where the spatial evolution of the perturbations is rapidly dominated by nonlinear effects. In particular, we use the Nyquist diagram to predict the occurrence of hydrodynamic and conditional instabilities. We analyse in detail the use of the Nyquist criterion and show that it is able to quantify the effect of the Mach number and the volume of the upstream volume cavity on the instabilities. Accurate global stability analysis of the compressible Navier-Stokes equations confirms the proposed results. Our approach is particularly suitable to perform a parametric analysis aimed to investigate the onset of the several instabilities.

Wavepacket signatures in jet resonance

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Jets undergoing resonance are characterized by multiple structures at the same frequency but different wavelengths. Typical decomposition methods such as snapshot or spectral proper orthogonal decomposition will group these structures into a single mode, presuming they are mutually coherent. In recent work we have explored the use of spectral linefitting to separate these waves from within a single complex mode. Here we will instead examine a combination of scale and energy based decompositions in an attempt to provide an alternative basis for this separation, testing the approach on both synthetic and experimental data.

Wednesday 1st of September

Session 7

Identification of Axisymmetric Coherent Structures in a Turbulent Bunsen Flame using the Resolvent Analysis

T. L. Kaiser, M. Casel, F. Zhang, T. Zirwes, H. Bockhorn, D. Trimis, K. Oberleithner

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Our study applies Spectral Proper Orthogonal Decomposition (SPOD) and Resolvent Analysis (RA) to investigate axisymmetric turbulent structures in a Bunsenflame at Re=15,000. Mean flow and instantaneous snapshots are obtained by Large Eddy Simulations. In the RA, a passive flame approach is applied, which means taking into account heat transfer, while neglecting source terms in the energy equation caused by chemical reaction. Furthermore, in the RA the flow is considered incompressible. Our results show that SPOD and RA are in good agreement for low frequencies, showing a low rank behavior within a certain range of frequencies, which is more pronounced than for non-reacting conditions. The dominant optimal response corresponds to the axisymmetric Kelvin-Helmholtz (KH) waves in the shear layer. We show that the evolution mechanism of these modes is significantly different than in non-reacting conditions: While for the cold flow, the forcing shows typical Orr-structures in the nozzle boundary layer, in the reacting case, the flow region close to the pilot burners appears to be the most receptive flow region to periodic forcing. Finally, a linear stability analysis is conducted to investigate the pronounced low-rank behavior of the flow: It is due to resonance with a marginally dampened hydrodynamic global mode

Resolvent analysis of a premixed slot flame

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The global response to forcing of a 2D laminar premixed slot flame with two-step chemical scheme is investigated via a linearized approach, where multi-physics coupling in a non-parallel reacting flow is accounted for. The flame transfer function obtained this way is in excellent agreement with nonlinear reference calculations, performed with the AVBP code. Numerical experiments of volume forcing are carried out, which reproduce the experimental process of injecting finite energies into the flame by external excitation, characterising its input-output behaviours. A simple algebraic formula is developed to identify the spatial structures of velocity perturbations such that the global heat release response is maximal, revealing the optimal receptivity of the flame. Forcing in line with receptivity structures leads to resonance-like peaks at frequencies where intrinsic thermoacoustic modes may occur, accurately predicted by the phases of flame transfer function close to an odd multiple of π. The standard full-rank global resolvent analysis is conducted to identify optimal forcing and response structures, giving insight to the dominant amplification mechanism in the flame. The present linear analysis opens new ways for the physical discussion of instability dynamics in flames.

Identification and Linear Modelling of Swirl Fluctuations in Swirl Combustors

K. Oberleithner, J. Müller, F. Lückoff, T. Kaiser

Laboratory for Flow Instabilities and Dynamics, Technische Universität Berlin, Germany

Modern gas turbines operate at lean premixed conditions using strongly swirled flows for flame stabilization and enhanced turbulent mixing. These strongly sheared flows are highly unstable and give rise to large-scale coherent structure that interact with the flame and drive thermoacoustic instabilities and high-amplitude pressure oscillations. Recent application of global stability and resolvent analysis have substantially improved our understanding of the formation of coherent structures in this context. However, one key mechanism, the generation of swirl fluctuations, has not been addressed conclusively so far, despite numerous experimental evidences for its importance for thermoacoustic instability. It is currently unknown whether these fluctuations are a consequence of hydrodynamic instability and whether they can be modelled using linearized methods. In this talk we present experimental data taken inside a swirl combustor and compare determined spectral modes with results from resolvent analysis based on the mean field obtained from LESs. We find excellent correspondence between the empirical modes and the resolvent modes proving that, indeed, the swirl fluctuations can be modelled with linearized methods. We further discuss the mechanism leading to these fluctuations differentiating between inertial waves that are propagating in the jet core region and shear driven modes.

On the generation of entropy noise in a shock containing nozzle of high-performance aircraft at afterburner

C. Tam

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High performance aircraft operate at high jet temperature and velocity. Measured noise data indicate that at afterburner condition their noise contain components not found in high temperature supersonic laboratory model jets. The combustion process inside an afterburner is highly unsteady and incomplete. Residual combustion takes place in the jet plume. This suggests that the flow from the afterburner into the jet nozzle would contain significant amount of hot and cold temperature blobs, generally referred to as entropy waves. It is known that when entropy waves move through a non-uniform mean flow, indirect combustion noise (also called entropy noise) would be generated. Military styled nozzles have a rather abrupt area change at and near the throat. This induces the formation of internal shocks inside the nozzle. This paper investigates the generation of entropy noise when strong entropy blobs or waves are convected through the internal shocks. It is found that the result of entropy blobs-shock interaction could lead to the radiation of intense entropy noise out of the nozzle exit into the jet plume as fast waves with a speed equal to sound speed plus jet flow speed. These fast waves create highly supersonic flow disturbances in the jet flow leading to strong Mach wave radiation. It is proposed that this Mach wave radiation is the source of a new noise component observed in the spectra of the F-22A aircraft. Detailed analysis of the F-22A noise data provides support for the proposal.

Session 8

Once again on the quadrupole nature of low-speed jet noise

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Detailed investigation of noise structure of relatively low-speed subsonic jets is presented. For the analysis different datasets are used including experimental data obtained by the azimuthal decomposition technique and LES numerical data obtained by different solvers and numerical schemes for jet Mach numbers 0.4-0.5. Experimental data provide reference points and serve for validation purposes. Numerical simulation, in turn, allows gathering synchronous pressure time histories at different far field points and performing careful analysis of amplitude-phase characteristics of the acoustic field for each azimuthal mode. Amplitude-phase portraits of the first three azimuthal modes clearly confirm quadrupole nature of noise radiated at low and mid-frequencies. Moreover, it can be concluded that the noise is radiated by a superposition of uncorrelated compact quadrupoles distributed over the region extended in the axial direction so that the total source domain is noncompact. This means that the azimuthal decomposition of the far field of the turbulent jet makes it possible to distinguish the spatial structure of the noise sources. On the other hand, wavepackets footprints are reliably identified in the near field of the jet but unlike point quadrupoles give no significant input into the far field noise in this range of jet velocities. At the same time, in the presence of reflecting surfaces, the mechanism of instability waves can be significant and even dominant in comparison with the quadrupole mechanism described above. Therefore the strategy of noise control could be different for low-speed/high-speed and/or installed/uninstalled jets. The work has been partly supported by the Russian Science Foundation, project 19-71-10064.

Resolvent-based estimation of jet-noise source

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The estimation of aeroacoustic noise sources is an important step for the understanding of physical mechanisms behind the sound generation and for further development of noise control strategies. In the present study we employ a resolvent-based methodology to estimate the noise source statistics of both a synthetic line wavepacket source model and a large eddy simulation database of a Mach 0.4 fully turbulent jet using a small number of sensors. Good agreement is observed for both cases with near exact match for the synthetic case. The preliminary results highlight the pertinence of resolvent-based estimation in aeroacoustics, as the method avoids the compact-source assumption used in beamforming frameworks and is thus suitable for the estimation of source statistics using microphone arrays, which can also be placed in the near pressure field of the source. Nonetheless, the method seems a viable alternative to acoustic beamforming, particularly for non-compact sources typical in aeroacoustics, whose wavepacket features are accurately identified in both cases. Future work will include a more complete formulation of the Lighthill's tensor and will account for the jet helical modes to improve the accuracy of source estimation.

On the absence of shear noise component in sound radiation of a turbulent jet

S.A. Chernyshev, V.F. Kopiev

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The noise generation by a subsonic turbulent jet is investigated. Local processes associated with the dynamics of small-scale vortex structures are considered as the noise generation mechanism. The analysis is carried out within the framework of an acoustic analogy, in which the linearized Euler equations are used as the propagation operator, and compact quadrupole sources are modeled by a stochastic field. The main problem with this approach is associated with the so-called shear noise. This is one of the components of sound emitted by a compact quadrupole source located in the sheared mean flow due to hydrodynamic interaction between the source and mean flow vorticity. On the one hand, the source represents small-scale fluctuations that stretch by the mean shear and this effect does not disappear when the quadrupole size tends to zero. On the other hand, the source excites the large-scale oscillations of the mean flow. Both of these processes generate a sound radiation constituting the shear noise. Amplitude of the shear noise is proportional to the ratio of the mean vorticity to the frequency and can reach a great value at low frequency and thin mixing layer of the jet. It is still unclear whether the shear noise is realized in the jet, or it is cancelled due to some hydrodynamic compensation mechanism so that the interaction of the quadrupole sources with the mean flow of the jet reduces only to the effect of refraction. Recent measurements made by the azimuthal decomposition technique indicate, rather, an absence of the shear noise in the jet acoustic field. This paper proposes a new approach to modeling of the sound sources based on the separation of hydrodynamic and acoustic variables. The results obtained explain the observed complex directivity pattern of the jet sound field and demonstrate the absence of the shear component in it. These results are taken as the basis for the developed low-order model of sound sources in turbulent flows. The work has been partly supported by the Russian Foundation of Basic Research (grant number 19-01-00229a)

Wavepacket-based BBSAN sound-source modelling

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A two-point model is used to investigate the underlying source mechanisms for broadband shock-associated noise (BBSAN) in shock-containing supersonic jets. In the model presented, the generation of BBSAN is assumed to arise from the nonlinear interaction between downstream-propagating coherent structures with the quasi-periodic shock cells in the jet plume. The turbulent perturbations are represented as axially-extended wavepackets and the shock cells are modelled as a set of stationary waveguide modes. The source characteristics of both the turbulent and shock components are extracted from the hydrodynamic region of large-eddy simulation and particle image velocimetry datasets. Apart from using extracted data, a reduced-order description of the wavepacket structure is obtained using parabolised stability equations. The validity of the model is tested by comparing far-field sound pressure level predictions to azimuthally-decomposed experimental acoustic data from a cold Mach 1.5 underexpanded jet. At polar angles and frequencies where BBSAN dominates, encouraging comparisons of the radiated noise spectra for the first three azimuthal modes, in both frequency and amplitude ($\pm$ 2dB/St at peak frequency), reinforce the suitability of using reduced-order wavepacket sources for predicting BBSAN peaks. On the other hand, wavepacket jitter is found to have a critical role in recovering sound amplitude at inter-peak frequencies.

Supersonic jet noise predictions — impact of using numerical optimization to determine the turbulence structure within a non-parallel flow based Generalized acoustic analogy

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In this talk we analyse acoustic predictions using Goldstein's analogy at a fixed of jet Mach number of 1.5. We obtain both the mean flow and turbulence structure from a Large Eddy Simulations (LES) database of two axisymmetric round jets (isothermal and heated) and use an asymptotic theory in the full non-parallel mean flow to determine the propagator tensor at low frequencies. The turbulence enters the low frequency acoustic spectrum formula through the R_{1212} Reynolds stress auto-covariance tensor component (where suffix 1, is the streamwise and 2, the radial direction). The acoustic analogy assumes that this source term is known and modelled it using the LES database to determine the parameters that regulate the streamwise and transverse decorrelation of R_{1212} within an exponential functional form with algebraic tails for the long-time behaviour. The novel aspect of the work is that the parameters are found via a numerical optimization scheme that we have previously validated for aero-acoustic problems. The generic nature of the optimization process allows us to assess the impact of various functional forms for R_{1212} including wave-packets. We discuss these acoustic prediction results and assess the impact of modelling R_{1212} in the various approaches we have described.

Session 9

Reynolds-stress modelling for linear resolvent analysis

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A large number of recent studies have established that resolvent analysis provides quite accurate predictions of coherent "response" structures in jet turbulence. This approach is grounded in well-established linear analysis, derived directly from the Reynolds Averaged Navier-Stokes (RANS) equations. However, in canonical resolvent modelling, the nonlinear generalised Reynolds stresses are represented by "forcing" modes that in general do not match the actual flow data. Our approach includes the Reynolds stresses in the state vector of the resolvent model. Thus we obtain a "second order" resolvent model, which reproduce stresses in the flow better than regular resolvent analysis, and offers different predictions of the dominant modes of velocity fluctuations. We will demonstrate the application of this method to turbulent channel flow, where predictions are compared to DNS data, and to standard resolvent analysis results with and without an eddy viscosity model.

Non-linear transition and turbulence dynamics of a model shear layer

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A model shear-layer flow was recently introduced by Nogueira & Cavalieri (J. Fluid Mech. 2021). The flow is a confined shear layer between horizontal walls, driven by a body force. The configuration allows Fourier expansions in the streamwise and spanwise directions, which greatly simplifies computations and analysis using methods from linear stability and from non-lineary dynamical systems. The results reported in the cited paper show a limit cycle, where Kelvin-Helmholtz vortices and streamwise streaks vary in amplitude and modulate each other in a self-sustaining cycle that also involves oblique waves. The cycle appears as a time-periodic behaviour of the Kelvin-Helmholtz vortices, which alternatively grow or decay in time as a function of the mean-flow state, in what is referred to as permanently actuated, periodically unstable (PAPU) flow. In this work we modify this model shear layer by using free-slip boundary conditions on the walls, instead of the free-slip condition in Nogueira & Cavalieri. This brings the flow closer to standard transitional and turbulent shear layers and jets, as no boundary-layer wall-dynamics are developed, maintaining nonetheless the periodicity in streamwise and spanwise directions. Direct numerical simulations of the flow are carried out for various Reynolds numbers Re. At low Re the flow displays a PAPU limit cycle similar to the observations of Nogueira & Cavalieri. Further increases of the Reynolds number allow tracking more complex behaviour, including the appearance of a quasi-periodic solution and the transition to chaos and an attractor merging crisis. At sufficiently high Reynolds number the solutions display jitter in the amplitudes and phases of vortices and streaks, in a behaviour that is reminiscent of observations of turbulent jets. The present shear layer appears as a promising flow for fundamental studies of non-linear dynamics of typical coherent structures observed in turbulent jets.

An efficient algorithm for computing resolvent modes for three-dimensional jets

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Resolvent analysis of the Navier-Stokes equations has proven useful for understanding and modeling the dynamics of coherent structures and their radiated sound in axisymmetric jets. However, application of resolvent analysis to more complex jets with non-axisymmetric mean profiles has been hindered by the poor scaling with problem size of methods used to compute resolvent modes, i.e., the singular modes of the resolvent operator, leading to prohibitively high computational cost for most three-dimensional problems. 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, drastically reducing CPU and memory costs for large systems. The efficiency and cost-scaling of our algorithm are demonstrated using both two- and three-dimensional jets.

On the use of the data- and physics-driven approaches for jet noise modelling

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The large difference in complexity between the high Reynolds-number turbulence and acoustic waves in the audible range of wavelengths was exploited by many jet noise theories. Typically, either acoustic analogies or alternative approaches such as the wavepacket model are considered where the sound propagation is treated separately from the effective source modelling. In turn, the source modelling relies on space-time-resolved data obtained from Large Eddy Simulations (LES) or experiments. In comparison with the experiment, in many LES cases, the useful signal is limited in time, which also limits the advantage of the Laplace-based analysis methods, which use the ergodicity assumption. On the other hand, the problem of extraction of low-order structures from highly complex noisy fields, for example separating the deterministic chaotic structures from the pure stochastic noise fields, has been a subject in signal processing and dynamic systems theory since 1980s. One popular approach is based on phase space partitioning/symbolisation of the noisy signal data, extraction of patterns, construction of the surrogate datasets, which mimic the spectral properties of the original signal and then populating a sufficiently high-dimensional phase space with the realisations of the original signal (often called training dataset) to accelerate the statistical convergence. In many cases, the patterns of the symbolised signal can be conveniently represented by networks or graphs. One promising approach in this area, called Permutation Entropy analysis, has been discussed in the series of works. The idea behind it lies in counting of occurrence of symbolic patterns appearing in the discrete signal. In the present work the aim is to extend the data-driven pattern recognition approach and apply it for the analysis of turbulent fluctuating velocity field obtained from a validated LES of a high-speed subsonic single-stream jet. The case considered is a cold single-stream static jet issuing from a profiled convergent nozzle. Having validated the LES solution, turbulent velocity and pressure fluctuations are computed from several representative jet locations in the jet. A new symbolization algorithm is developed to extract the relevant patterns from the flow signal. The recurrence of the patterns is analyzed for different symbolisation choices. To facilitate the analysis with the goal to uncover the hidden low-dimensional structures, the approach based on the idea of Monadas will be employed as well as machine learning techniques. The Monadas term was originally introduced by Newton and further exploited by Arnold for the analysis of binary sequences at the output of simple maps (residual operators).

Installed jt noise simulation in an industrial framework

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Jet noise during takeoff remains a major component of total aircraft community noise for state-of-the-art commercial aircraft. Engines are more likely to be close-coupled with the wing as their size and bypass ratios increase. This trend might cause an increase of the acoustic interactions between the jet and the airframe, named jet-related installation effects. This prompts us to increase our effort to understand, simulate, evaluate and reduce installed jet noise: the jet noise sources, the acoustic propagation as well as the jet-airframe interaction sources in close-coupled configurations. In this work, we are going to focus on installed jet noise regarding industrial configurations showing the complementarity between two methods. The first one, high-fidelity simulation relies on scale-resolving CFD coupled with a Ffowcs Williams-Hawkings analogy and, the second one, a wavepacket source model coupled with a boundary element solver for the propagation. We will show the benefit of being able to use these two methods together to understand and predict installed jet noise by applying them on the same realistic industrial configuration. A RANS solution will be used to construct the Ffowcs Williams-Hawkings porous coupling surface for the scale-resolving simulation, but also as a base flow for wavepacket models. We will compare the methods in terms of acoustic directivity and we will review the potential of using wavepacket models jointly with the scale-resolving simulation.