Compte-rendu de fin de projet

Projet ANR-12-BS09-0024

Cool Jazz

Programme Blanc SIMI9 2012

A IDENTIFICATION

Acronyme du projet	Cool Jazz
Titre du projet	Control-oriented linear and nonlinear modelling of jet aeroacoustics
Coordinateur du projet (société/organisme)	Lutz LESSHAFFT (Laboratoire d'Hydrodynamique, CNRS)
Période du projet (date de début – date de fin)	01/2013 07/2016
Site web du projet, le cas échéant	http://yakari.polytechnique.fr/jetnoise/

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Date de rédaction	31/07/2016

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Liste des partenaires présents à la fin du projet (société/organisme et responsable scientifique)	Institut Pprime, CNRS (Peter JORDAN) LIMSI, CNRS (François LUSSEYRAN) LadHyX, CNRS/X (Lutz LESSHAFFT)

B RÉSUMÉ CONSOLIDÉ PUBLIC

B.1 RÉSUMÉ CONSOLIDÉ PUBLIC EN FRANÇAIS

Les paquets d'ondes dans les jets turbulents et leur potentiel pour le contrôle

Caractériser les mécanismes physiques à l'origine des paquets d'ondes, les cibler pour réduire le bruit de jet

Le projet "Cool Jazz" étudie la dynamique des paquets d'ondes dans les jets turbulents subsoniques, leur rôle dans la génération du bruit de jet, ainsi que la possibilité de leur contrôle pour réduire ce bruit. Sur le plan fondamental, l'étude vise d'abord à expliquer comment ces structures cohérentes sont générées dans les jets turbulents à haut nombre de Reynolds, pour ensuite étudier leur dynamique à l'aide de la théorie des instabilités linéaires, ce qui fournit les clés pour comprendre leur rôle dans la génération de bruit acoustique. Sur le plan applicatif, cela permet de concevoir des stratégies de réduction du bruit de jet basées sur un contrôle en boucle fermée de la dynamique de ces paquets d'ondes.

Une démarche transverse qui fait appel aux expériences, à la théorie des instabilités et du contrôle, et à l'analyse des systèmes dynamiques

Dans ce projet, les paquets d'ondes sont étudiés par trois approches complémentaires : l'extraction des structures cohérentes à partir de données expérimentales et numériques, le calcul des instabilités linéaires des jets et l'étude du caractère deterministe de ces écoulements turbulents comme des systèmes dynamiques. L'expertise requise dans chacun de ces domaines est fournie par les différents partenaires de l'étude. Ainsi, cela a permis de construire des modèles d'ordre réduit en se basant sur les paquets d'ondes identifiés, afin d'obtenir les prédictions nécessaires pour la conception du contrôle. À chaque étape, le succès de la modélisation et du contrôle est validé par confrontation aux données expérimentales et numériques.

De larges bases de données expérimentales ont été construites pour des nombres de Mach de 0,4 et 0,9. Leur étude a permis de démontrer que les structures cohérentes des jets, définies en tant que modes propres de la densité spectrale, correspondent, au sens statistique, à la réponse linéaire du jet à un forçage optimal obtenu par analyse de stabilité. La non-linearité dans les modèles construits agit comme un forçage stochastique des structures linéaires. Les paquets d'ondes permettent de modéliser efficacement l'écoulement, et ils s'avèrent être particulièrement contrôlables.

Ces résultats ont été mis en valeur dans un grand nombre de publications et de présentations aux conférences internationales, et les données obtenues ont été mises à disposition de la communauté scientifique. Enfin, pour clôturer le projet, un colloque international sur le thème "Jet Noise Modelling and Control" se tiendra à l'École polytechnique en septembre 2016.

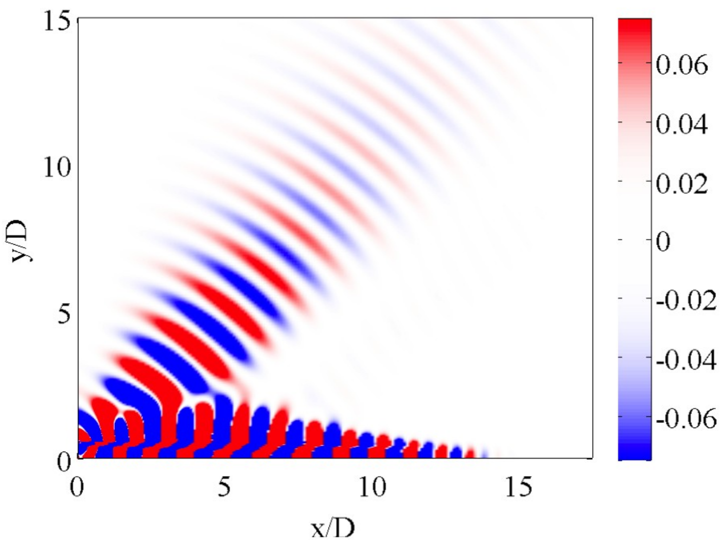

Figure 1: Fluctuations de la masse volumique dans un paquet d'ondes obtenu par analyse linéaire globale, dans un jet à Ma=0.9 et Re=1 000 000. Le champ acoustique est caractérisé par un faisceau très directif.

Le projet Cool Jazz est un projet de recherche fondamentale, associant les laboratoires LadHyX, Pprime et LIMSI, coordonné par Lutz Lesshafft. Le projet a commencé en janvier 2013 et a duré 43 mois. Il a bénéficié d'une aide ANR de 397 k€ pour un coût global de l'ordre de 1,5 M€.

B.2 RÉSUMÉ CONSOLIDÉ PUBLIC EN ANGLAIS

Wavepackets in turbulent jets and their potential for flow control

Characterise the physical mechanisms behind coherent wavepackets, use these as targets for jet noise reduction:

The Cool Jazz project explores the dynamics of coherent wavepackets in subsonic turbulent jets, their role in the generation of jet noise, and the prospects of noise reduction through closed-loop flow control. On a fundamental level, the study first aims to elucidate how coherent wavepacket structures arise in high Reynolds number jet turbulence, how the underlying mechanisms can be described by linear instability theory, and how these near-field fluctuations radiate sound into the far field. It is then investigated if wavepackets can be targeted for the purpose of closed-loop control of turbulent jets, with the perspective of reducing jet noise.

An integrated approach that combines experiments, instability and control theory, and dynamical systems analysis:

Wavepackets are investigated from three different perspectives: by extracting coherent structures from experimental and numerical data, by computing linear instability flow structures, and by characterising the deterministic properties of dynamical systems. Special expertise in these areas is provided by the respective consortium partners. Reduced-order models are then built on the basis of the identified wavepacket structures, in order to obtain dynamical predictions for the purpose of control design. Modelling and control success is validated against experimental and numerical data at every stage.

Extensive databases have been generated with near-field and far-field data from jet experiments at Ma=0.4 and Ma=0.9. It has been demonstrated that coherent structures extracted as eigenmodes of the cross-spectral density correspond to the linear flow response to optimal forcing, as obtained from instability analysis, in a statistical sense. Nonlinearity enters the dynamics in the form of a stochastic forcing of linear structures. It has further been shown that such wavepackets represent an efficient basis for flow modelling, and that these structures are highly controllable.

The project has led to a large number of journal publications and conference contributions. The generated data is publically available. An international colloquium on "Jet Noise Modelling and Control" is held at Ecole polytechnique in September 2016 as a result of the project.

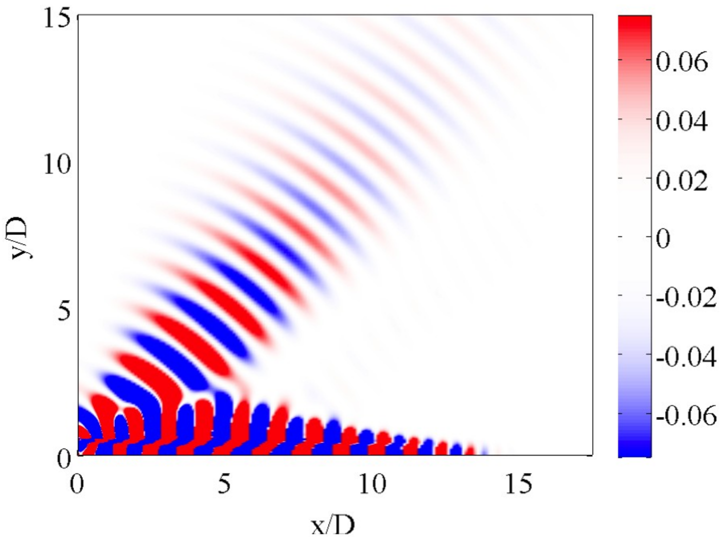

Figure 2: Density fluctuations in a wavepacket, obtained from global linear analysis, in a jet at Mach number Ma=0.9. The acoustic field is characterised by a highly directive beam pattern.

The Cool Jazz project is a fundamental research project, carried out at the CNRS laboratories LadHyX, Pprime and LIMSI, coordinated by Lutz Lesshafft. The project started in January 2013, and lasted over a period of 43 months. It has received 397 k€ in funding from the ANR, for a global project cost of approximately 1.5 M€.

C Mémoire scientifique

Mémoire scientifique confidentiel : non

C.1 Résumé du mémoire

The Cool Jazz project explores the dynamics of coherent wavepackets in subsonic turbulent jets, their role in the generation of jet noise, and the prospects of noise reduction through closed-loop flow control. On a fundamental level, the study first aims to elucidate how coherent wavepacket structures arise in high Reynolds number jet turbulence, how the underlying mechanisms can be described by linear instability theory, and how these near-field fluctuations radiate sound into the far field. It is then investigated if wavepackets can be targeted for the purpose of closed-loop control of turbulent jets, with the perspective of reducing jet noise.

The study of wavepackets is approached from three different perspectives: by extracting coherent structures from experimental and numerical data, by computing linear instability flow structures, and by characterising the deterministic properties of dynamical systems. Reduced-order models are then built on the basis of the identified wavepacket structures, in order to obtain dynamical predictions for the purpose of control design. Modelling and control success is validated against experimental and numerical data at every stage.

Extensive databases have been generated with near-field and far-field data from jet experiments at Ma=0.4 and Ma=0.9. It has been demonstrated that coherent structures extracted as eigenmodes of the cross-spectral density correspond to the linear flow response to optimal forcing, as obtained from instability analysis, in a statistical sense. Nonlinearity

enters the dynamics in the form of a stochastic forcing of linear structures. It has further been shown that such wavepackets represent an efficient basis for flow modelling, and that these structures are highly controllable.

C.2 Enjeux et problématique, état de l'art

In order to achieve a significant reduction of jet noise, a key element to future air traffic development, the Cool Jazz project explores the potential of active flow control in jets. Our approach targets the large-scale structures in turbulent subsonic jets, which are commonly acknowledged to represent the dominant source of directive noise.

The objectives are, on the one hand, to further the fundamental understanding of the turbulent flow dynamics that give rise to noise production, and on the other hand to test the feasability of their active control.

In order to formulate control strategies, reduced-order models of jet dynamics must be devised that are capable of predicting the effect of control input on the flow behaviour, with low computational effort but sufficient accuracy. We seek to demonstrate that *wavepackets* constitute the salient dynamical elements in turbulent jets, and that these structures provide the keystone to successful modelling.

Apart from the practical use of wavepacket structures for the purpose of control-oriented modelling, one main objective of the Cool Jazz project is to justify the observed presence of wavepackets in turbulent jets on theoretical grounds, and to fully characterise their properties on a physical basis, by means of instability analysis.

It has long been noted that coherent structures in highly *nonlinear* jet turbulence bear the traits of instability wavepackets, which can be described by *linear* analysis. However, a theoretical justification has so far been wanting, and the Cool Jazz project aims to elucidate this long-standing question. Furthermore, previous efforts of linear instability modelling have consistently fallen short of capturing the development of measured wavepackets in the region downstream of the potential core. Better agreement is sought by employing a fully global instability approach, and by investigating the effect of fine-scale turbulence on the large-scale instability structures.

A related key question is by what physical mechanisms wavepackets generate noise. Instability-based models in the past have been found to significantly underpredict the radiated noise level. Analysis of the experimental data obtained by the Pprime group prior to the Cool Jazz project suggested that "jitter" (low-frequency modulations of turbulent wavepackets) may be the element that makes stochastic wavepackets a much more efficient sound source when compared to the static structures obtained from classical instability analysis. The question how the effect of jitter may be accounted for in a linear modelling framework has been an important focus in our project.

On the practical side, real-time active control through upstream actuation requires a model that predicts how the upstream dynamics influence the downstream dynamics. The controllability of downstream dynamics hinges on the degree of coherence in the streamwise direction, and under the paradigm of the Cool Jazz project, this coherence is expected to be provided by wavepacket structures. A thorough analysis of experimental data, from a dynamical systems perspective, is necessary in order to assess the deterministic nature of convecting flow perturbations. Next, explicit transfer functions need to be formulated that approximate the link between upstream and downstream dynamics. The design of such transfer functions relies on the dynamics of wavepacket models, which are either empirically educed through data-driven system identification techniques, or obtained from linear instability analysis.

The feasability of active control based on such modelling has first been tested in configurations of reduced complexity. The final and most ambitious goal has been to implement a model-based control strategy in an experiment, in order to reduce the noise radiated by a high Reynolds number turbulent jet.

C.3 APPROCHE SCIENTIFIQUE ET TECHNIQUE

Our approach to the modelling of noise-emitting flow structures in jets integrates experiment, numerical analysis and theory at every stage of the project. The study of coherent *wavepackets* is the central element of our approach, as we start from the premise that these structures are responsible for that part of the jet noise which creates most nuisances, and which is most likely to be accessible to control.

Jet experiments at the Pprime facility "Bruit et Vent" run at Mach numbers between 0.4 and 0.9, with Reynolds numbers up to 10^6. Coherent wavepackets are extracted from experimental data in the form of eigenfunctions of the cross-spectral density (CSD), obtained from two-point time-series measurements. In addition to these experiments, numerical data from large-eddy simulations (LES) has been graciously made available by Guillaume Brès (Cascade Technologies), for a flow configuration that matches the experiments at Ma=0.9.

Linear instability wavepackets are computed in many different contexts and with a variety of classical and advanced formalisms, including parabolized stability equations (PSE), time-stepped linear Euler equations with boundary forcing (LEE), global frequency response analysis (FR, a.k.a. resolvent analysis), and global eigenmode analysis. LEE and FR calculations are carried out in a fully compressible framework, such that the acoustic far field is contained in the solutions. All these calculations solve for the growth and decay of linear perturbations in a pre-defined basic flow, in most cases given by an experimentally measured steady mean flow, or the corresponding mean flow from LES. A slowly time-varying basic flow is used in some cases, in order to achieve "jittering" wavepacket solutions.

Reduced-order models are built on the basis of spatial wavepacket structures, empirically defined as POD modes of experimental data, or computed from PSE. The transfer functions that link the dynamics in separated points in the flow are educed from nonlinear and linear auto-regressive moving-average (N/ARMAX) techniques, which fall into the category of machine learning and require calibration on training data.

C.4 RÉSULTATS OBTENUS

New jet experiments have been conducted at Ma=0.4 **[L1]** and Ma=0.9 **[L2]**, and the results (near-field and far-field) have been made available to the partners and to the community in openly accessible form, together with pre-existing data at the same operating conditions. These data have served throughout the project both as a basis for the conception of models and as a reference for their validation. A high-quality numerical LES database **[L3]**, generated for identical flow conditions as in the Ma=0.9 experiment, has been obtained under a confidentiality agreement from an external collaboration with Cascade technologies (USA).

Frequency response analysis [L4] has been performed for both configurations (Mach numbers 0.4 and 0.9). This analysis identifies the flow forcing of low-amplitude perturbations that gives rise to the most energetic instability response. In both Mach number settings, the results clearly show that by far the strongest flow oscillations in the jet are wavepacket structures that are triggered by incoming perturbations in the boundary layer of the nozzle duct. At Ma=0.9, these wavepackets agree well with experimentally measured pressure fluctuations along the centreline, but within similar limits as previously published PSE-based results. At Ma=0.4, extensive two-point PIV measurements are available from the experiment, allowing the extraction of 3D wavepackets for a much richer comparison. This enabled us to explore a novel interpretation of linear instability wavepackets, on the theoretical basis of turbulent flow *statistics*. These significant results demonstrate that linear instability analysis captures, in a way that is rigorously justified by theory, the most energetic coherent structures in a stochastically excited turbulent jet. Nonlinear dynamics are accounted for in the form of forcing input to the linear equations [L5]. The elaboration of this formalism and the experimental-theoretical comparison is the fruit of intense collaboration between Pprime and LadHyX, and our international partner André Cavalieri (Brazil).

Having noted, already prior to the start of Cool Jazz, that PSE and LEE wavepackets computed for steady mean flows compare poorly to experimental results in some respects (wavepacket shape downstream of the potential core, underprediction of sound intensity), the introduction of "jitter" via base flow modulations was hoped to remedy these shortcomings. To this end, unsteady basic flow states were constructed through low-pass filtering of experimental and LES data, and linear instability analysis was performed on these [L7]. By this method, agreement with the observed wavepackets and sound levels was clearly improved, but remained unsatisfactory. The approach has thus been invalidated.

Within the potential core of the jet, close to the nozzle, PSE wavepackets do provide a good representation of perturbation growth. Reduced-order models have therefore been constructed on that basis [L8], and it has been demonstrated by comparison with the experiment that such models successfully predict the spatial evolution of fluctuations downstream of a sensor near the nozzle. The range of validity extends over several jet diameters downstream. The same technique has been applied to simulation data obtained for a plane shear layer [L10], and the resulting models have been used for active control (see discussion of [L11] below).

The important question, for the purpose of low-order modelling, to what degree the dynamics of the turbulent present spatio-temporal coherence, has been investigated by means of dynamical system analysis [L9]. It has been found that the deterministic dynamics contained in experimentally recorded time series of pressure fluctuations is adequately represented by approximately 10 degrees of freedom. Low-order models have then been constructed in the form of POD mode superpositions [L12], and the time-dependence of these superpositions has been derived from ARMA and ARMAX machine-learning algorithms. Comparison between the endogenous ARMA and the exogenous ARMAX models clearly points to the importance of external excitation for the jet dynamics. Extension of the procedure to nonlinear NARMAX models has led to the important conclusion that the nonlinear coupling between POD wavepackets is negligibly weak, such that any nonlinear flow dynamics may be regarded as exogenous input to a linear ROM system.

The reduced-order modelling techniques described above have been implemented for active closed-loop control in direct numerical simulations of a plane shear layer [L11]. The control targets the growth of shear instabilities, via a feedforward actuation in phase opposition to incoming perturbations. Vortex pairing is significantly delayed in the controlled simulations.

Predictive models based on dynamic mode decomposition (DMD) [L14] have been attempted, but given the success of POD, PSE and empirical models, this alternative route has not been followed through. Considerable progress has however been made on the important technical issue of de-biaising noisy experimental data for the purpose of DMD. Conditioning of the data via the ARMA method allows to discard randomness, and to retain only the deterministic part of the dynamics.

Several side projects have sprung from the main line of our research plan. We mention a machine-learning algorithm for closed-loop control with sparse data input [P14], and studies of intrinsically driven wavepackets in buoyant jets [P13, P15, P16].

C.5 Exploitation des résultats

Apart from the communication of scientific progress through the usual channels, the results of the Cool Jazz project are made available to the community through the open sharing of our data. This encompasses the experimental database (in post-processed form for practical reasons) as well as numerical datasets of reduced-order models and wavepackets structures. This data will enable other researchers to pursue alternative control approaches, and to test their results against our benchmark. The public database on the Cool Jazz website will be continuously updated, and future results will be added.

C.6 Discussion et Conclusions

The objectives of the Cool Jazz project have been attained to a large extent. If the ultimate goal of noise-reduction in an actively controlled experiment has not been realised at present, very significant progress has been achieved on most of the initial questions:

1. Can coherent turbulence structures be modelled as forced linear instability wavepackets evolving in the mean flow, and is this analogy justifiable on theoretical grounds?
2. How does nonlinearity enter the modelling of turbulent jet dynamics in terms of linear wavepackets?
3. Are coherent wavepackets the appropriate target structures for the control of high Reynolds number jets?

Ad 1: **Wavepackets obtained from linear global frequency response analysis on a mean flow correspond precisely to the eigenmodes of the cross-spectral density tensor ("most energetic" coherent structures) at any given frequency in the same unsteady turbulent flow.** This equivalence strictly holds under the idealised assumption that all nonlinear dynamics are uncorrelated in space, as we have demonstrated [P7,C14] on the basis of stochastic analysis. The strong analogy between coherent turbulent structures and linear instability properties of the mean flow has riddled the community for decades. The question now appears to be resolved on a fundamental level, backed up by experimental validation.

Ad 2: **Nonlinearitiy affects the linear wavepacket dynamics in a way that is best modelled as exogenous forcing, in the sense that it continuously provides the triggering of a linear instability response.** This conclusion is a pristine example of the converging complementary approaches pioneered by each of the consortium partners. In the linear instability approach **[L5]**, nonlinear terms in the Navier-Stokes equations are accounted for as right-hand side forcing terms. This interpretation is justified by dynamical system characterisation **[L9]**, carried out in parallel, which shows that (i) the turbulent jet dynamics are driven extrinsically rather than intrinsically (ARMAX versus ARMA), and that (ii) the nature of wavepacket dynamics is linear rather than nonlinear (ARMAX versus NARMAX). Finally, the comparison with processed experimental data **[L1]** validates the predictions from linear instability analysis.

Ad 3: **Wavepackets represent the salient dynamic ingredients in high Reynolds number jets that are both observable and controllable.** Dynamical systems characterisation **[L9]** has revealed, for the first time in a quantitative framework, that the dynamics inside and beyond the potential core of a turbulent jet are coherent and deterministic to an astonishing degree. Validation of the ARMAX-based reduced-order model **[L12]** has then demonstrated that wavepackets are not only observable (as was known before), but also very well controllable. Much simpler modelling based on empirically measured transfer functions **[L8,L10]** leads to the same conclusion. Control success has so far been demonstrated for the related case of a free shear layer **[L11]**.

Results with regard to noise generation are less conclusive. Some new understanding of the role of the spatially decaying coherence in wavepackets has been reached, but these studies were pushed mostly outside of the Cool Jazz project, by our international collaborators. Stochastic analysis of instability wavepackets is believed to provide a promising framework for future studies of coherence decay and associated sound generation.

Similarly, the control strategies that have been formulated so far target the vortical near-field dynamics of wavepackets, rather than the radiated sound. In order to advance on the questions of noise generation and noise reduction, future work will first need to be based on LES rather than experimental data. Furthermore, for the perspective of experimental noise control implementation, the actuator technology will require much attention. In our current configuration, actuation through pulsed control jets creates significant noise by itself.

The progress that has been achieved through the Cool Jazz program was only possible owing to the close cooperation and the complementary expertise among the consortium partners. Particular credit is due to Onofrio Semeraro, who, through his parallel involvement at LadHyX and Limsi, was the driving force behind much of the collaborative dynamism. Just as instrumental for the project was the collaboration with our international partners at ITA, Caltech, Stanford and in Cambridge.

Serious problems in the early phase of the project could be overcome only thanks to these international partnerships: The departure of Peter Schmid, Bernd Noack and Damien Biau from their institutions, and the tragic loss of Joël Delville, posed an acute threat to the success of Cool Jazz. Furthermore, following the recommendations given in the initial project review, we had to renounce the capability of running LES simulations within the consortium.

Through the collaboration with our Stanford partners, we were lucky to be able to fill this gap to a large extent.

The project has opened exciting new perspectives for jet modelling and control. Our international consortium will continue to explore these avenues, and we are hopeful to acquire funding for a follow-up Cool Jazz 2 project.

D Liste des livrables

Date de livraison	N°	Titre	Nature	Partenaires (souligner le responsable)	Commentaires
10/2013	L1	Experimental database Ma=0.4	data	Pprime	
01/2015	L2	Experimental database Ma=0.9	data	Pprime	
09/2015	L3	LES database	data	Pprime, Cascade	confidential; provided by external collaborator
06/2015	L4	linear PSE and FRM	report: P3, C10	LadHyX, Pprime	
05/2016	L5	nonlinear PSE and FRM	report: P7, C14	LadHyX, Pprime, ITA	
	L6	Floquet analysis			abandoned
09/2014	L7	PDE models with validation	report: C1, C2	Pprime, ITA, Caltech, Stanford	
06/2014	L8	Reduced-order models	report: C21, C6, P4	Pprime, ITA	
07/2016	L9	Dynamical system characterization	report: P5	LIMSI, LadHyX, Pprime	
05/2016	L10	Input-output relation for simulation	report: P9, C9	Pprime, ITA	
05/2016	L11	Control applied to simulation	report: P9, C9	Pprime, ITA	
06/2014	L12	input-output relation for experiment	report: P4, C21	Pprime, LadHyX, Limsi, ITA	
	L13	control law for experiment			in progress
01/2016	L14	Model-predictive control using DMD	report: C35, software		Matlab toolbox
	L15	Model-based control: reproduction of control simulations			abandoned
	L16	Model-based control: model & control hierarchy			abandoned
	L17	Model-based control for experiment			abandoned
	L18	Noise reduction through active control in experiment			not yet achieved
	L19	Noise reduction through active control in LES			abandoned

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P2. Jaunet, Jordan & Cavalieri (2017): "Two-point coherence of wavepackets in turbulent jets", Physical Review Fluids, vol. 2, 024604.

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P4. Sasaki, Piantanida, Cavalieri & Jordan (2017): "Real-time modelling of wavepackets in turbulent jets", Journal of Fluid Mechanics, vol. 821, p. 458.

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P7. Lesshafft, Semeraro, Jaunet, Cavalieri & Jordan (2019): "Resolvent-based modelling of coherent wavepackets in a turbulent jet", Physical Review Fluids, vol. 4, in press.

P8. Breakey, Jordan, Cavalieri, Nogueira, Leon, Colonius & Rodriguez (2017): "Experimental study of turbulent-jet wave packets and their acoustic efficiency", Physical Review Fluids, vol. 2, 124601.

P9. Sasaki, Tissot, Cavalieri, Silvestre, Jordan & Biau: "Closed-loop control of a free shear flow: a framework using the parabolized stability equations‟, Theoretical and Computational Fluid Dynamics, vol. 32, p. 765.

P10. Tissot, Lajus, Cavalieri & Jordan: "Wave packets and Orr mechanism in turbulent jets‟, Physical Review Fluids, vol. 2, 093901.

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C2. Zhang, Jordan, Lehnasch, Cavalieri & Agarwal: "Just enough jitter for jet noise", 20th AIAA/CEAS Aeroacoustics Conference, AIAA Paper 2014-3061, 2014.

C3. Brès, Jaunet, Le Rallic, Jordan, Colonius & Lele: "Large eddy simulation for jet noise: the importance of getting the boundary layer right", 21st AIAA/CEAS Aeroacoustics Conference, AIAA Paper 2015-2535, 2015.

C4. Brès, Jaunet, Le Rallic, Jordan, Towne, Schmidt, Colonius, Cavalieri & Lele: "Large eddy simulation for jet noise: azimuthal decomposition and intermittency of the radiated sound", 22nd AIAA/CEAS Aeroacoustics Conference, AIAA Paper 2015-3050, 2015.

C5. Jaunet, Braud, Boissonneau, Jordan & Cavalieri: "Dual-plane, time-resolved, stereo PIV for wavepacket eduction in a turbulent subsonic jet", 21st AIAA/CEAS Aeroacoustics Conference, AIAA Paper, 2015.

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C12. Tissot, Zhang, Lajus, Cavalieri, Jordan & Colonius: "Sensitivity of wavepackets in jets to non-linear effects: the role of the critical layer", VI Ercoftac Symposium on Global Flow Instability and Control, Crete, 2015.

C13. Towne, Cavalieri, Jordan, Colonius, Jaunet & Brès: "Trapped waves in turbulent jets", VI Ercoftac Symposium on Global Flow Instability and Control, Crete, 2015.
C14. Semeraro, Jaunet, Jordan, Cavalieri & Lesshafft: "Stochastic and harmonic optimal forcing in subsonic jets", 22th AIAA/CEAS Aeroacoustics Conference, AIAA Paper 2016-2935, 2016.
C15. Jaunet, Jordan & Cavalieri: "Two-point coherence of wavepackets in turbulent jets", 22nd AIAA/CEAS Aeroacoustics Conference, AIAA Paper, 2016.
C16. Semeraro, Lusseyran, Pastur & Jordan: "Nonlinear temporal dynamics of axisymmetric wavepackets in subsonic turbulent jets", XXIV International Congress of Theoretical and Applied Mechanics, Montréal, 2016.
C17. Semeraro, Jaunet, Jordan & Lesshafft: "Stochastic and deterministic optimal forcing in subsonic jets: an experimental and numerical analysis", European Fluid Mechanics Conference, Sevilla, 2016.
C18. Semeraro, Lusseyran, Pastur & Jordan:"Qualitative dynamics of wavepackets in turbulent jets", 61st meeting of the American Physical Society (Division of Fluid Dynamics), Portland, 2016.

Communications (conférence) mono-partennaire:
C19. Lesshafft: "Jet noise from coherent wavepackets", invited seminar at Imperial College London, June 7, 2013.
C20. Lesshafft: "Modélisation du bruit de jet par réponse fréquentielle", invited seminar at ONERA-DSNA, March 27, 2014.
C21. Piantanida, Le Rallic & Jordan: "ARMAX system identification applied to a subsonic turbulent jet", 20th AIAA/CEAS Aeroacoustics Conference, AIAA Paper 2014-3058, 2014.
C22. Lesshafft, Coenen, Garnaud & Sevilla: "Modal instability analysis of light jets", IUTAM-ABCM Symposium on Laminar-Turbulent Transition, Rio de Janeiro, 2014.
C23. Semeraro & Lesshafft: "Optimal forcing of subsonic jets", 10th European Fluid Mechanics Conference, Copenhagen, 2014.
C24. Semeraro, Lesshafft & Sandberg: "Wavepackets in subsonic jets using optimal forcing", 59th meeting of the American Physical Society (Division of Fluid Dynamics), San Francisco, 2014.
C25. Semeraro, Lesshafft & Sandberg:"Instability wavepackets in optimally forced subsonic jets", Journée des Fluides sur le Plateau, Orsay, 2015.
C26. Semeraro: "Noise from wavepackets in subsonic jets", invited seminar at IMFT Toulouse, April 2015.
C27. Chakravarthy, Lesshafft & Huerre: "Effect of Buoyancy on the Instability of Light Jets and Plumes", Proceedings of the 5th International Conference on Jets, Wakes and Separated Flows, Stockholm, 2015.
C28. Semeraro, Lesshafft & Sandberg: "Can jet noise be predicted using linear instability wavepackets?", Proceedings of the 5th International Conference on Jets, Wakes and Separated Flows, Stockholm, 2015.
C29. Semeraro: "Can jet noise be predicted using linear instability wavepackets?", invited conference at Ecole d'été du non-linéaire, Peyresq, August 2015.
C30. Lesshafft: "Sound emission from instability wavepackets in jets", invited seminar at Jiao Tong University, Shanghai, September 6, 2015.
C31. Jordan: "Trapped waves in turbulent jets", invited seminar at Imperial College London, October 16, 2015.
C32. Lesshafft: "Linear instability wavepackets in jets", invited seminar at Instituto Tecnológico de Aeronáutica, Sao José dos Campos (Brazil), February 22, 2016.
C33. Lesshafft: "Spielarten globaler Instabilitätsanalyse am Beispiel des Freistrahls", invited seminar at RWTH Aachen (Aachen, Germany), May 13, 2016.
C34. Semeraro: "Wavepackets in subsonic jets", *invited seminar* at Politecnico Milano, May 2016.
C35. Lesshafft: "Harmonic and Stochastic Wavepackets in Jets", invited seminar at DAMTP (University of Cambridge, UK), June 3, 2016.
C36. Semeraro & Mathelin: "An open-source toolbox for data-driven linear system identification", CNRS Technical Report, 2016.
C37. Huerre, Chakravarthy & Lesshafft: "Local and global instability of buoyant jets and plumes", XXIV International Congress of Theoretical and Applied Mechanics, Montréal, 2016.