Conditional analysis for studying sound-source mechanisms in jets

A. Cavalieri, F. Kerhervé, P. Jordan
B. Y. Gervais & J. Delville

peter.jordan@univ-poitiers.fr

Institut Pprime, UPR 3346,
CNRS, Université de Poitiers, ENSMA

An overview of our efforts to understand jet noise source mechanisms

P. Jordan

peter.jordan@univ-poitiers.fr

Institut Pprime, UPR 3346,
CNRS, Université de Poitiers, ENSMA

A. Agarwal
J. Freund
T. Colonius
S. Lele
D. Papamoschou
M. Samimy
D. Juvé
C. Bogey
G. Tadmor
B. Noack
J. Delville
P. Comte
Y. Gervais
G. Daviller
F. Kerhervé
M. Koenig
A. Cavalieri
B. C. Tinney
M. Wei

Presentation overview

1. Motivation: the ambiguity of aeroacoustic theory (a 4-slide synthesis from 1952 to 2010)

2. The structure of the turbulent jet: stochastic versus deterministic dynamics

3. The danger of time-averaged statistical handles

4. Frequency-domain versus time-frequency analysis

5. Wavepackets: space-time intermittency and source efficiency

6. Conditional analysis 1: Wavelets, flow visualisation & a jittering source model

7. Conditional analysis 2: Linear Stochastic Estimation

Résumé & perspectives

8. Control of jet noise

1. Motivation: the amiguity of aeroacoustic theory

Exp Fluids (2008) 44:1–21
DOI 10.1007/s00348-007-0395-y

REVIEW ARTICLE

Subsonic jet aeroacoustics: associating experiment, modelling and simulation

Peter Jordan · Yves Gervais

1. Motivation: the amiguity of aeroacoustic theory

Lighthill (1952)

$$\frac{\partial^2 p'}{\partial t^2} - c_o^2 \Delta p' = 0$$

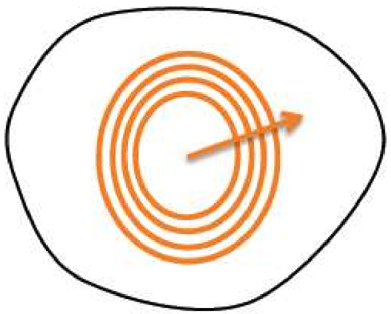
Lilley (1974)

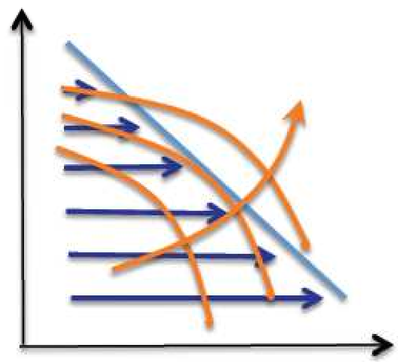
$$\frac{1}{c_o^2}\frac{D^3 p'}{Dt^3} - 2\frac{dU_1}{dx_2}\frac{\partial^2 p'}{\partial x_1 \partial x_2} = 0.$$

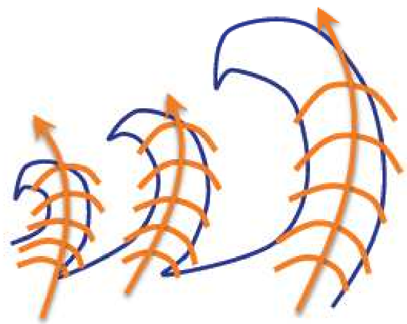
Goldstein (2003,2005)
Sinayoko & Agarwal (2010)

$$\boldsymbol{q} = \overline{\boldsymbol{q}} + \boldsymbol{q}'$$

$$L_{\overline{\boldsymbol{q}}}(\boldsymbol{q}') = 0$$







1. Motivation: the amiguity of aeroacoustic theory

Lighthill (1952)

Powell (1964)

Lilley (1974)

Doak (1975, 1989, 1998)

Howe (1975)

Möhring (1978)

Goldstein (2003, 2005)

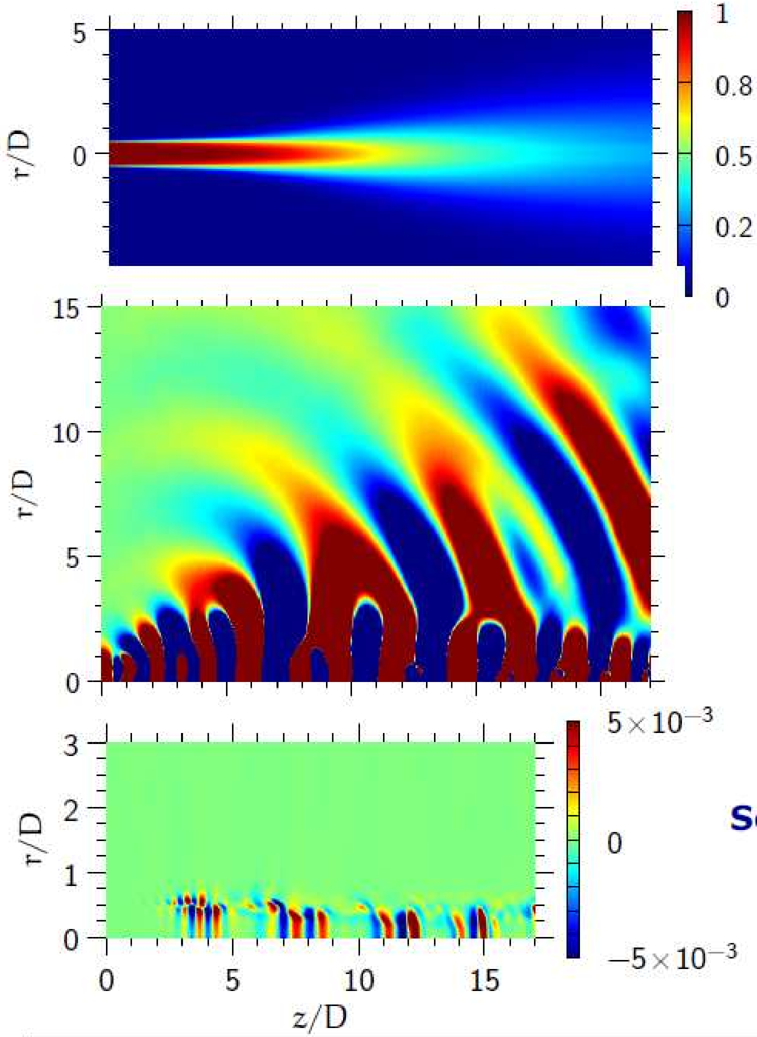
Sinayoko & Agarwal (2010)

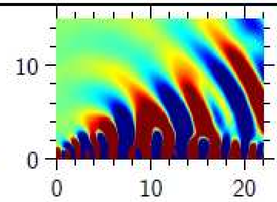
...there are many more!

Acoustic analogies:

- **Extrapolation tool?**
- **Tool for identifying physical mechanisms?**

Generalised acoustic analogy: Goldstein (2003, 2005), Sinayoko & Agarwal (2010)

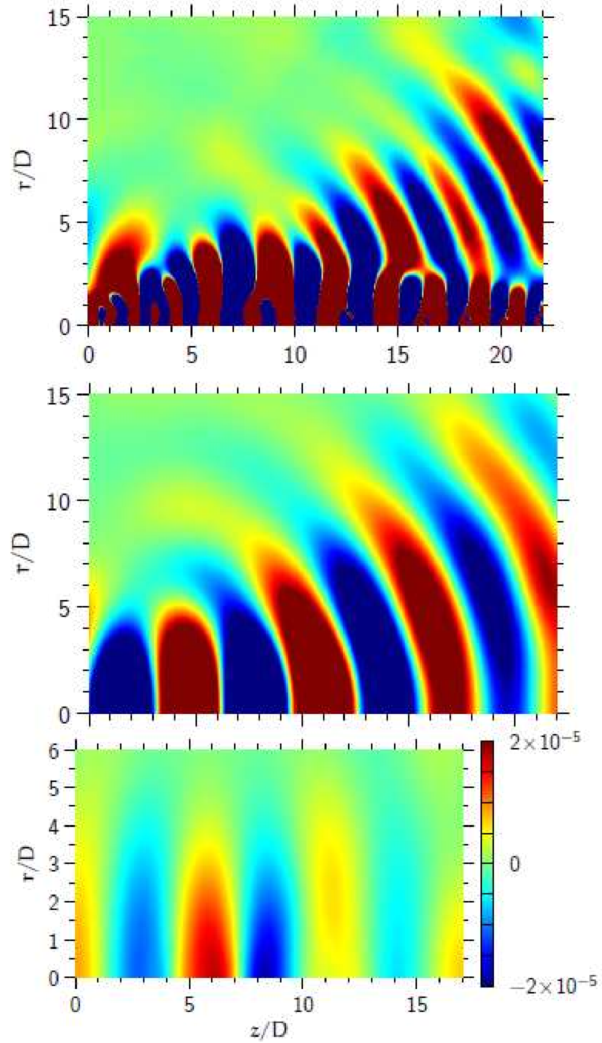




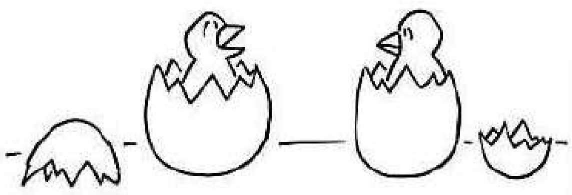
Base flow

Perturbation field

Sound source



Current theoretical frameworks can leave you a little confused as to what to look for in experimental or numerical data



"Wow! — this discredits all *my* theories."

Understanding is incomplete...

...and so modelling is a problem

2. The structure of the turbulent jet: stochastic versus deterministic dynamics

Exp Fluids (2008) 44:1–21
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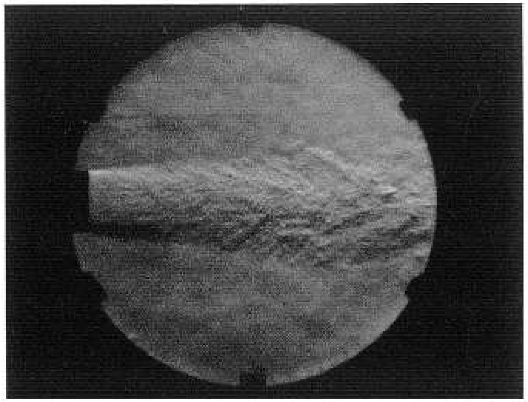
REVIEW ARTICLE

Subsonic jet aeroacoustics: associating experiment, modelling and simulation

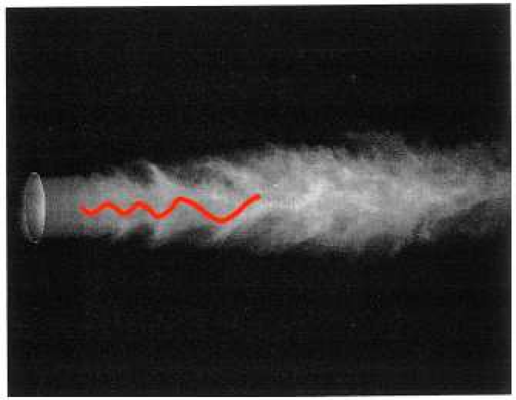
Peter Jordan · Yves Gervais

2. The structure of the turbulent jet: stochastic versus deterministic dynamics

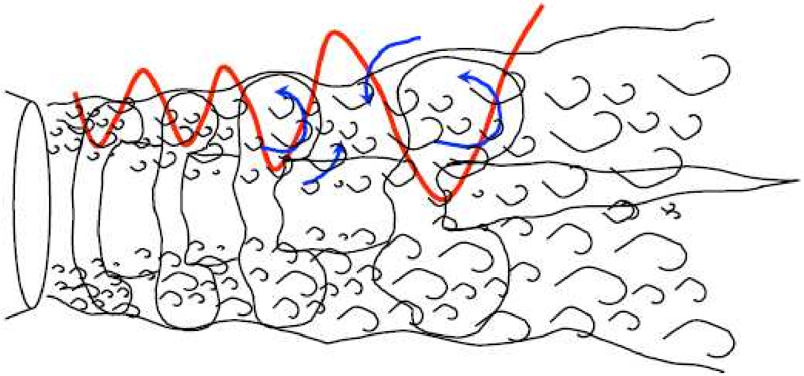
Crow & Champagne (1971)

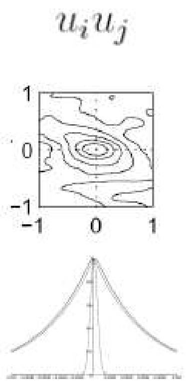


Instantaneous Schlieren image



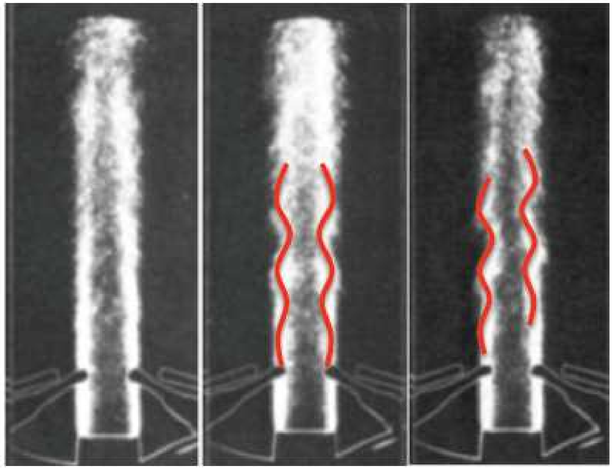
Instantaneous CO2 fog visualisation





2. The structure of the turbulent jet: stochastic versus deterministic dynamics

Schlieren photography by Moore (1977)

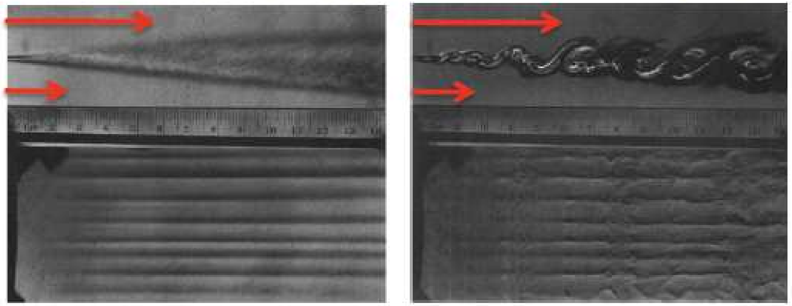


Time-average

Conditional average using axisymmetric nearfield signature

Conditional average using antisymmetric nearfield signature

Schlieren photography by Bernal & Roshko (1986)

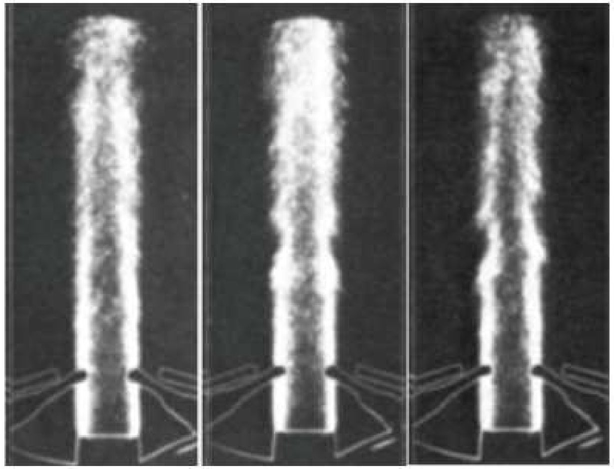


Time-average

Instantaneous image

2. The structure of the turbulent jet: stochastic versus deterministic dynamics

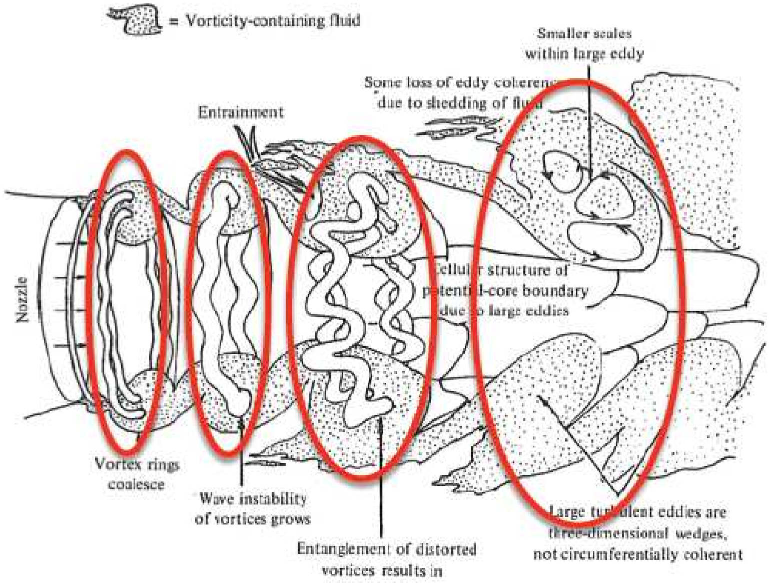
Schlieren photography by Moore (1977)



Time-average

Conditional average using axisymmetric nearfield signature

Conditional average using antisymmetric nearfield signature



Schematic cartoon of coherent structures, by Yule (1978) based on flow visualisation,

Organised eddies have internal complexity…but this is on a different scale to the axially coherent fluid motion ,

Their ordered character is most visible in the hydrodynamic pressure footprint (show in red)

Some thoughts from the past: 'order in chaos!'

"The apparently intimate connexion between jet stability and noise generation appears worthy of further investigation" – Mollo-Christensen & Narashima (1959)

"[jet noise] is of interest as a problem in fluid dynamics in the class of problems which involve the interaction between instability, turbulence and wave emission" – Mollo-Christensen (1963)

"There appear to be at least two distinguishable types of emitted sound, one dominating at very low frequencies and another dominating at high frequencies. A relation which gives a smooth interpolation between these asymptotic ranges would prove useful, if one could be invented." – Mollo-Christensen (1963)

"The data suggest that one may perhaps represent the fluctuating [hydrodynamic] pressure field in terms of rather simple functions. For example, one may consider the jet as a...semi-infinite antenna for sound..." – Mollo-Christensen (1968)

"...although the velocity signal is random, one should expect to see intermittently a rather regular spatial structure in the shear layer." – Mollo-Christensen (1968)

Some thoughts from the past: 'order in chaos!'

"It is suggested that turbulence, at least as far as some of the lower order statistical measures are concerned, may be more regular than we may think it is, if we could only find a new way of looking at it." – Mollo-Christensen (1968)

"The mechanics of turbulence remains obscure, so that it comes as a matter of some relief to find that the motions which now interest us are coherent on a large scale...Such large eddies might be readily recognisable as a coherent transverse motion more in the category of a complicated laminar flow than chaotic turbulence. In any event the eddies generating the noise seem to be much bigger than those eddies which have been the subject of intense turbulence study. They are very likely those large eddies which derive their energy from an instability of the mean motion..." – Bishop, Ffowcs-Williams & Smith (1971)

"These [measurements] suggest that hidden in the apparently random fluctuations in the mixing layer region is perhaps a very regular and ordered pattern of flow which has not been detected yet" – Fuchs (1972)

"Whether one views these structures as waves or vortices is, to some extent, a matter of viewpoint." – Brown & Roshko (1974)

"All this evidence suggests that the turbulence in the mixing layer of the jet behaves like a train similar to the hydrodynamic stability waves propagating in the shear flow." – Chan (1974)

Some thoughts from the past: 'order in chaos!'

"The dominant role of the dynamics and interaction of the large structure in the overall mechanism that eventually brings the two fluids into intimate contact becomes apparent. It is clear that any theoretical attempts to model the complex mixing process in the shear layer must take this ubiquitous large structure into account." – Dimotakis & Brown

"Turbulence research has advanced rapidly in the last decade with the widespread recognition of orderly large-scale structure in many kinds of turbulent shear flows...some measure of agreement seems to have been reached among investigators on the general properties of the coherent motions." – Crighton & Gaster (1976)

"...the turbulence establishes an equivalent laminar flow profile as far as large-scale modes are concerned." – Crighton & Gaster (1976)

"In the last years our understanding of turbulence, especially in jets, has changed rather dramatically. The reason is that jet turbulence has been found to be more regular than had been thought before." – Michalke (1977)

"This 'new-look' in shear-flow turbulence, contrary to the classical notion of essentially complete chaos and randomness, has engendered an unusually high contemporary interest in the large-scale structures." – Zaman & Hussain (1980)

Some thoughts from the past: 'order in chaos!'

"The last twenty years of research on turbulence have seen a growing realisation that the transport properties of most turbulence shear flows are dominated by large-scale vortex motions that are not random." – Cantwell (1981)

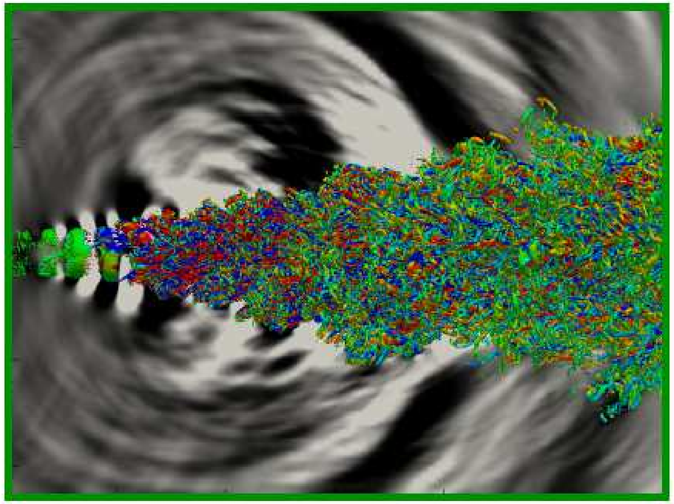
"Suddenly it was feasible and reasonable to draw a picture of turbulence! The hand, the eye, and the mind were brought into a new relationship that had never quite existed before; cartooning became an integral part of the study of turbulence." – Cantwell (1981)

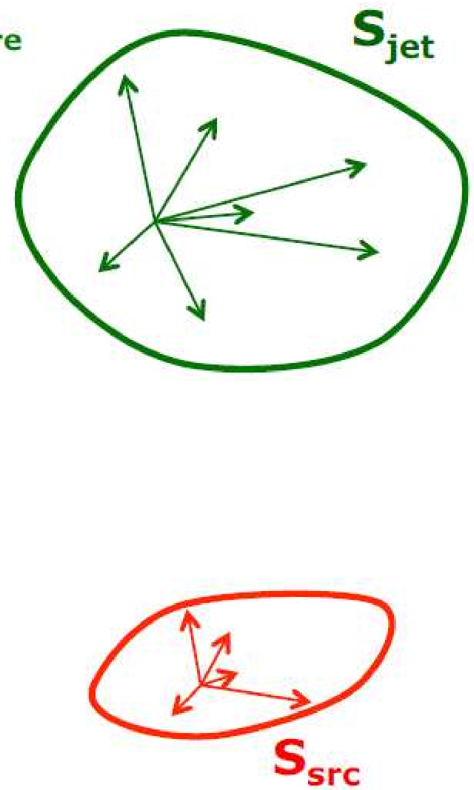
"Dynamics and kinematics of turbulence are defined as much by deterministic motions within characteristic eddies that persist over significant periods of time...as by random dynamical interactions between eddies. The distribution of these characteristic eddies or eigensolm is influenced by the initial and boundary conditions..." – Hunt (1992)

" The dynamics of transitional and turbulent flow is often dominated by organised structures with a life-time much longer than a characteristic time-scale of the surrounding small-scale turbulence" – Sorensen (1997)

Our working hypothesis: a flow subspace associated with sound production

We're stuck here





This is where we want to be,
This is where we can start thinking about modelling

What is the best way to look at the flow in order to ascertain
the salient features where sound production is concerned?

What is the dynamic law of this underlying order;
in particular where sound-production is concerned?

3. The danger of time-averaged statistical handles

2010-3963

16th AIAA/CEAS Aeroacoustic Conference and Exhibit, 7-9 June 2010, Stockholm

Intermittent sound generation in a free-shear flow

André V. G. Cavalieri,* Peter Jordan† and Yves Gervais‡

Institut Pprime, CNRS - University of Poitiers - Ensma, UPR 3346, Poitiers, France

Mingjun Wei§

New Mexico State University, Las Cruces, NM, USA

Jonathan B. Freund¶

University of Illinois at Urbana-Champaign, Urbana, IL, USA

Intermittent sound generation and its control in a free-shear flow

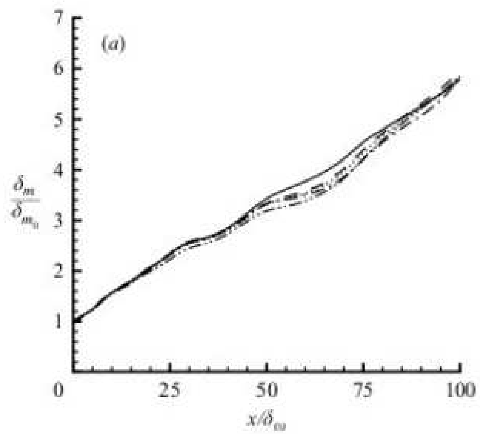
André V. G. Cavalieri,[1] Peter Jordan,[1] Yves Gervais,[1] Mingjun Wei,[2] and Jonathan B. Freund[3]

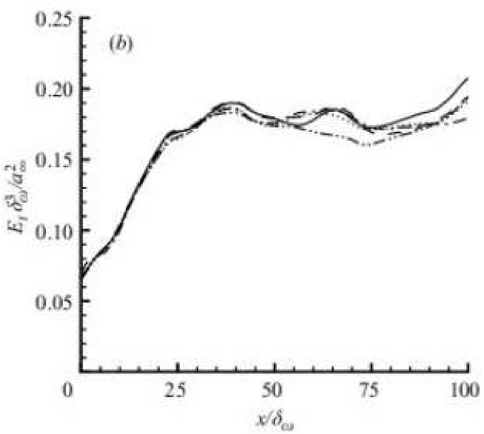
[1] *Institut Pprime, Poitiers, France*

[2] *New Mexico State University, Las Cruces, USA*

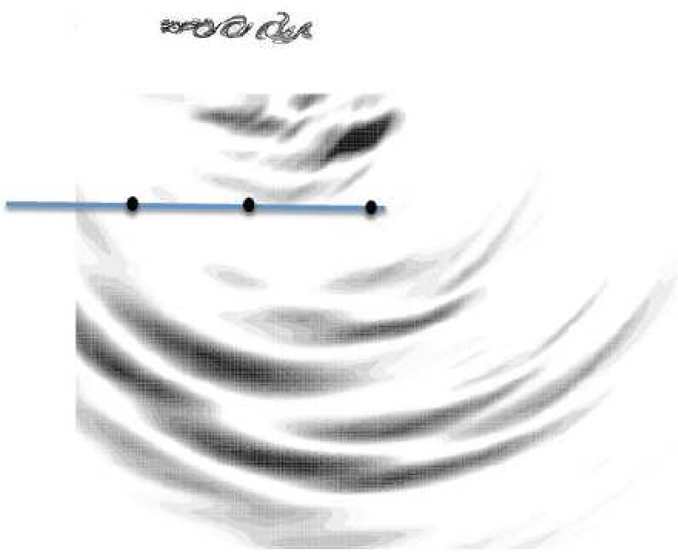
[3] *University of Illinois at Urbana-Champaign, Urbana, USA*

3. The danger of time-averaged statistical handles

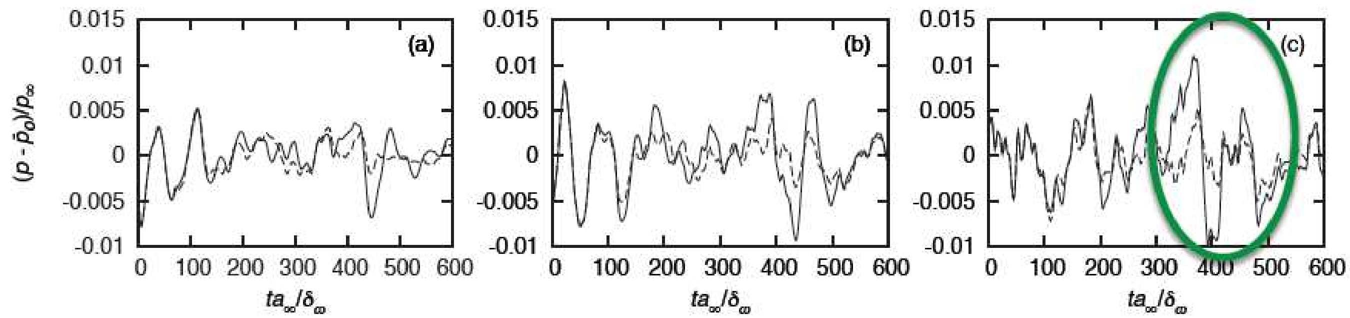




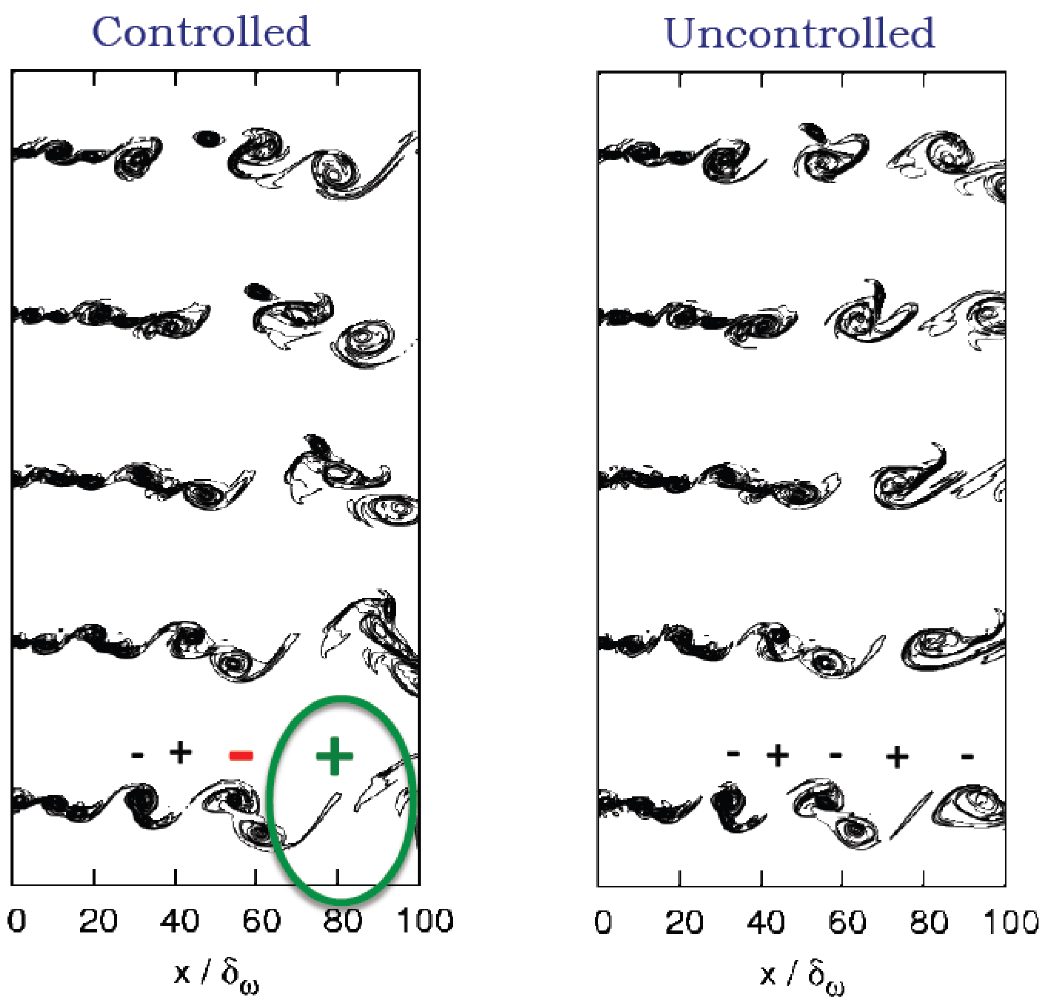
The efficiency of spatiotemporally localised flow events

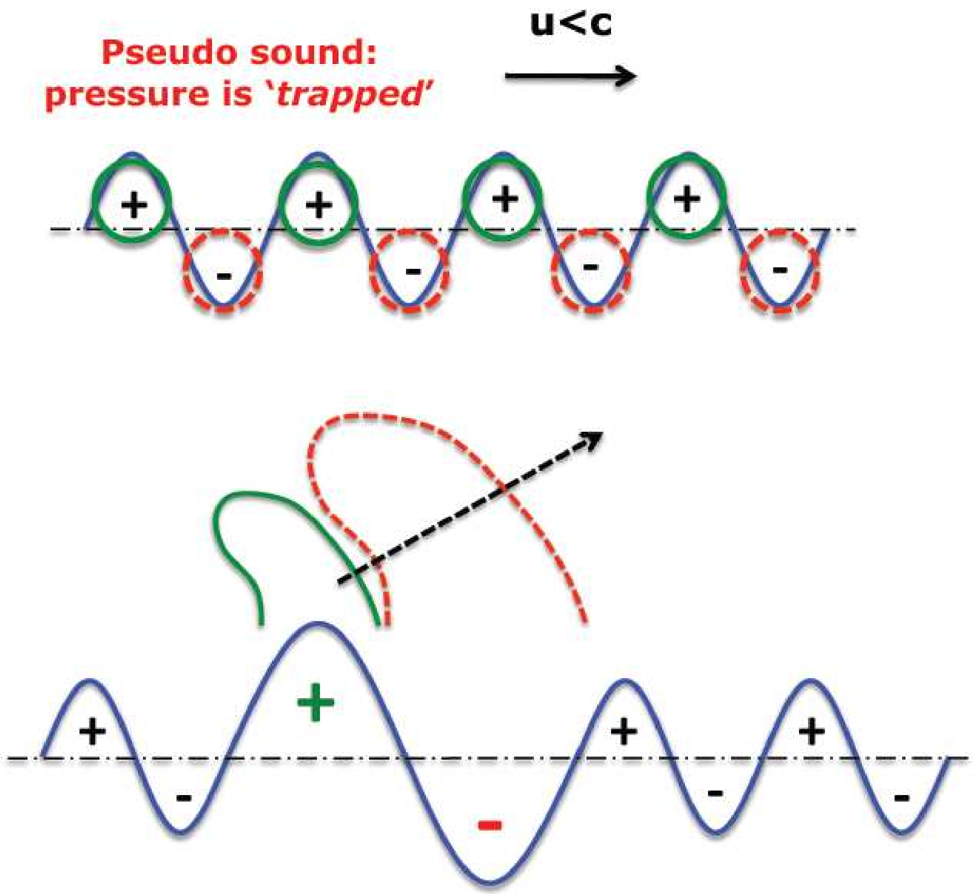


Over 70% noise reduction from this localised event



The efficiency of spatiotemporally localised flow events





Homogeneity in:

- space-scale,
- time-scale,
- energy (amplitude):

  - perfect cancellation
  - no sound radiation

Rupture in homogeneity:

  - IMPERFECT cancellation
  - *sound radiation*

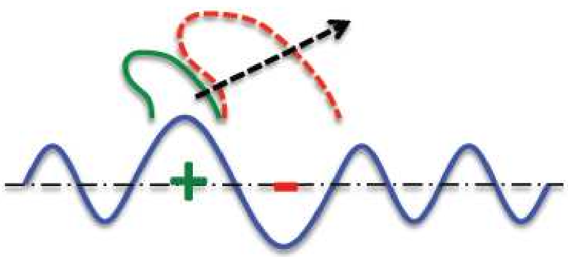
"The data suggest that one may perhaps represent the fluctuating [hydrodynamic] pressure field in terms of rather simple functions. For example, one may consider the jet as a...semi-infinite antenna for sound..." – Mollo-Christensen (1968)

What the study showed

1. Source mechanism can be understood by means of retarded-potential scenario

2. Evidence of wavepacket radiation

3. Localised space-time events underpin high source efficiency



4. Frequency-domain versus time-frequency analysis

Experiments in Fluids 37 (2004) 419–437
DOI 10.1007/s00348-004-0815-1

Two-point laser Doppler velocimetry measurements in a Mach 1.2 cold supersonic jet for statistical aeroacoustic source model

F. Kerhervé, P. Jordan, Y. Gervais, J.-C. Valière, P. Braud

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Modelling self- and shear-noise mechanisms in inhomogeneous, anisotropic turbulence

P. Jordan*, Y. Gervais
Laboratoire d'Etudes Aérodynamiques, CNRS UMR 6609, Université de Poitiers, Bâtiment K, Avenue du Recteur Pineau, 86022 Poitiers, France

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The frequency dependence of jet turbulence for noise source modelling

F. Kerhervé[a], J. Fitzpatrick[a,*], P. Jordan[b]
[a] *Mechanical and Manufacturing Engineering Department, Trinity College, Ireland*
[b] *Laboratoire d'Etudes Aérodynamiques UMR CNRS 6609, Poitiers, France*

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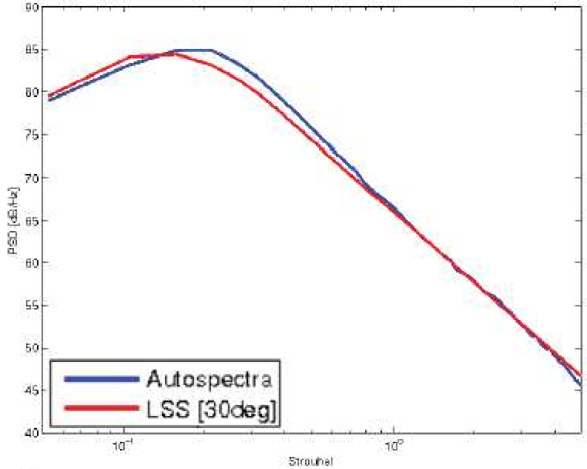
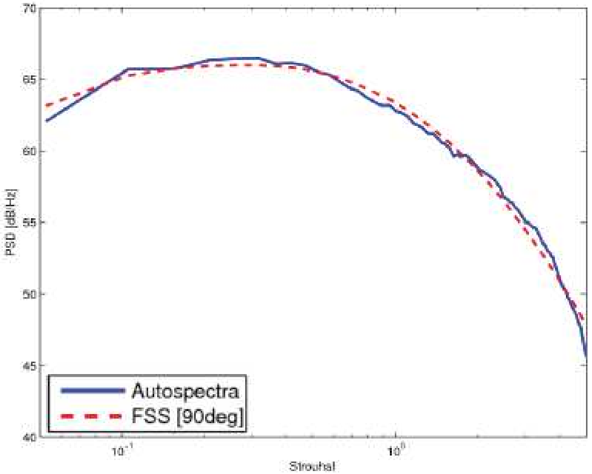
Farfield filtering and source imaging for the study of jet noise

M. Koenig*† A. Cavalieri*‡ P. Jordan* J. Delville*
Y. Gervais* D. Papamoschou§ M. Samimy¶ & S. Lele‖

*Institut Pprime, Branche Fluide, UPR 3346, CNRS, Université de Poitiers, ENSMA, France.
†SNECMA, Département acoustique, 77550 Moissy-Cramayel, France
‡Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil
§Departement of Mechanical and Aerospace Engineering, University of California Irvine, Irvine, CA, US
¶Gas Dynamics and Turbulence Laboratory, The Ohio State University, Columbus, OH, USA.
‖Department of Mechanical Engineering, Stanford University, Stanford, CA, USA

4. Frequency-domain versus time-frequency analysis



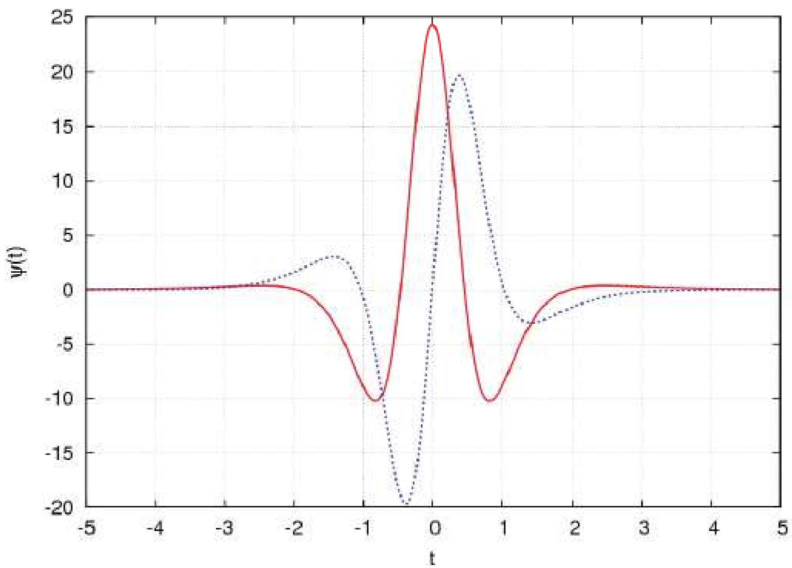


M. Koenig*, † A. Cavalieri*, ‡ P. Jordan*, J. Delville*,
Y. Gervais*, D. Papamoschou§, M. Samimy¶ & S. Lele‖

- Continuous Wavelet Transform :

$$\tilde{p}(s,t) = \int_{-\infty}^{\infty} p(\tau)\psi(s,t-\tau)d\tau$$

- Paul's wavelet (—— real part, – – – imaginary part) :



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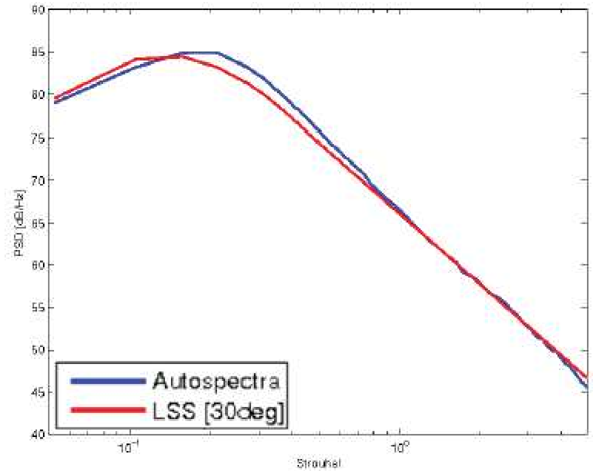

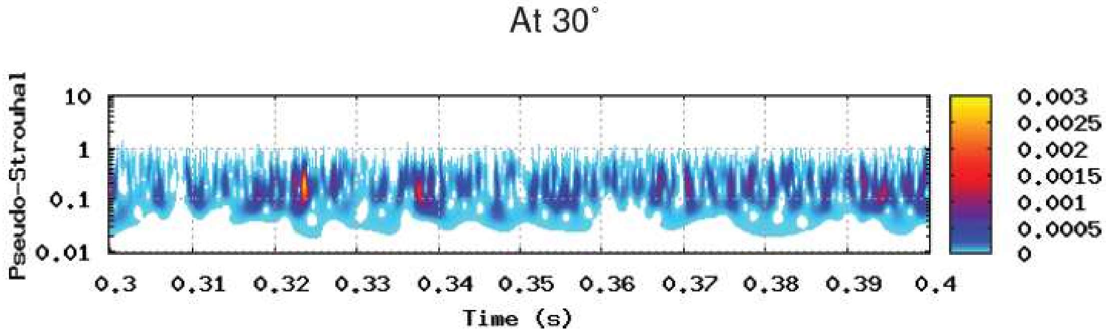

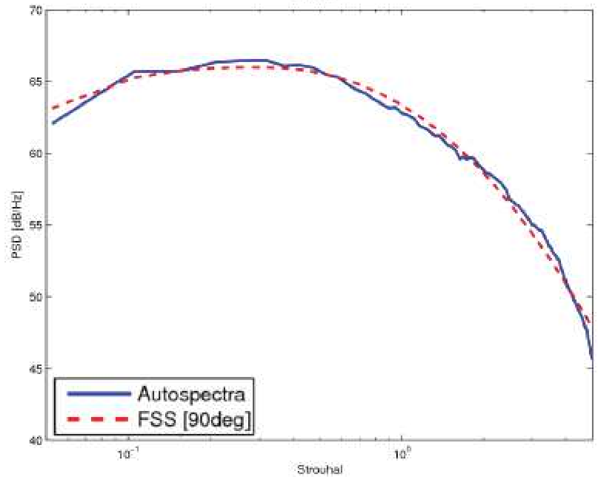

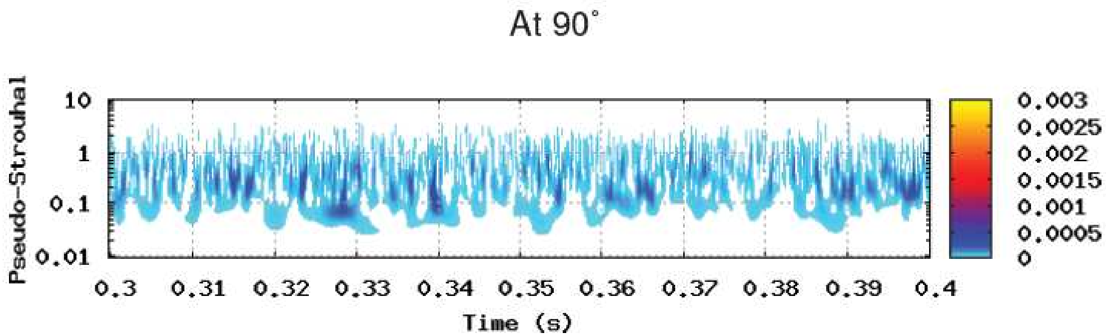

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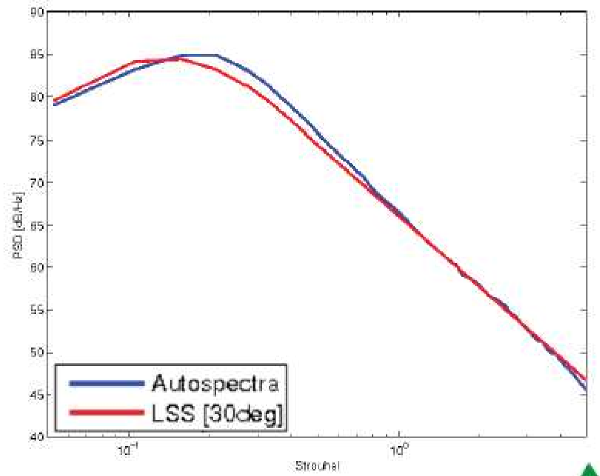
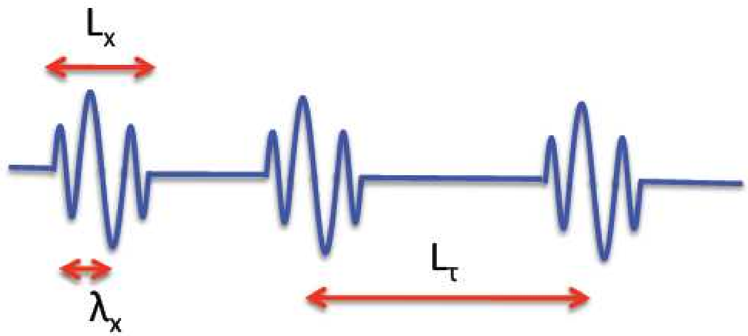
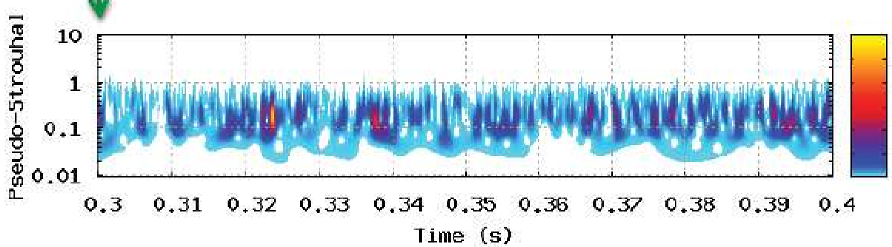


A structurally 'simple' waveform can produce a deceptively broadband Fourier spectrum.



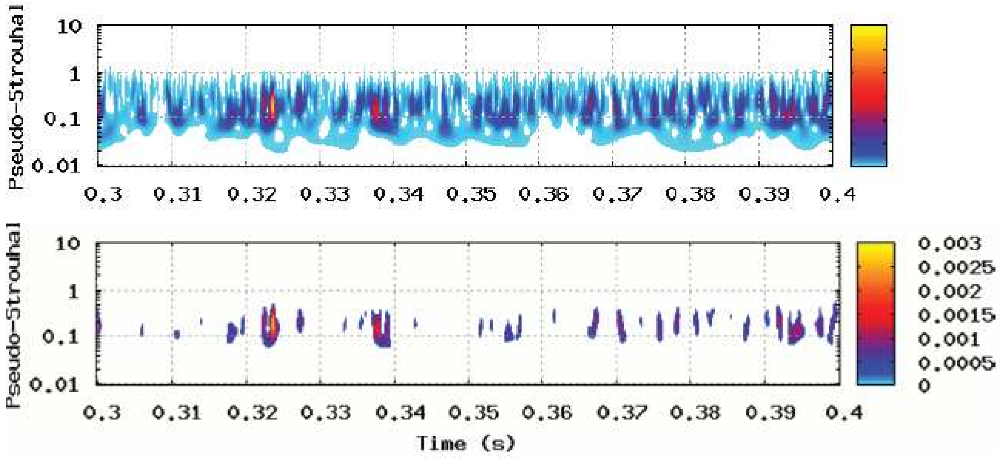
How many scales?
How many degrees of freedom?

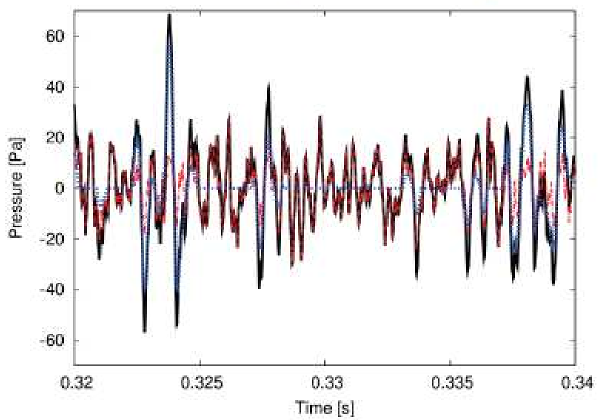
At 30°



4. Frequency-domain versus time-frequency analysis

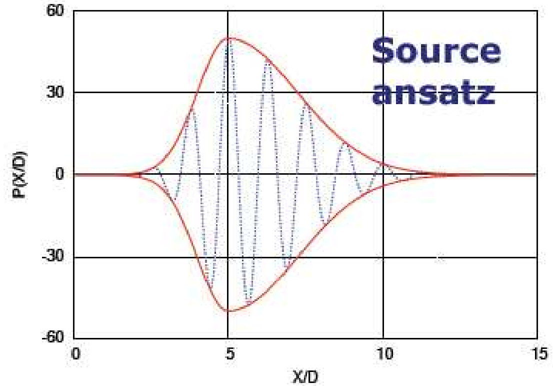
At 30°

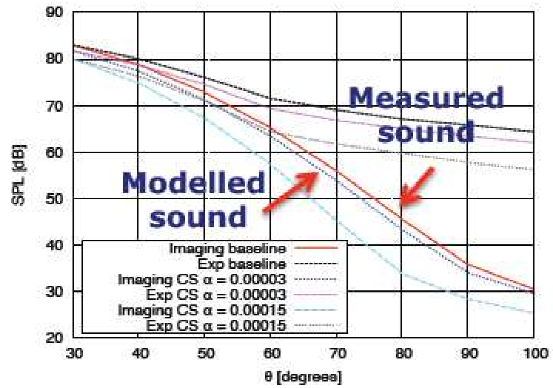




$$p_0(x, A_k) = \epsilon B(x) e^{i\alpha k},$$

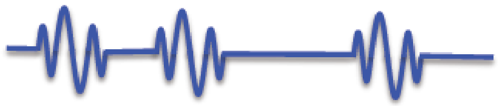
$$B(x) = \begin{cases} \exp(-b_1(x - x_0)^2), & x \leq x_0 \\ \exp(-b_2(x - x_0)^2), & x > x_0 \end{cases}$$





M. Koenig*† A. Cavalieri*‡ P. Jordan* J. Delville*
Y. Gervais* D. Papamoschou§ M. Samimy¶ & S. Lele||

What the study showed



1. **Experiments show low-angle radiation comprises high-amplitude, temporally localised, bursts,**

2. **Source dynamics may have fewer degrees of freedom than Fourier spectrum suggests,**

3. **Wavepacket model radiation shows quantitative agreement with measurements**

M. Koenig[*,†] A. Cavalieri[*,‡] P. Jordan[*] J. Delville[*]
Y. Gervais[*] D. Papamoschou[§] M. Samimy[¶] & S. Lele[||]

Institut Pprime

5. Wavepackets: space-time intermittency and source efficiency

16th AIAA/CEAS Aeroacoustic Conference and Exhibit, 7-9 June 2010, Stockholm

Jittering wave-packet models for subsonic jet noise

André V. G. Cavalieri*,† Peter Jordan‡ and Yves Gervais§

Institut Pprime, CNRS - University of Poitiers - Ensma, UPR 3346, Poitiers, France

Anurag Agarwal¶

University of Southampton, United Kingdom

Jittering wave-packet models for subsonic jet noise

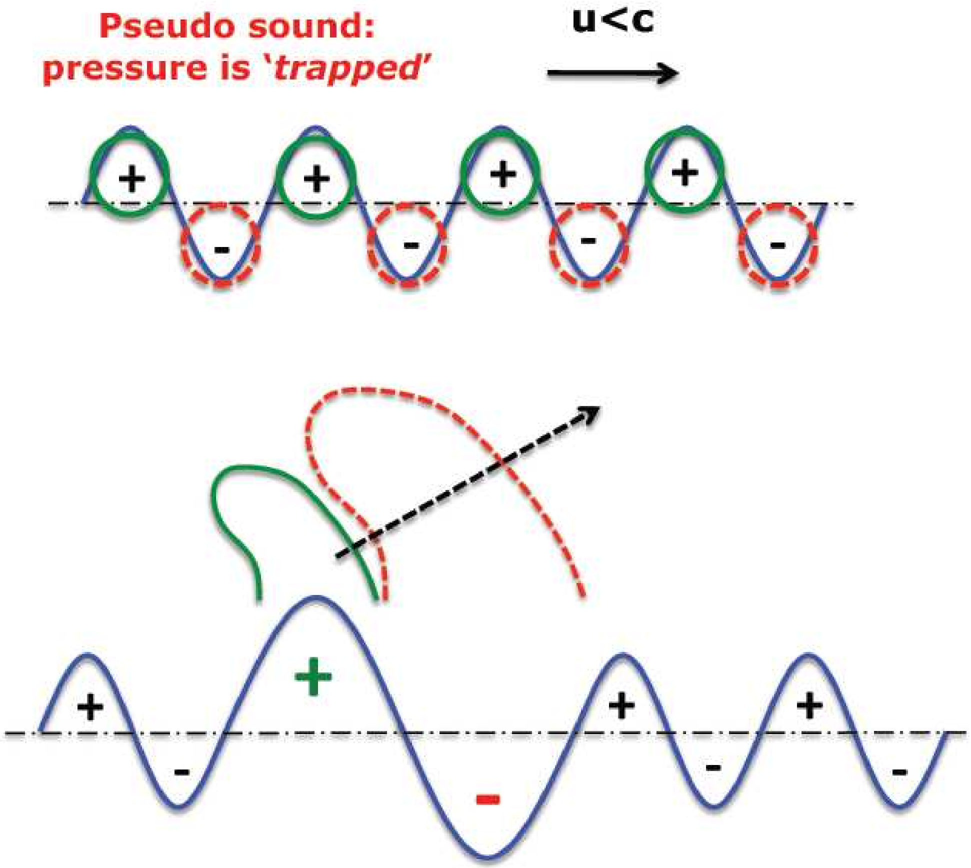
André V. G. Cavalieri[a,b], Peter Jordan[a], Anurag Agarwal[c], Yves Gervais[a]

[a] *Institut Pprime, CNRS – Université de Poitiers – ENSMA, UPR 3346, 43 rue de l'Aérodrome, 86036 Poitiers, France*

[b] *Instituto Tecnológico de Aeronáutica, Praça Mal. Eduardo Gomes, 50, Vila das Acácias, 12228-900, São José dos Campos – SP, Brazil*

[c] *Institute of Sound and Vibration Research, University of Southampton, University Road, Southampton, SO17 1BJ, UK*

5. Wavepackets: space-time intermittency and source efficiency



Homogeneity in:

- space-scale,
- time-scale,
- energy (amplitude):

  - perfect cancellation
  - no sound radiation

Rupture in homogeneity:

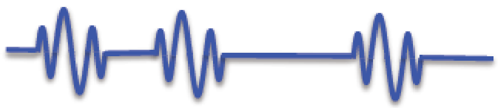
  - IMPERFECT cancellation
  - *sound radiation*

A hierarchy of wavepacket models

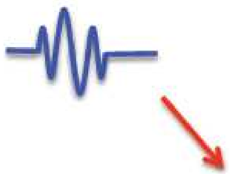
Model 1: effect of space and time localisation

Model 2: time variation of axial extension

Model 3: the jittering wavepacket

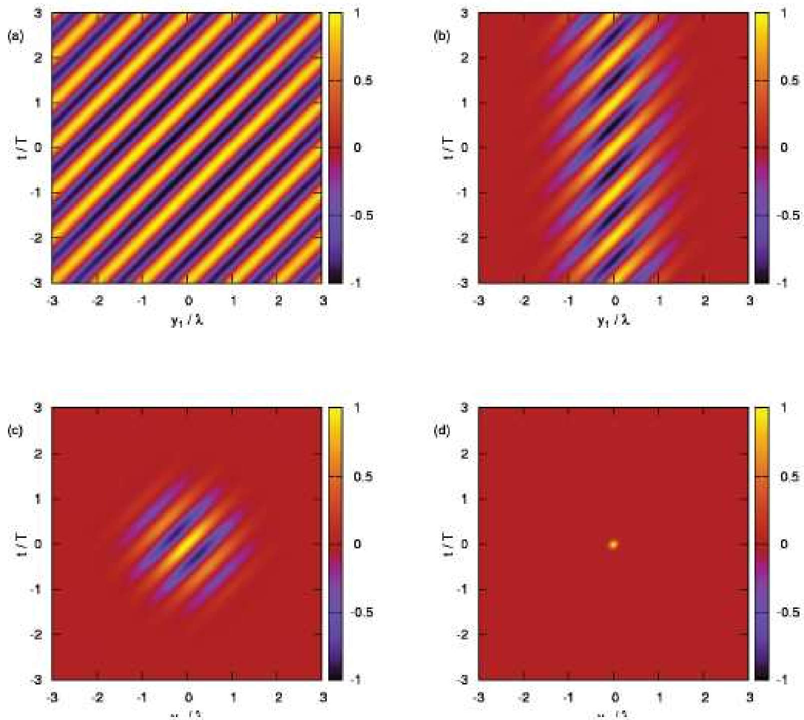


Model 1: effect of space and time localisation



$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} - \Delta p = \frac{\partial^2 \rho u_i u_j}{\partial x_i x_j} = \frac{\partial^2 T_{ij}}{\partial x_i x_j}$$

$$T_{11}(\vec{y},\tau) = 2\rho_0 U \tilde{u} \frac{\pi D^2}{4}\delta(y_2)\delta(y_3)\exp[i(\omega\tau - k y_1)]\exp\left(-\frac{y_1^2}{L^2}\right)\exp\left(-\frac{\tau^2}{\tau_c^2}\right)$$



Model 1: effect of space and time localisation

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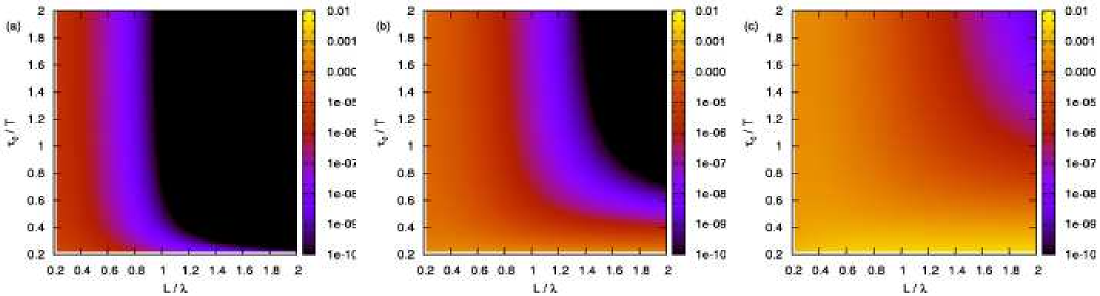
$$E_A = \int \iint_\Omega \frac{p^2}{\rho_0 c} \mathrm{d}\vec{x}\mathrm{d}t$$

$$E_S = \frac{1}{T} \int \iiint_S \frac{\rho_0 u^2}{2} \mathrm{d}\vec{y}\mathrm{d}\tau$$

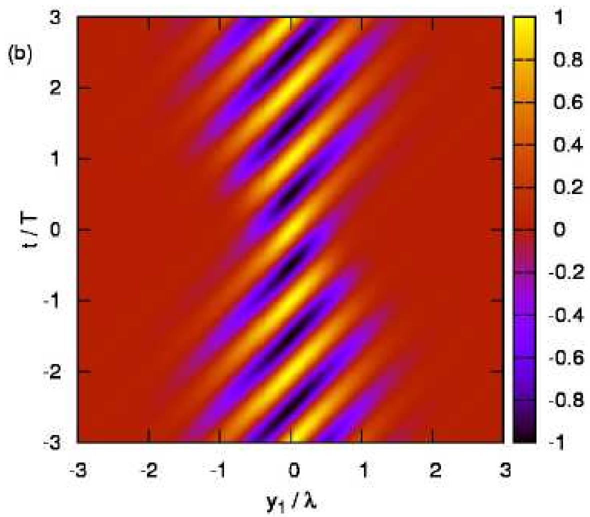
E_A/E_S, M = 0.3 E_A/E_S, M = 0.6 E_A/E_S, M = 0.9



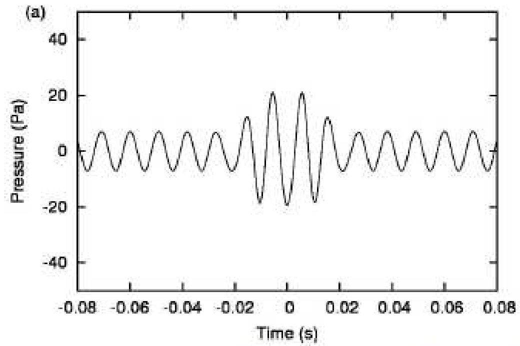
$$T_{11}(\vec{y},\tau) = 2\rho_0 U \tilde{u} \frac{\pi D^2}{4} \delta(y_2)\delta(y_3) \exp[i(\omega\tau - ky_1)] \exp\left(-\frac{y_1^2}{L^2(\tau)}\right)$$

$$L(\tau) = L_0 - \kappa \exp\left(-\frac{(\tau-\tau_0)^2}{\tau_L^2}\right)$$

$L_0 = \lambda,\ \kappa = L_0/2,\ \tau_L = T$



- Radiation is increased as the envelope is truncated.



Model 2: time variation of axial extension

$$T_{11}(\vec{y},\tau) = 2\rho_0 U\tilde{u}\frac{\pi D^2}{4}\delta(y_2)\delta(y_3)\exp[i(\omega\tau - ky_1)]\exp\left(-\frac{y_1^2}{L^2(\tau)}\right)$$

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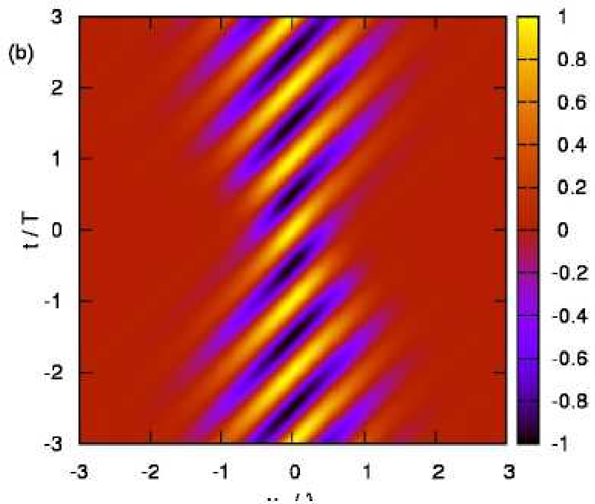
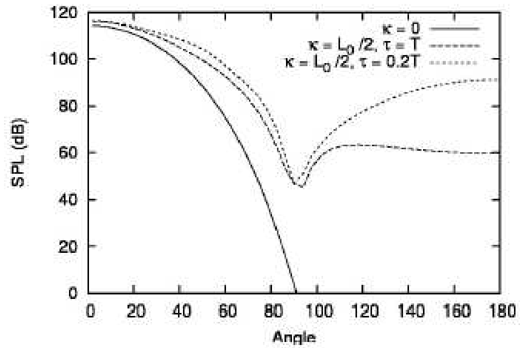


- Fast truncations intensify the bursts.



Model 3: the jittering wavepacket

$$T_{11}(\vec{y},\tau) = 2\rho_0 U\tilde{u}\frac{\pi D^2}{4}\delta(y_2)\delta(y_3)A(\tau)\exp(i(\omega\tau - ky_1))\exp\left(-\frac{y_1^2}{L^2(\tau)}\right)$$

$$p(\vec{x},t) = -\frac{A\left(t-\frac{|x|}{c}\right)\rho_0 U\tilde{u}M_c^2(kD)^2 L\left(t-\frac{|x|}{c}\right)\sqrt{\pi}\cos^2\theta}{8|x|}e^{\left(-\frac{L^2\left(t-\frac{|x|}{c}\right)k^2(1-M_c\cos\theta)^2}{4}\right)}e^{i\omega\left(t-\frac{|x|}{c}\right)}$$

We use LES data to evaluate this model

5. Wavepackets: space-time intermittency and source efficiency

6. Conditional analysis 1: Wavelets, flow visualisation & a jittering source model

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IUTAM Symposium on Computational Aero-Acoustics for Aircraft Noise Prediction

Using LES to explore the effect of temperature on sound-source mechanisms in jets

André V. G. Cavalieri[a,b], Guillaume Daviller[a], Pierre Comte[a], Peter Jordan[a]

[a]Institut P', CNRS - Université de Poitiers - ENSMA, UPR 3346, Département Fluides, Thermique, Combustion, CEAT, 43 Route de l'Aérodrome, F86036 Poitiers Cedex, France
[b]Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil

Using LES to explore sound-source mechanisms in jets

André V. G. Cavalieri[a,b], Guillaume Daviller[a], Pierre Comte[a], Peter Jordan[a], Gilead Tadmor[c], Yves Gervais[a]

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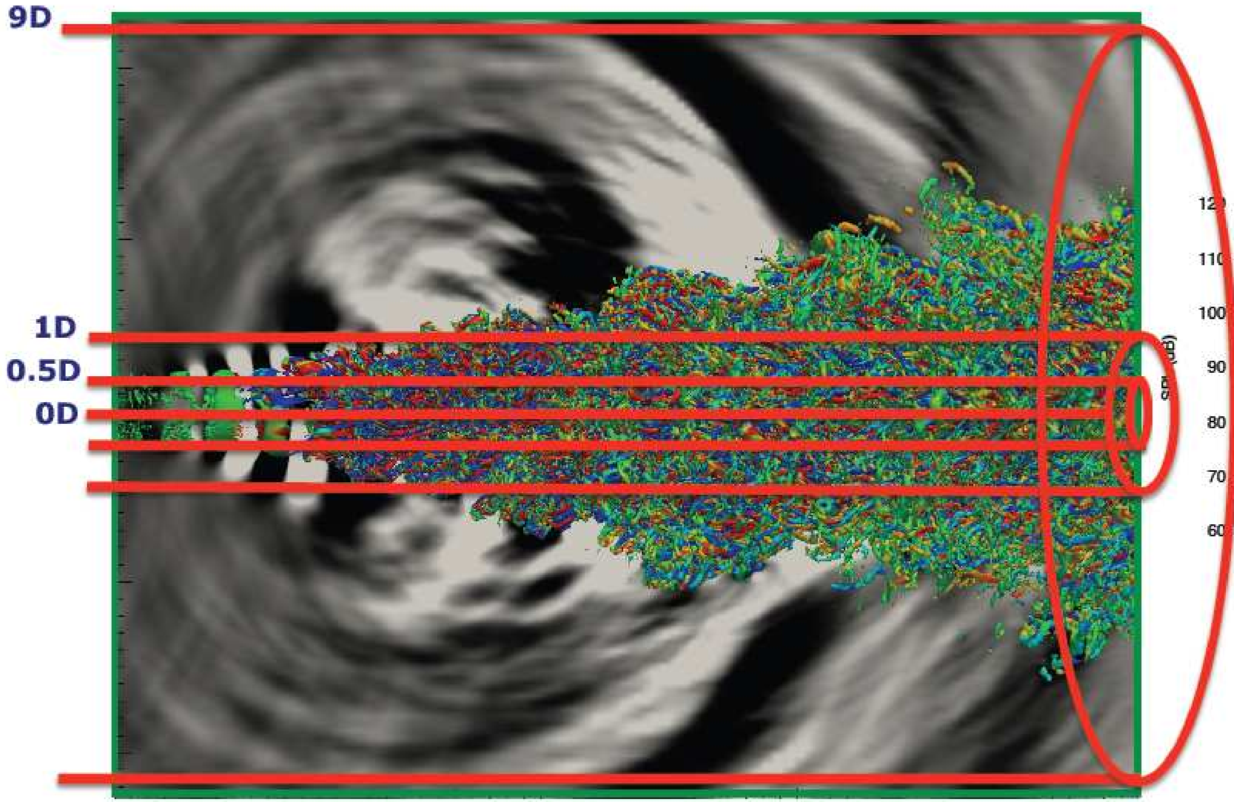
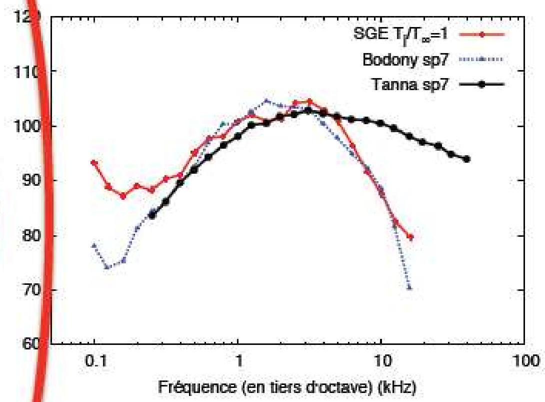
[b]Instituto Tecnológico de Aeronáutica, Praça Marechal Eduardo Gomes, 50, Vila das Acácias, CEP 12228-900 - São José dos Campos, Brazil
[c]Department of Electrical and Computer Engineering, Northeastern University, 360 Huntington Avenue, Boston, MA 02115-5000, USA

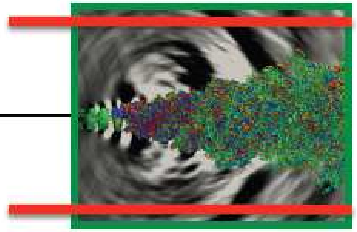
1. M_a=0.9; T_j/T_a=1; Re=400000;

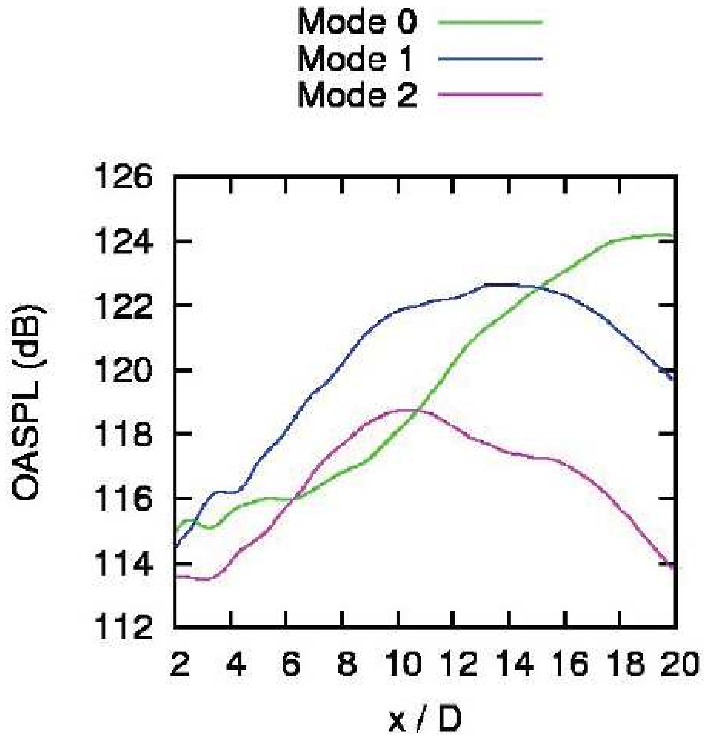
19 Million grid-points;
4th order in space;
2^{nd} order in time;





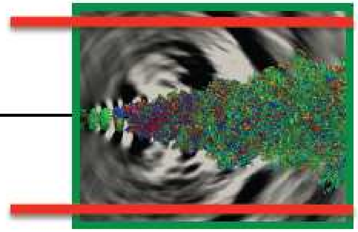
Azimuthal structure of sound field



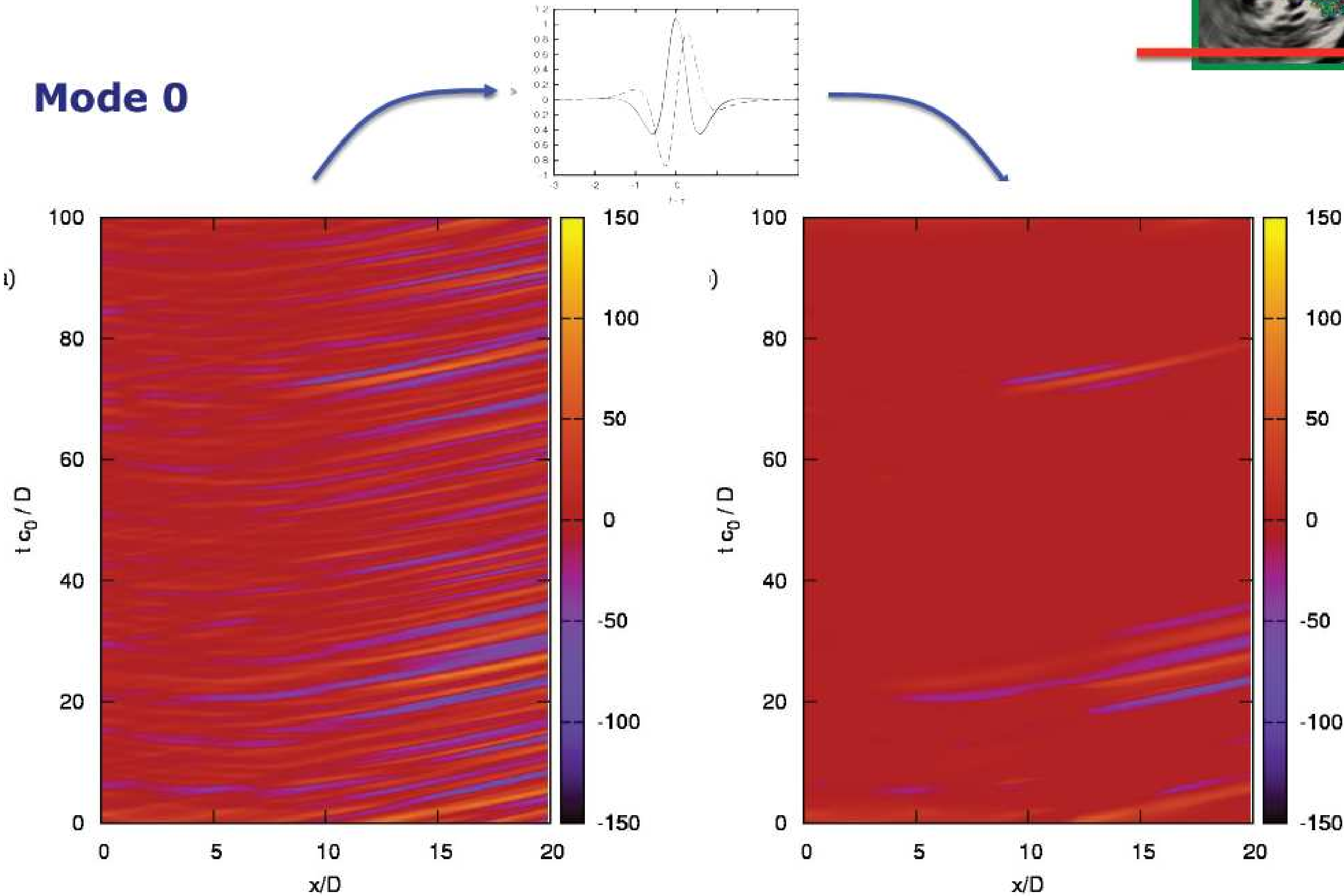


Downstream radiation largely axisymmetric, suggests a longitudinal 'pumping' mechanism

Wavelet filtering: localise temporal inhomogeneity



Mode 0



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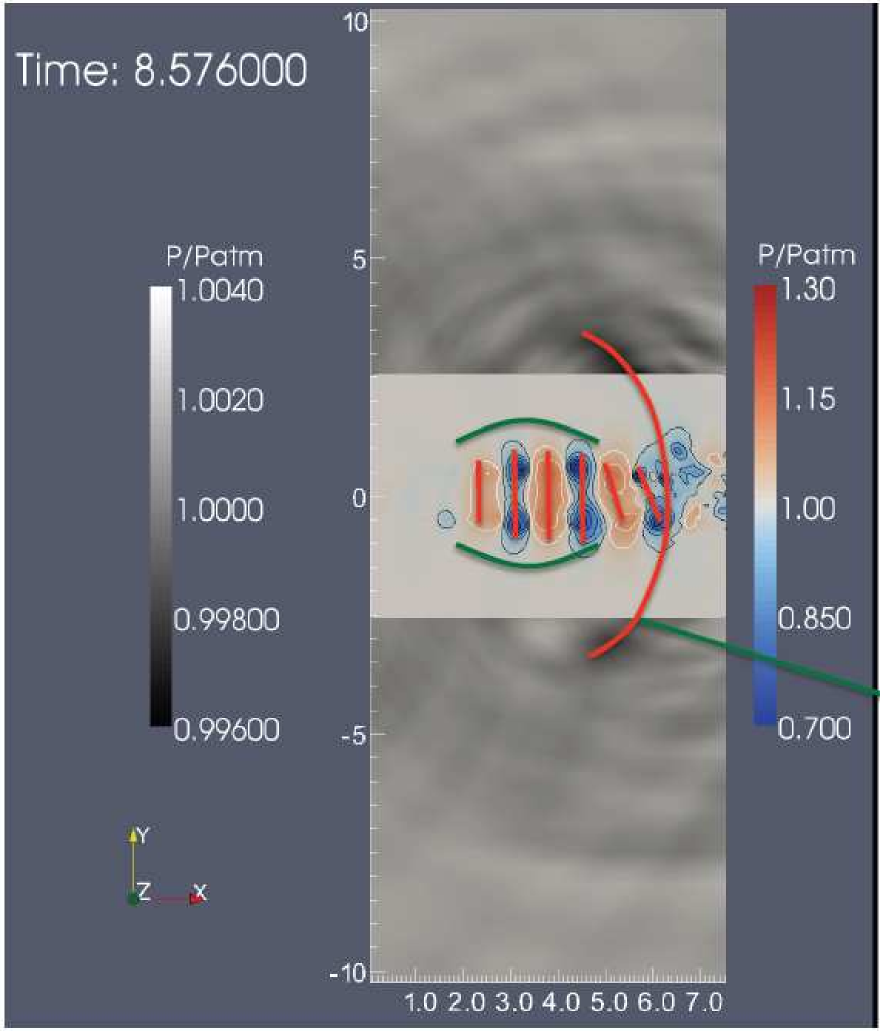
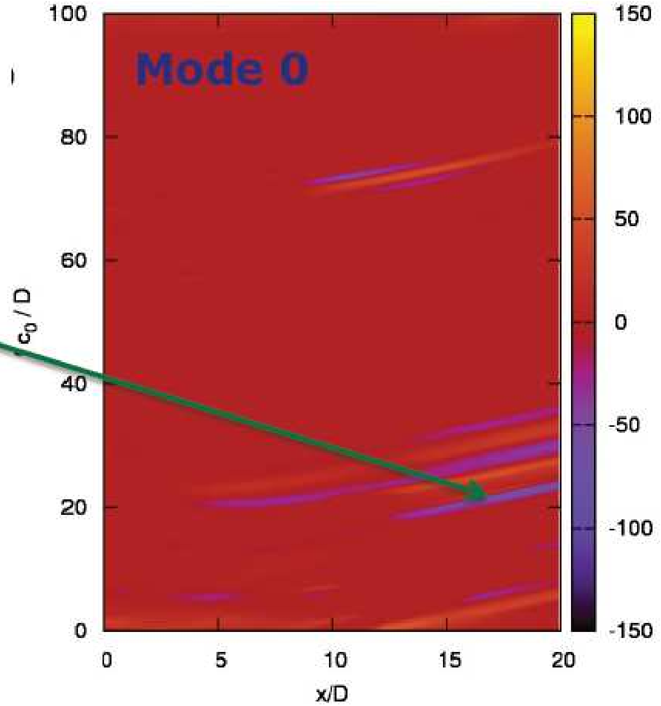
Source mechanism: flow visualisation



Axisymmetric wavepacket amplitude on the increase,

Downstream truncation due to tilting of axisymmetric structures,

Strong axisymmetric, propagative depression released.



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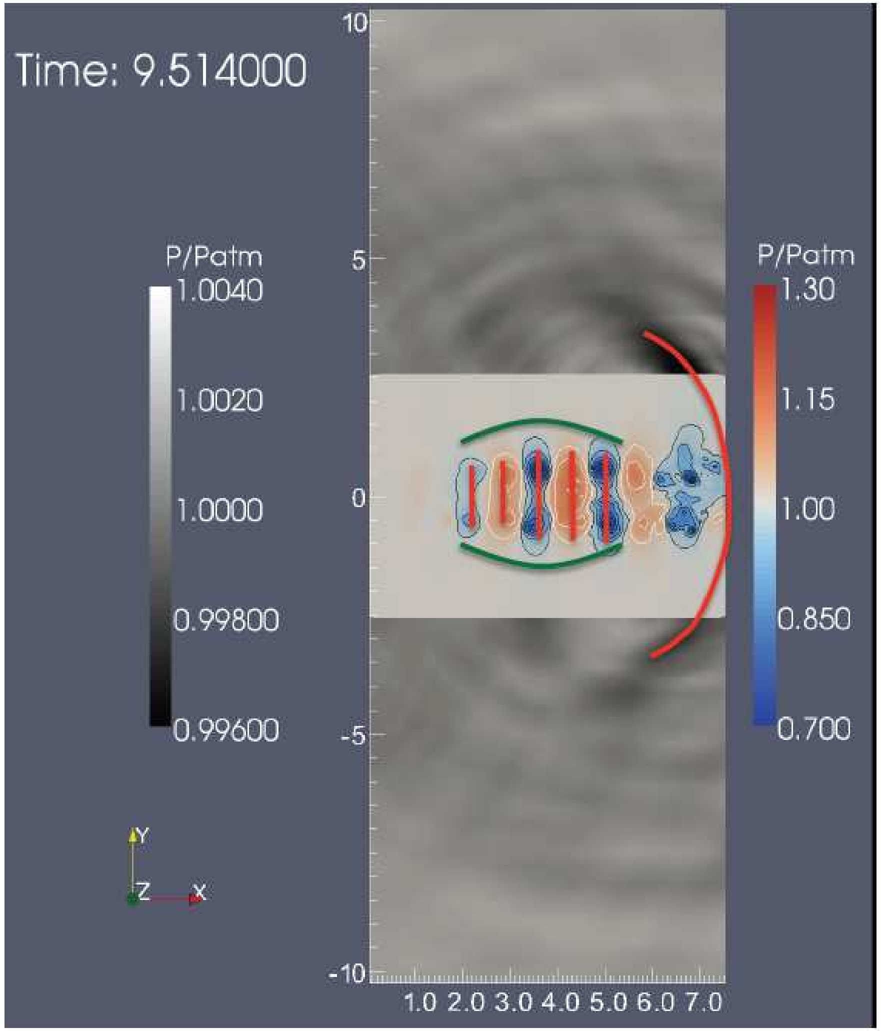
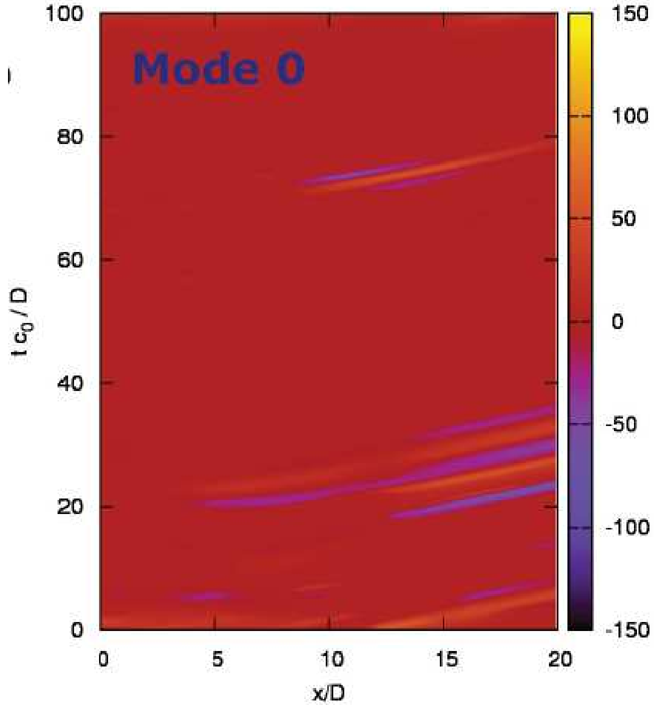
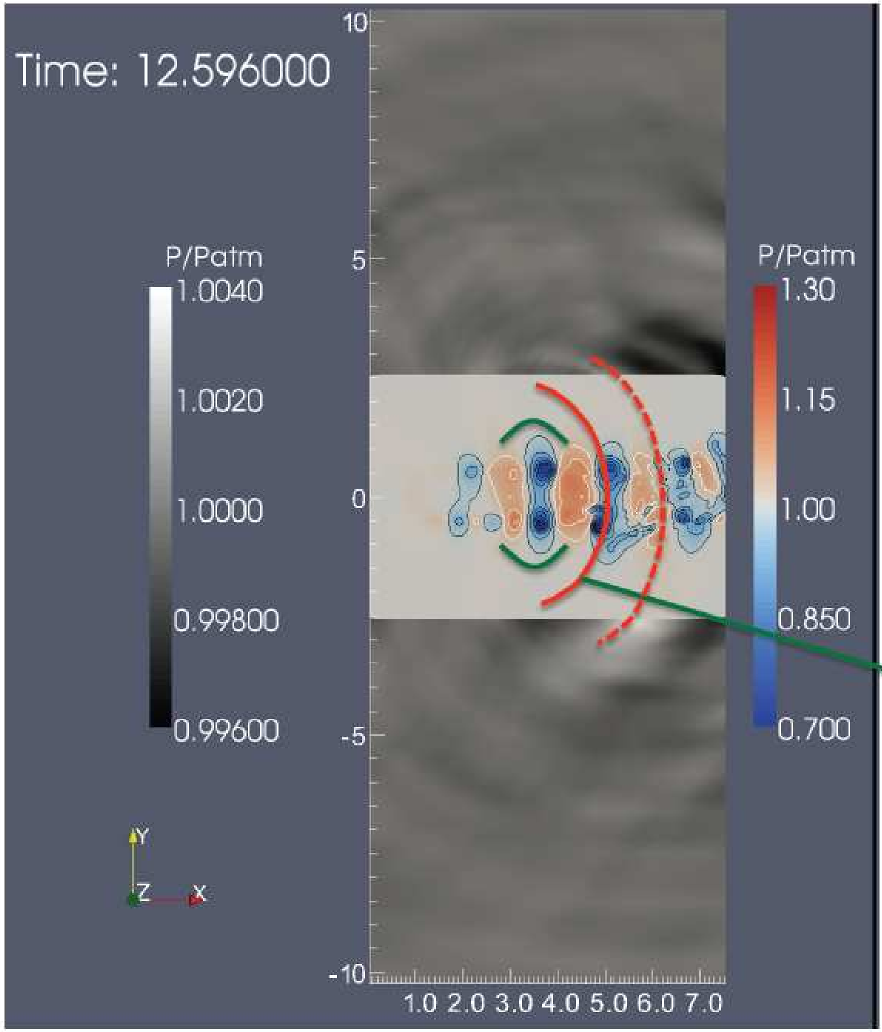
Source mechanism: flow visualisation



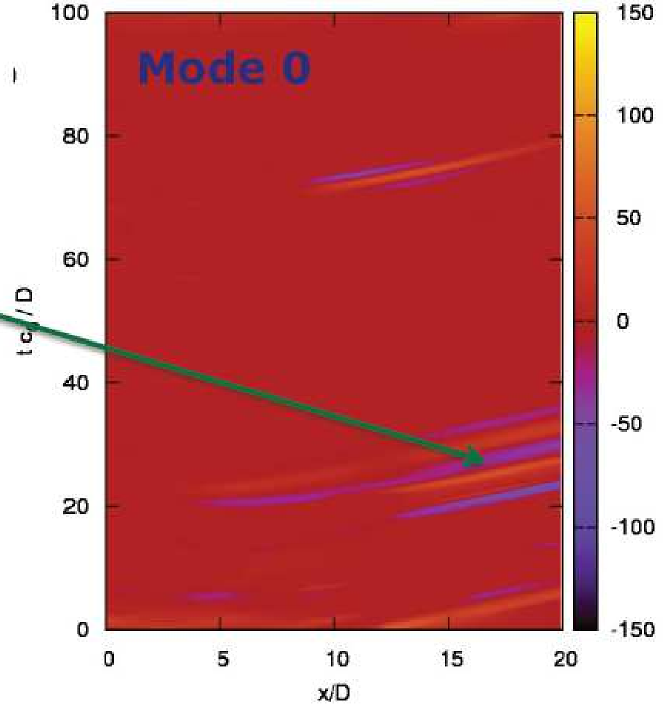
Axisymmetric wavepacket envelope extends, amplitude remains high,



Source mechanism: flow visualisation



Axisymmetric wavepacket envelope truncates, both upstream and downstream,



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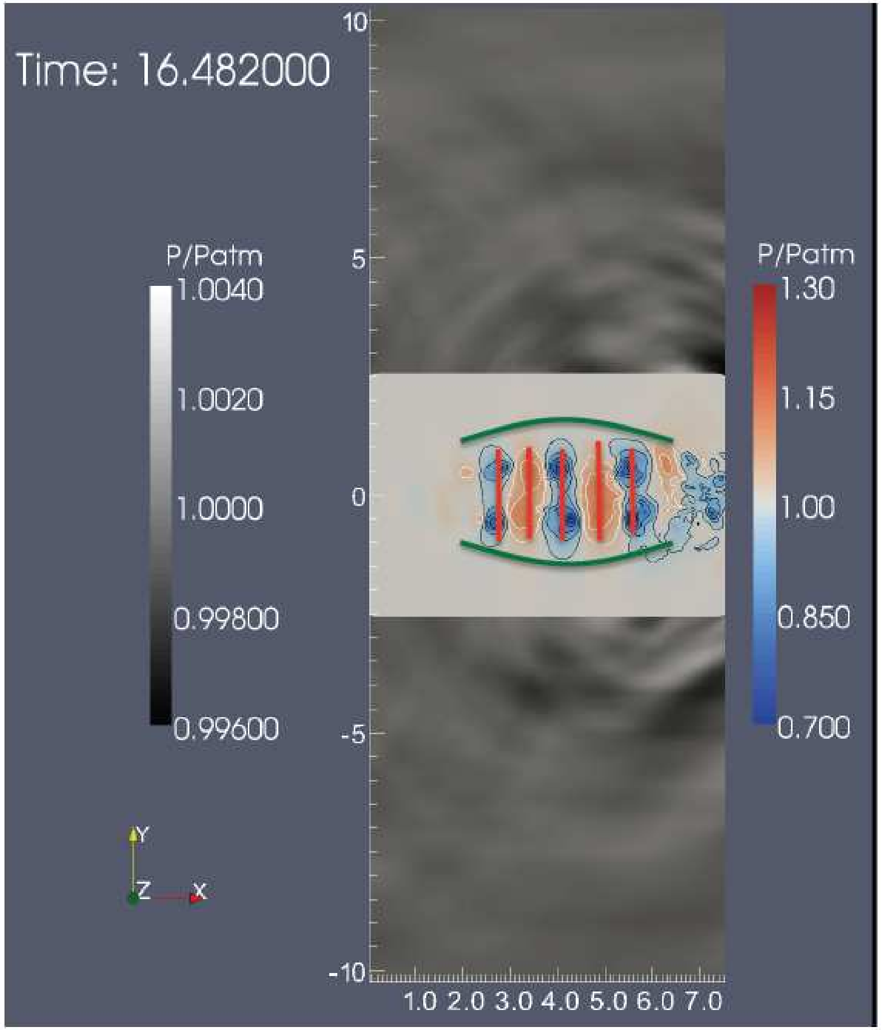
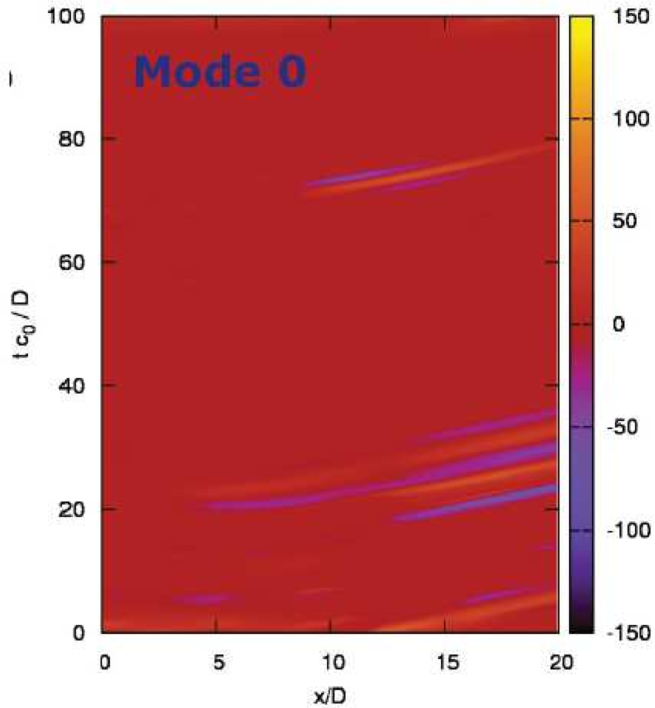
Source mechanism: flow visualisation



Flow regains axisymmetric organisation with extended envelope,



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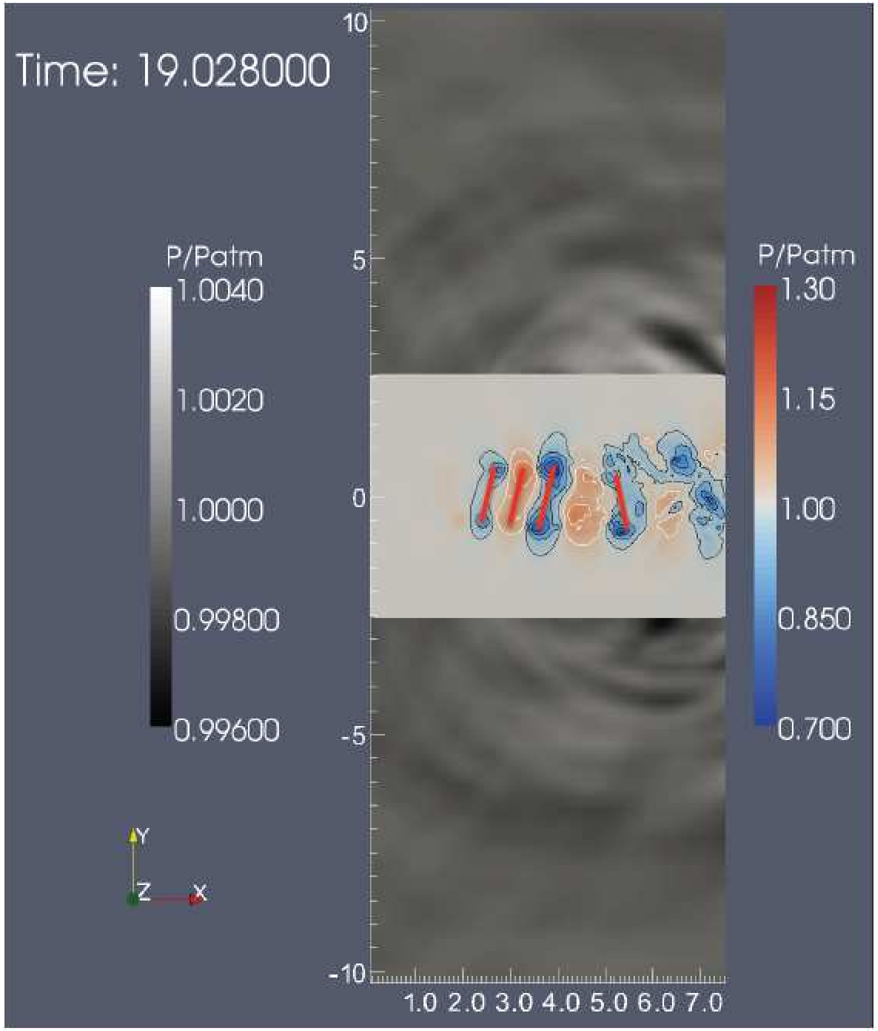
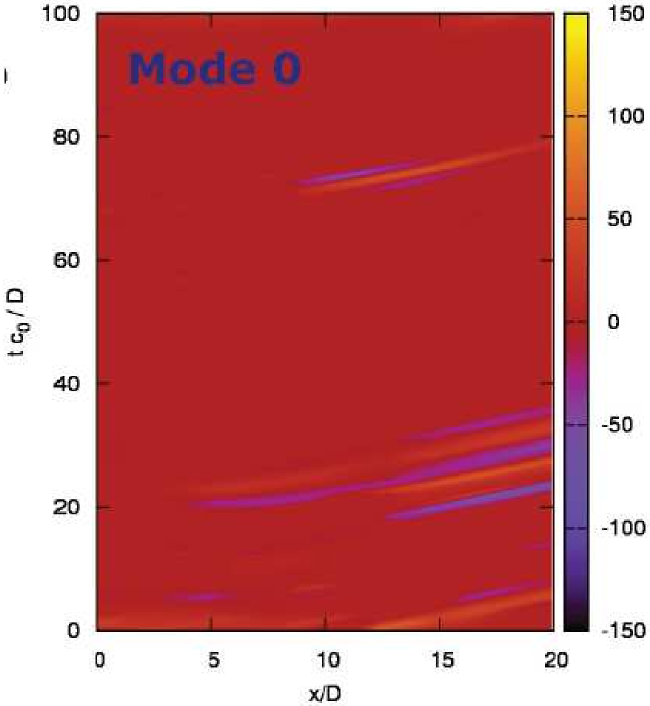
Source mechanism: flow visualisation



Another switch from axisymmetry to antisymmetry



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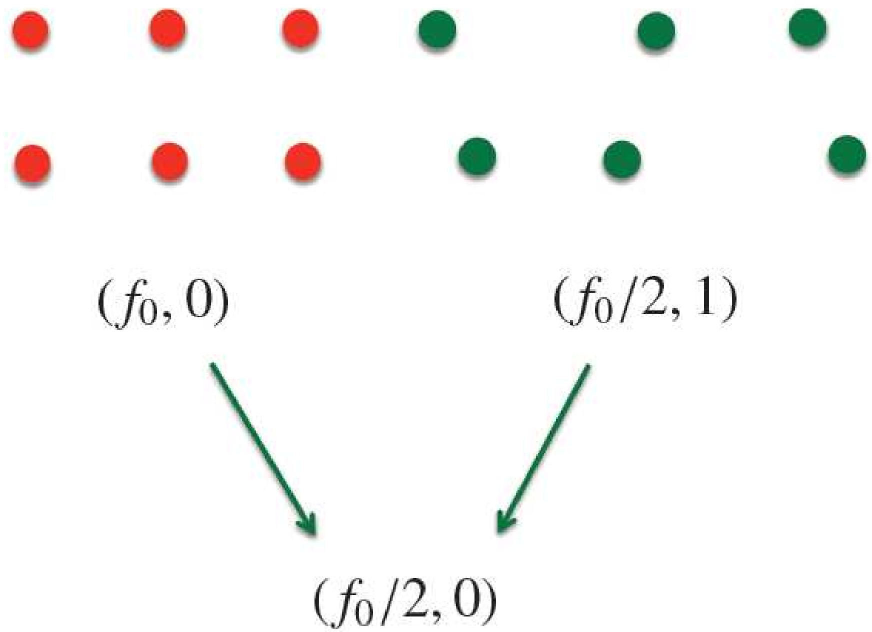
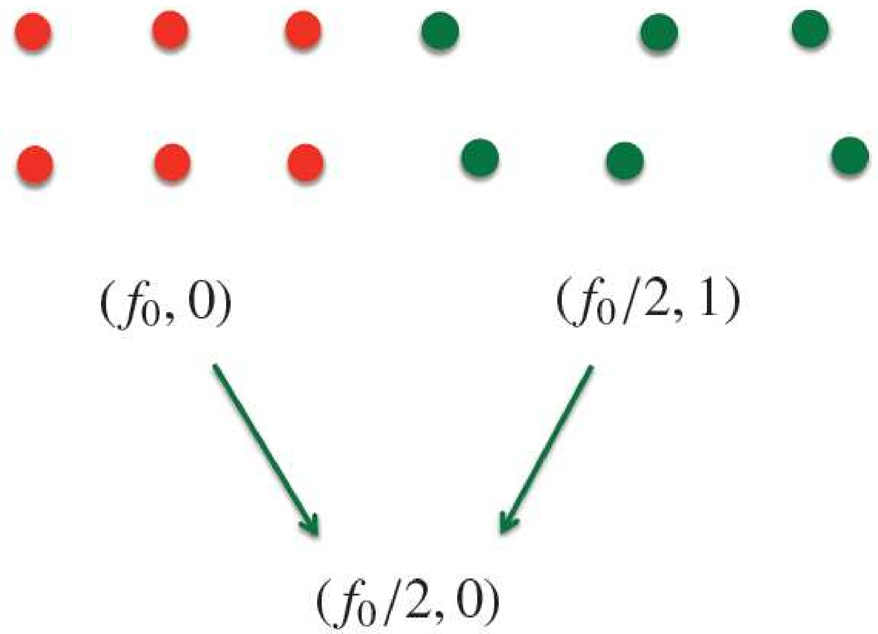
Source mechanism: kinematics



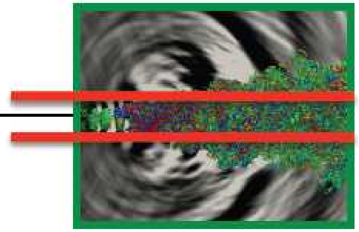
Source mechanism: dynamics

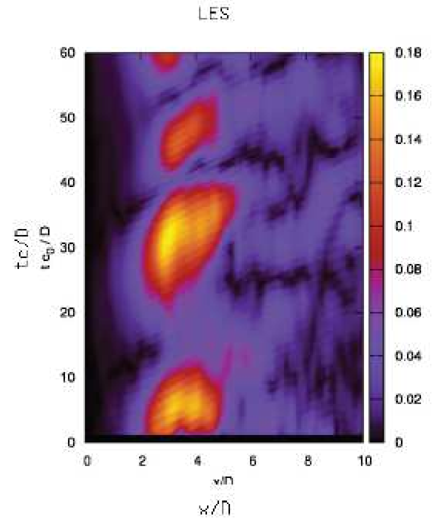


?

$$C(\overline{U}, m_1)\frac{dm_0}{dt} = f(m_0) \quad ?$$

Quantitative verification

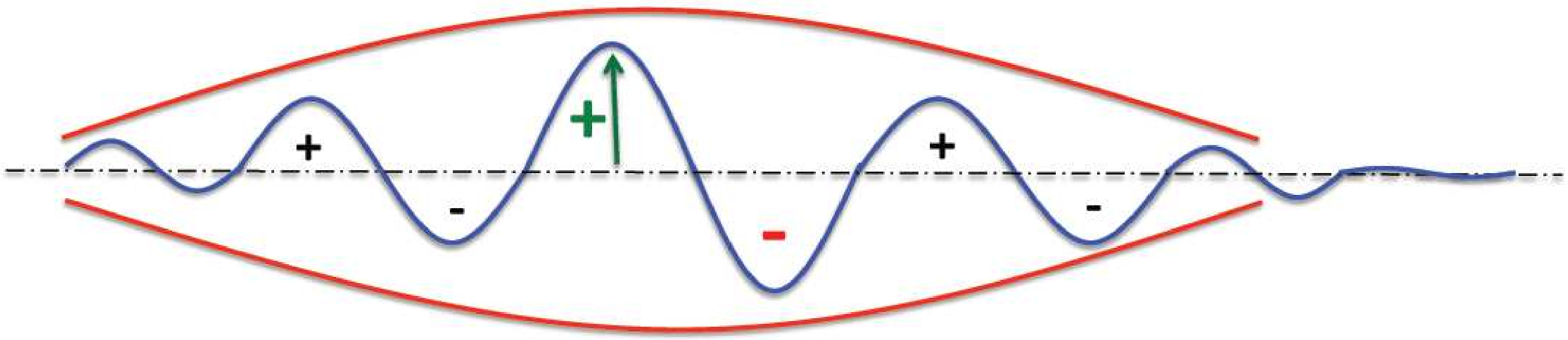




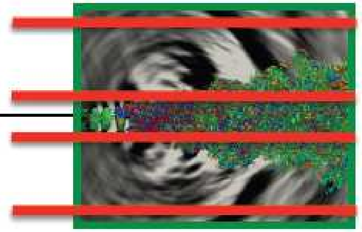
Short-time
Fourier transform

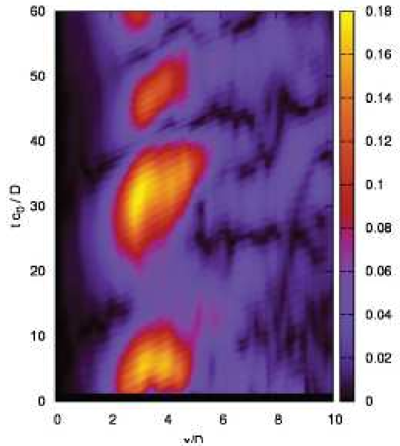
$$T_{11}(\vec{y},\tau) = 2\rho_0 U\tilde{u}\frac{\pi D^2}{4}\delta(y_2)\delta(y_3)A(\tau)\exp(i(\omega\tau - k y_1))\exp\left(-\frac{y_1^2}{L^2(\tau)}\right)$$

$$p(\vec{x},t) = -\frac{A\left(t-\frac{|x|}{c}\right)\rho_0 U\tilde{u} M_c^2 (kD)^2 L\left(t-\frac{|x|}{c}\right)\sqrt{\pi}\cos^2\theta}{8|x|} e^{\left(-\frac{L^2\left(t-\frac{|x|}{c}\right)k^2(1-M_c\cos\theta)^2}{4}\right)} e^{i\omega\left(t-\frac{|x|}{c}\right)}$$



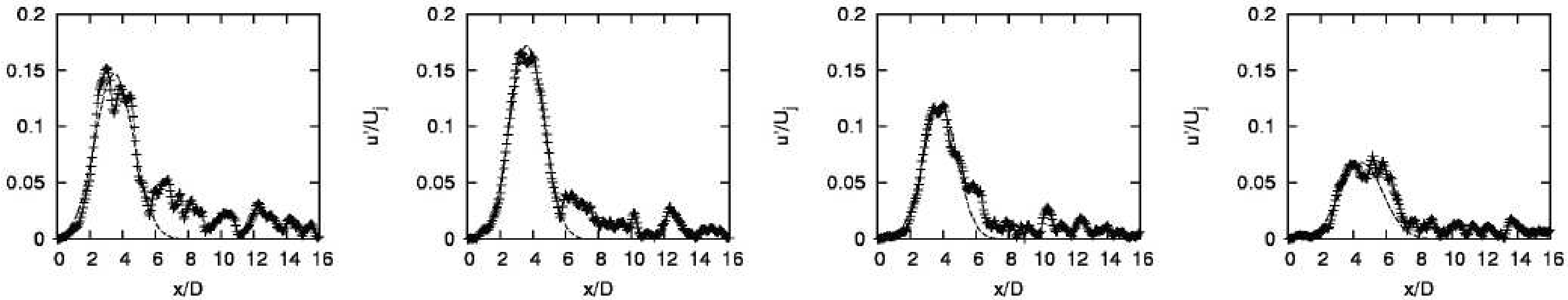
Quantitative verification



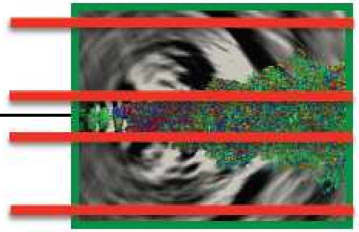


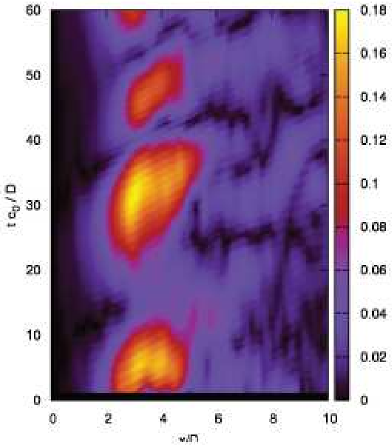
$$T_{11}(\vec{y},\tau) = 2\rho_0 U\tilde{u}\frac{\pi D^2}{4}\delta(y_2)\delta(y_3)A(\tau)\exp(i(\omega\tau - ky_1))\exp\left(-\frac{y_1^2}{L^2(\tau)}\right)$$

Gaussian fit to data to obtain time-varying amplitude and length scale



Quantitative verification





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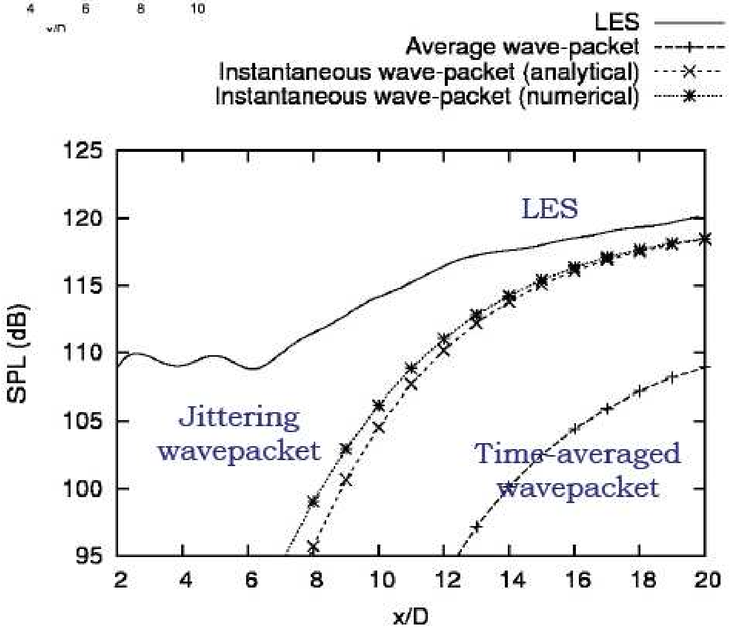
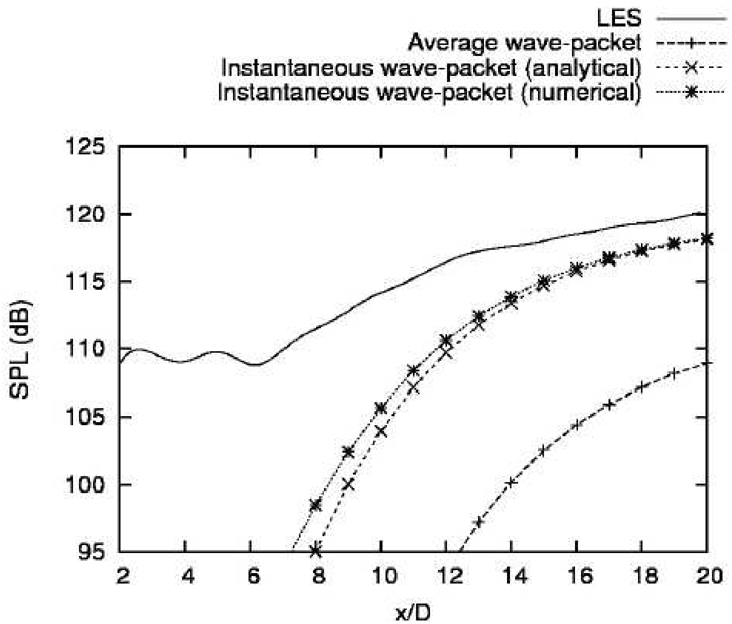




What the study showed

1. **A jittering, axisymmetric wavepacket found to underpin high-amplitude low-angle radiation**

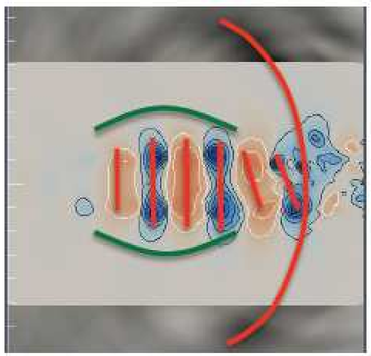
2. **A simplified line-source model, with analytical solution, gives farfield levels to within 1.5dB !**

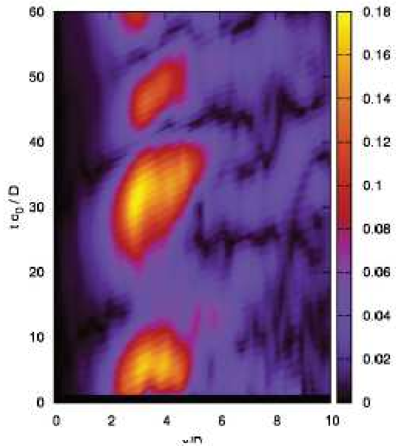
- Looks like we've got the flow kinematics and acoustic dynamics right.

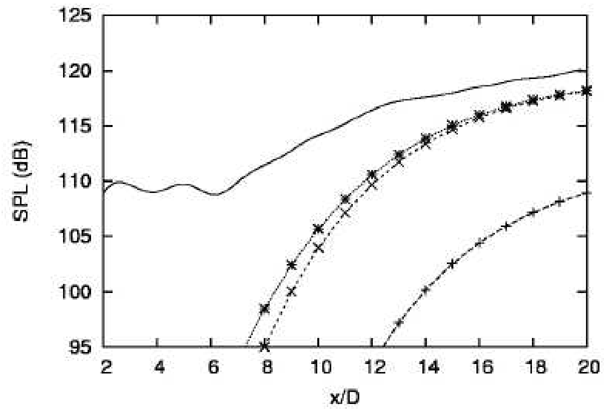
3. **...but, are the flow dynamics linear or non-linear?**

$$C(\overline{U}, m_1)\frac{dm_0}{dt} \overset{?}{=} f(m_0) \;?$$

Collaboration with
T. Colonius (Caltech)
J. Freund (Urbana-Champaign)
to investigate this







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Gilead Tadmor[c], Yves Gervais[a]

7. Conditional analysis 2: Linear Stochastic Estimation

Exp Fluids
DOI 10.1007/s00348-006-0199-5
RESEARCH ARTICLE

On spectral linear stochastic estimation

C. E. Tinney · F. Coiffet · J. Delville · A. M. Hall · P. Jordan · M. N. Glauser

American Institute of Aeronautics and Astronautics

Identifying noisy and quiet modes in a jet

P. Jordan*, M. Schlegel†, O. Stalnov‡, B.R. Noack†, and C.E. Tinney*

*Laboratoire d'Études Aérodynamiques, CNRS UMR 6609, Université de Poitiers, France
†Institute of Fluid Dynamics and Technical Acoustics, Berlin University of Technology, Berlin, Germany
‡University of Tel Aviv, Israel

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A time-resolved estimate of the turbulence and sound source mechanisms in a subsonic jet flow

C. E. TINNEY†*, P. JORDAN†, A. M. HALL‡, J. DELVILLE† and M. N. GLAUSER‡

†Université de Poitiers, LEA/CEAT, UMR CNRS 6609, 43 Route de l'Aérodrome, 86036 Poitiers, France
‡Department of Mechanical & Aerospace Engineering, Syracuse University, 151 Link Hall, Syracuse, NY 13244-1240, USA

Under consideration for publication in J. Fluid Mech.

On least-order flow representations for aerodynamics and aeroacoustics

By MICHAEL SCHLEGEL[1] †, BERND R. NOACK[1], OLIVER LEHMANN[1], ANDREAS DILLMANN[2], ELMAR GRÖSCHEL[3,4], WOLFGANG SCHRÖDER[3], MINGJUN WEI[5], JONATHAN B. FREUND[6] AND PETER JORDAN[7]

Jet turbulence characteristics associated with downstream and sideline sound emission

F. Kerhervé*, P. Jordan*, J. Delville*, C. Bogey† & D. Juvé†

*Institut Pprime, CNRS UPR 3346, Université de Poitiers, ENSMA, France
†Laboratoire de Mécanique des Fluides et d'Acoustique, CNRS UMR 5509, Ecole Centrale de Lyon, France

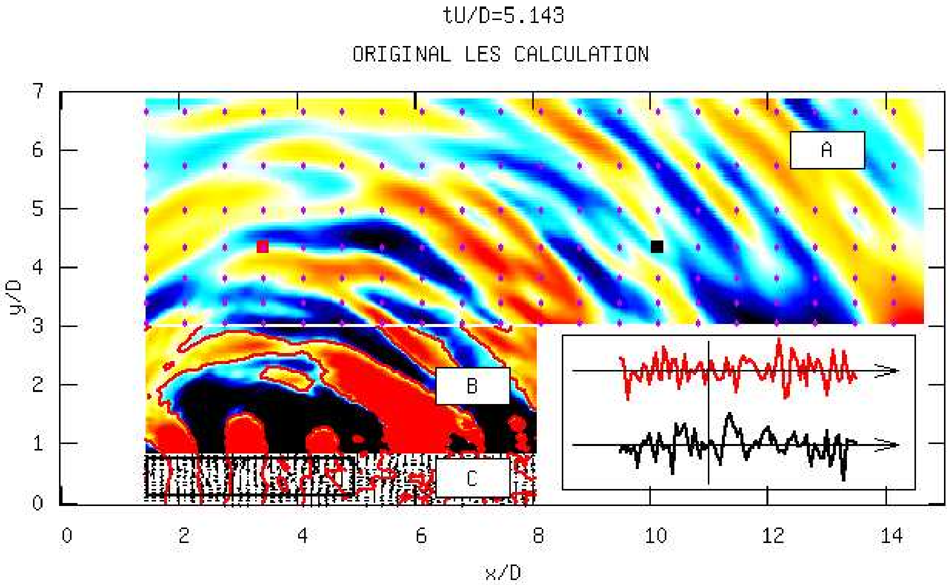
7. Conditional analysis 2: Linear Stochastic Estimation

3 steps:

1. **Filter acoustic field into low- and high-angle radiation**

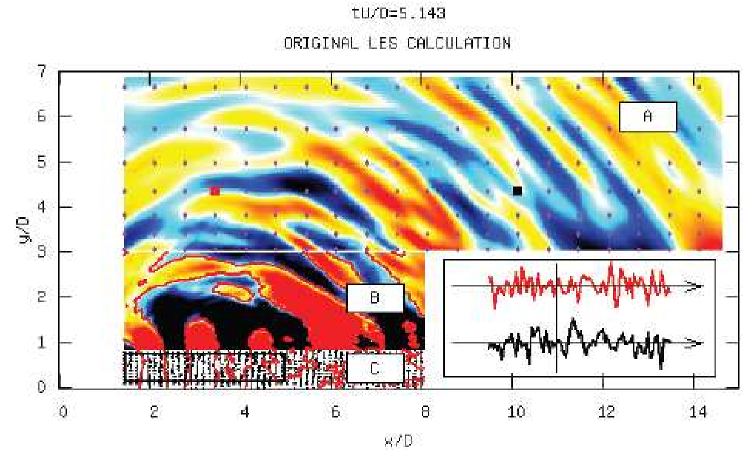
2. **Use low-angle field as conditional (or trigger) event**

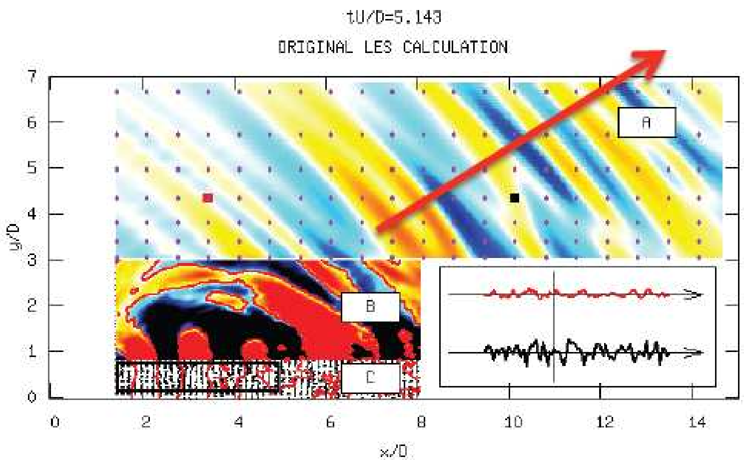
3. **Evaluate the conditional space-time structure of the *turbulent pressure and velocity fields* within the jet.**

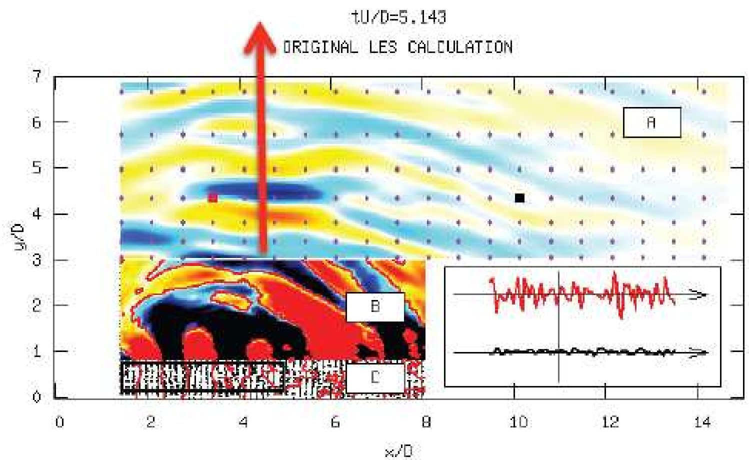


6. Conditional analysis 2: Linear Stochastic Estimation

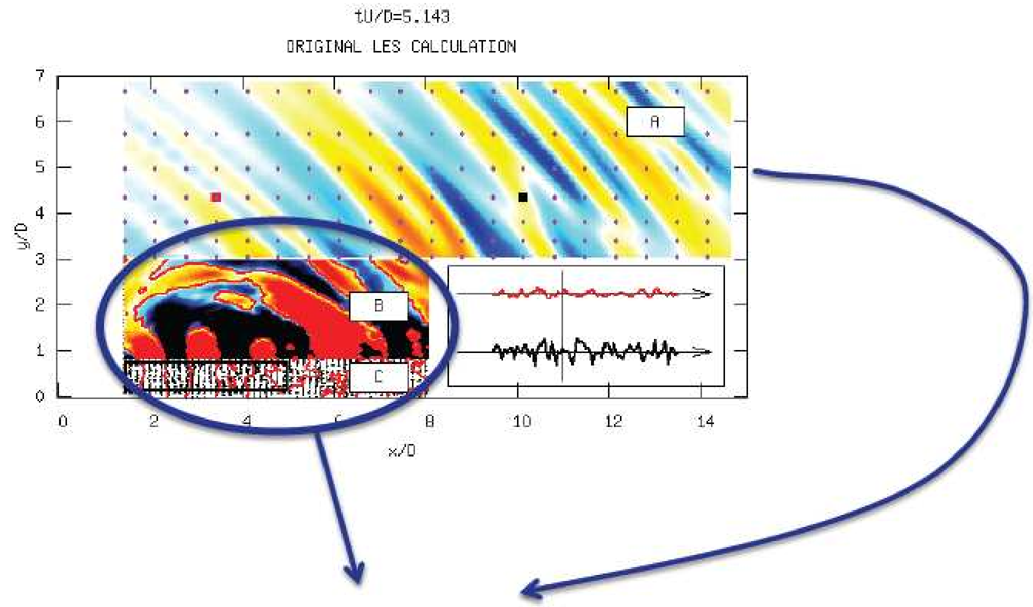
1. Filter acoustic field into low- and high-angle radiation







2. Use low-angle field as conditional (or trigger) event

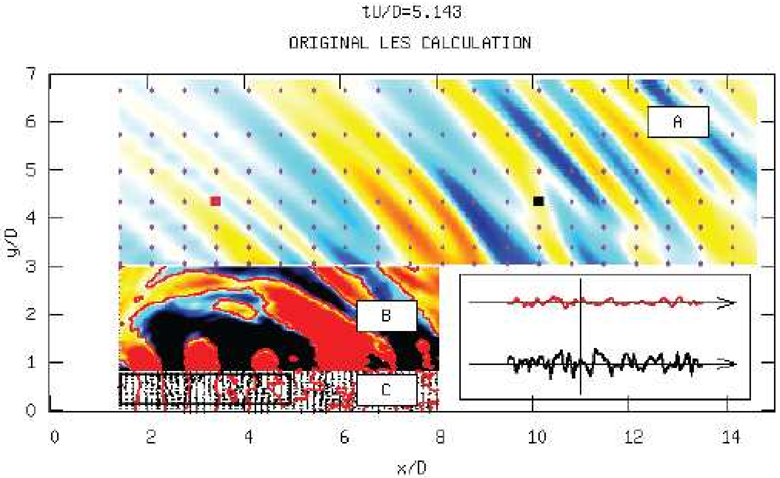


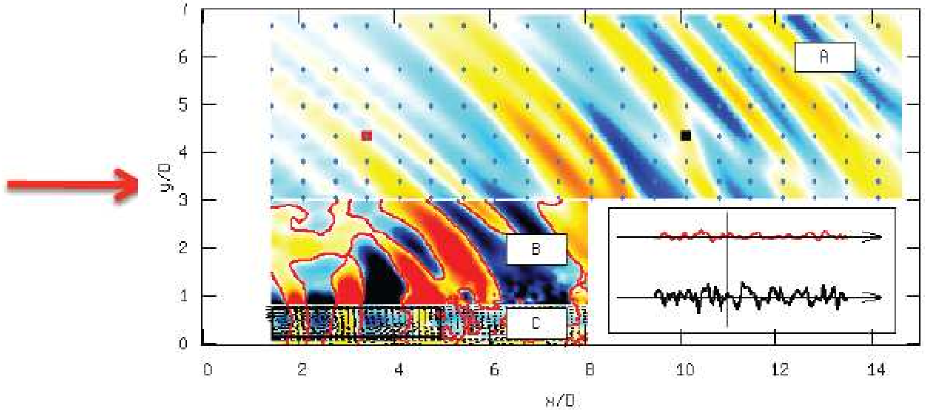
$$\hat{q}(\vec{x},t) = < \vec{q'}(\vec{x},t) | E(\vec{y}, t + t_E) >$$

6. Conditional analysis 2: Linear Stochastic Estimation

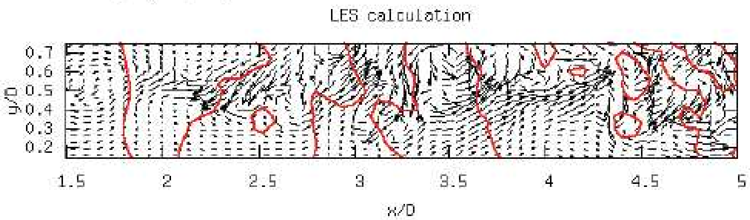
3. Compute conditional (x,t) structure of the turbulent pressure and velocity fields.

$$\hat{q}(\vec{x},t) = < \vec{q}'(\vec{x},t) | E(\vec{y}, t+t_E) >$$

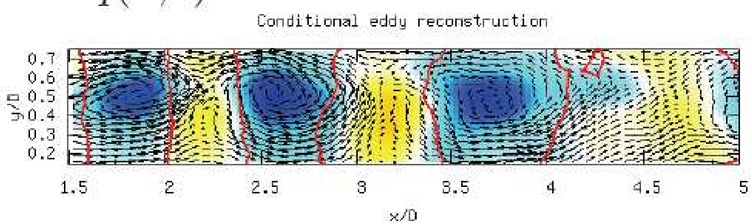




$\vec{q}'(\vec{x},t)$



$\hat{q}(\vec{x},t)$

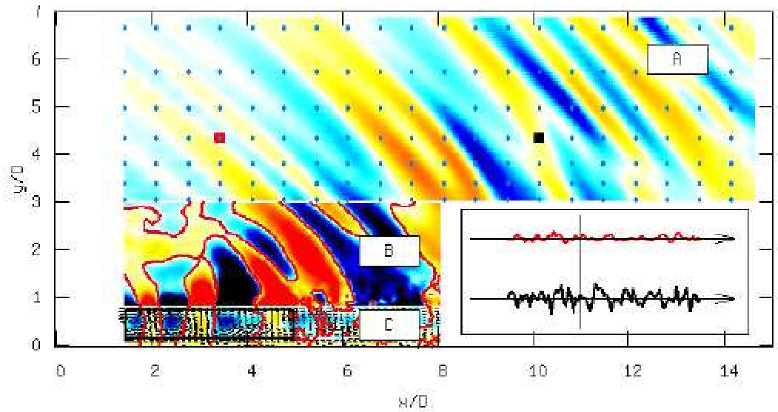


3. Compute conditional (x,t) structure of the turbulent pressure and velocity fields.

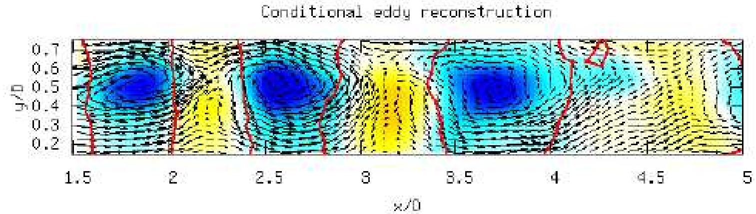
$$\hat{q}(\vec{x},t) = < \vec{q'}(\vec{x},t) | E(\vec{y}, t + t_E) >$$

"These [measurements] suggest that hidden in the apparently random fluctuations in the mixing layer region is perhaps a very regular and ordered pattern of flow which has not been detected yet"

– Fuchs (1972)

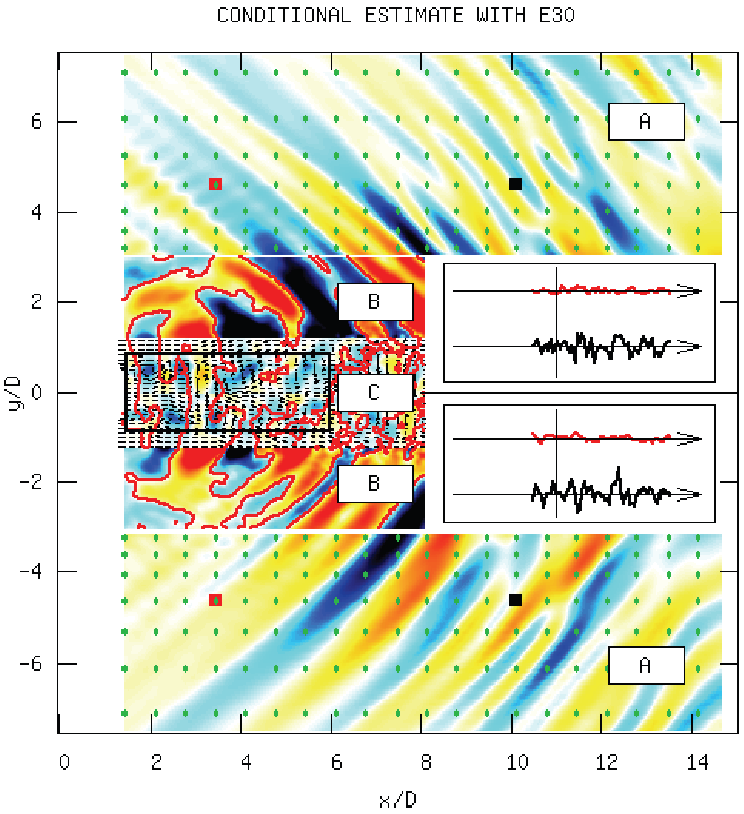


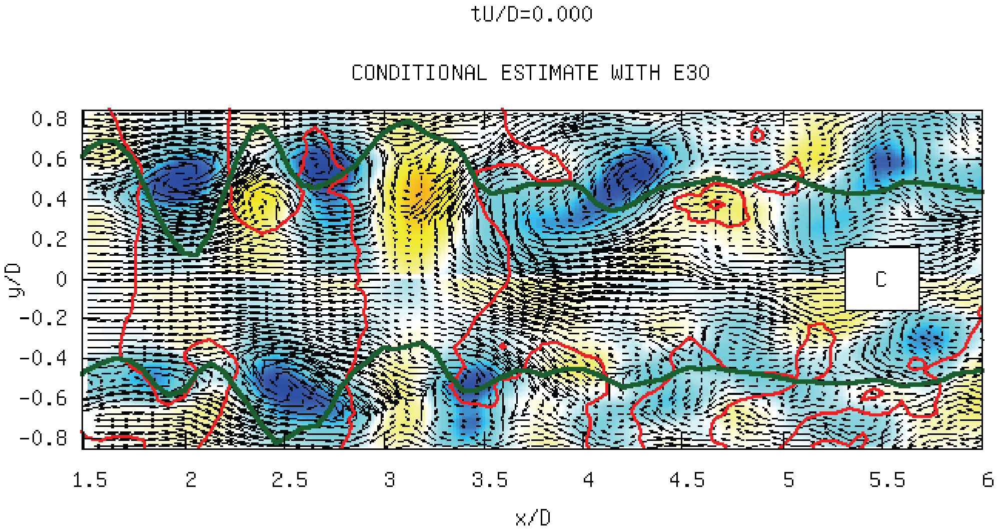
$\hat{q}(\vec{x},t)$



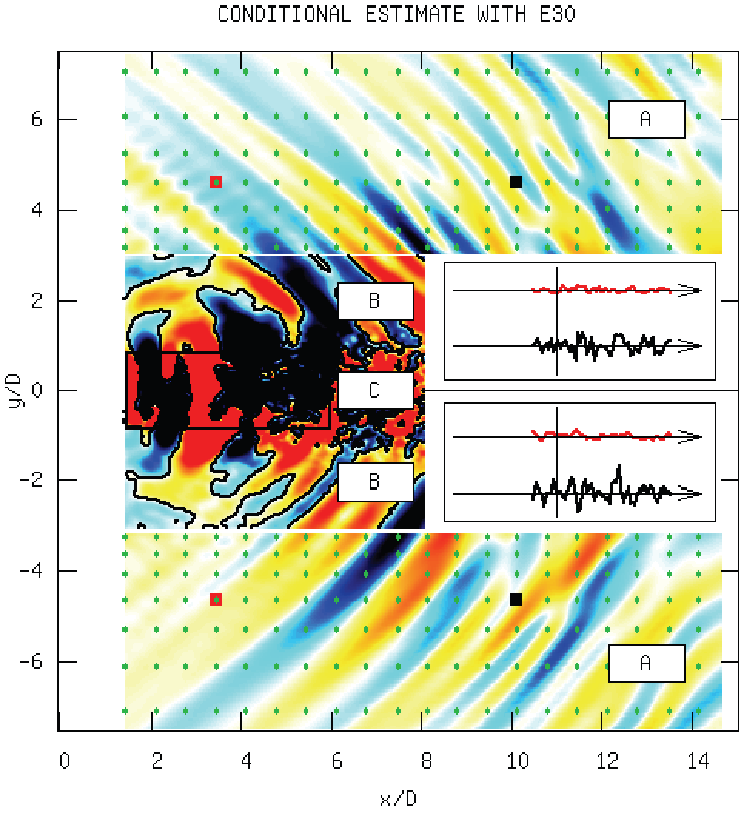
F. Kerhervé* P. Jordan* J. Delville*
C. Bogey† & D. Juvé†

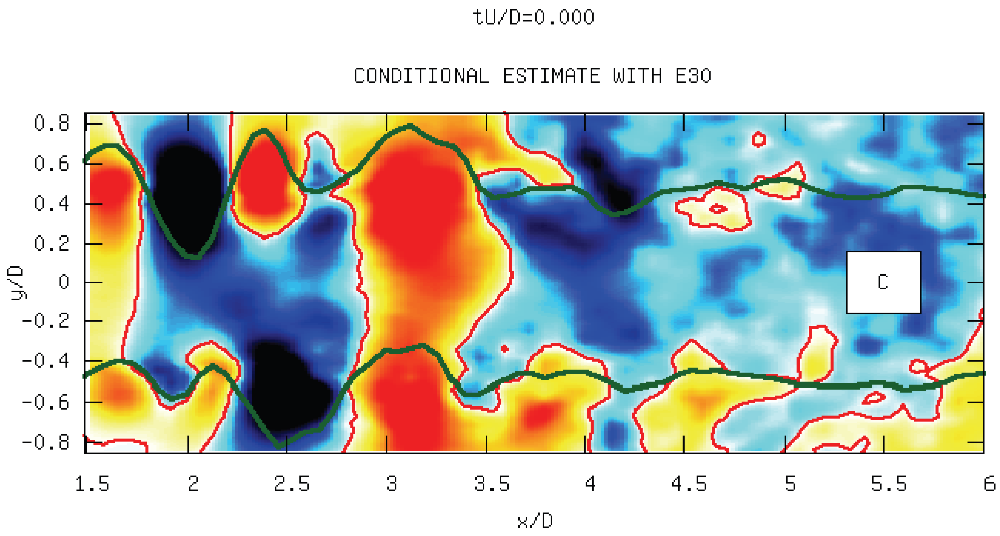
3. Compute conditional (x,t) structure of the turbulent pressure and velocity fields.



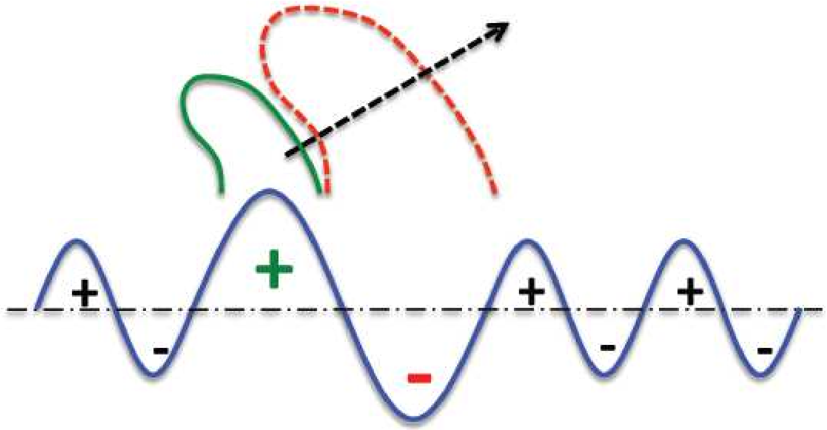


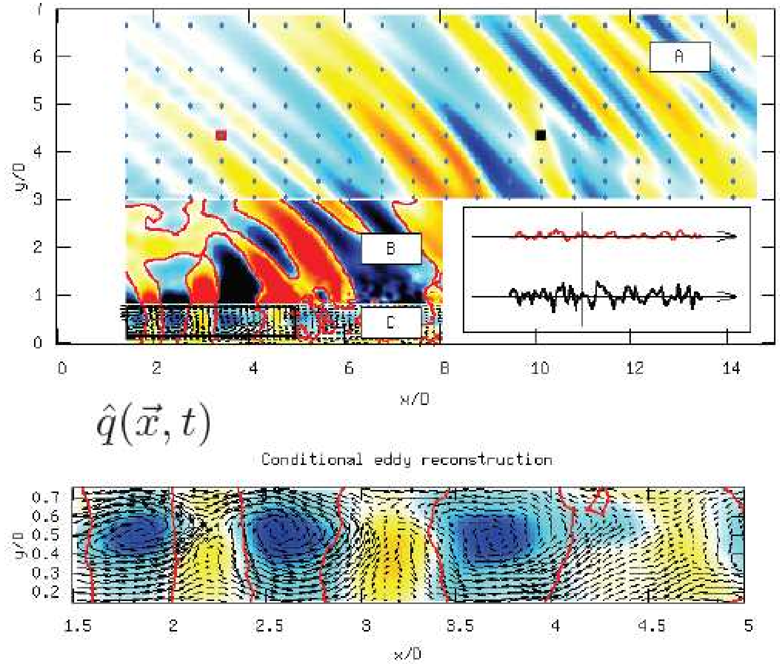
3. Compute conditional (x,t) structure of the turbulent pressure and velocity fields.





3. Compute conditional (x,t) structure of the turbulent pressure and velocity fields.



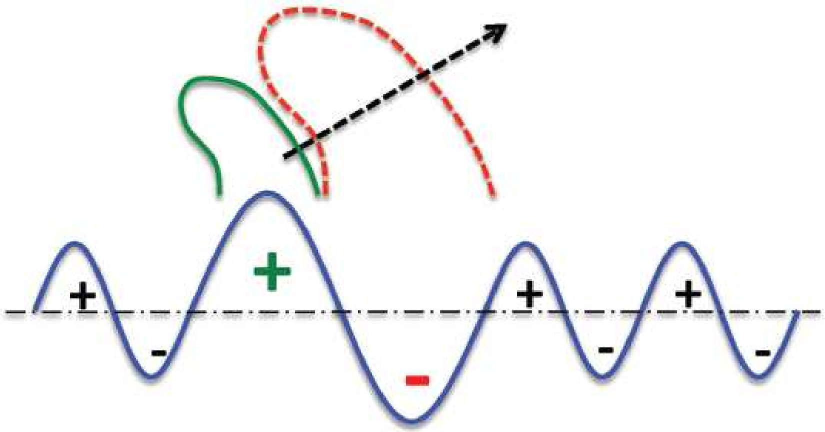


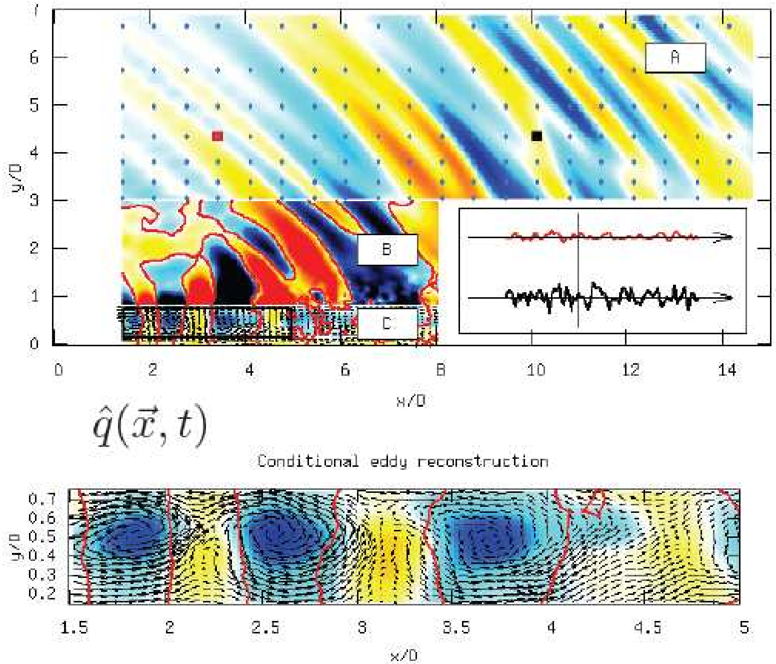
"Whether one views these structures as waves or vortices is, to some extent, a matter of viewpoint." – Brown & Roshko (1974)

"All this evidence suggests that the turbulence in the mixing layer of the jet behaves like a train similar to the hydrodynamic stability waves propagating in the shear flow." – Chan (1974)

6. Conditional analysis 2: Linear Stochastic Estimation

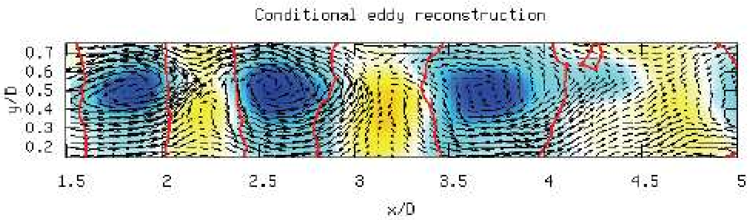
3. Compute conditional (x,t) structure of the turbulent pressure and velocity fields.





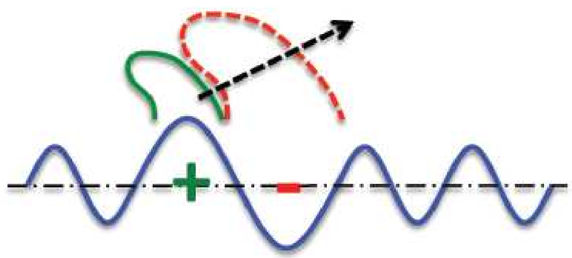
"The data suggest that one may perhaps represent the fluctuating [hydrodynamic] pressure field in terms of rather simple functions. For example, one may consider the jet as a...semi-infinite antenna for sound..." – Mollo-Christensen (1968)

What the study showed



1. **Sound-producing flow skeleton more organised than full LES solution**

2. **Evidence of wavepacket radiation for low-angle sound emission**



Experimental evidence of wavepackets at high Reynolds number

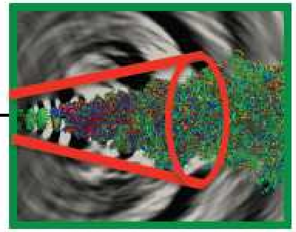
J. Fluid Mech. (2008), *vol.* 611, *pp.* 175–204.
doi:10.1017/S0022112008001833 Printed in the United Kingdom

The near pressure field of co-axial subsonic jets

C. E. TINNEY† AND P. JORDAN
Laboratoire d'Etudes Aérodynamiques – UMR CNRS 6609,
CNRS, Université de Poitiers, ENSMA, France

(Received 2 November 2006 and in revised form 18 March 2008)

Experimental evidence of wavepackets at high Reynolds number



Re=O(5.10⁶)

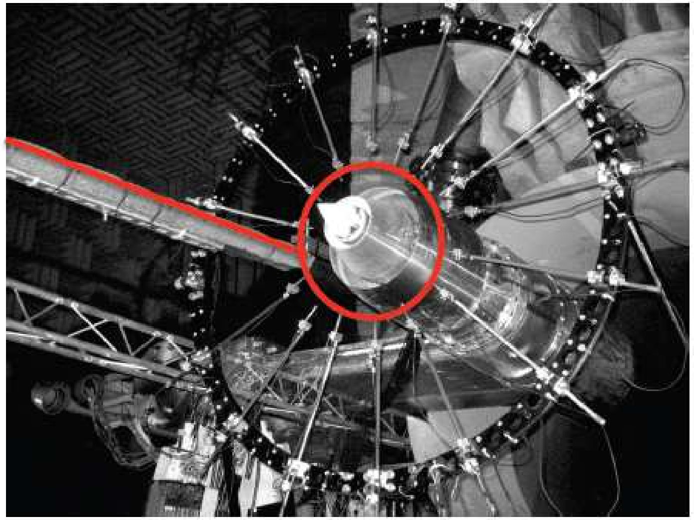


FIGURE 1. Experimental arrangement of the short-cowl co-axial nozzle (SCN) with the azimuthal and line arrays of microphones at the Noise Test Facility (NTF), QinetiQ.

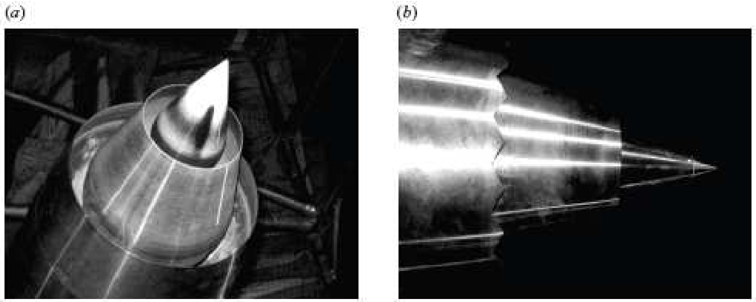
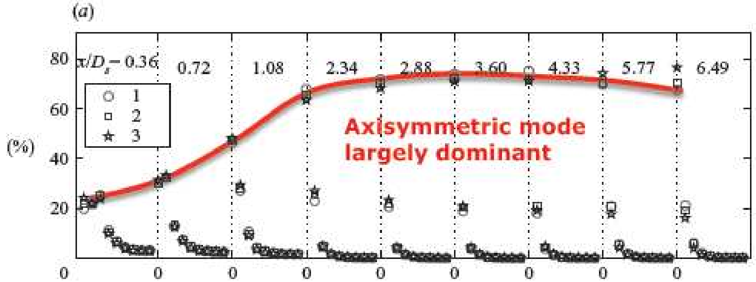
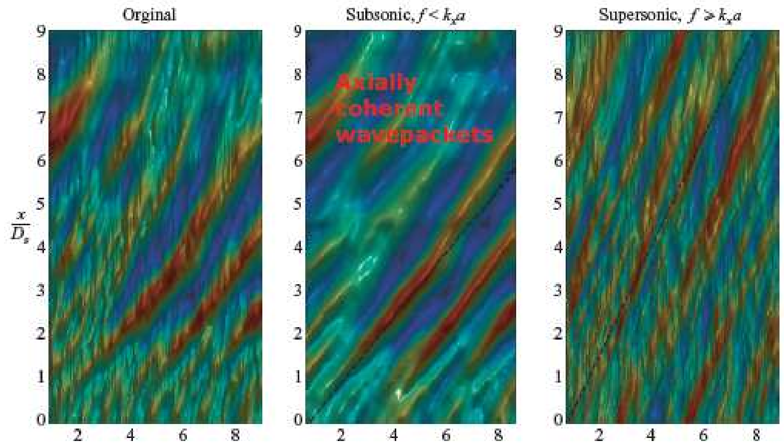


FIGURE 2. (a) Short-cowl nozzle (SCN). (b) Short-cowl nozzle with 20 serrations (SN).

Azimuthal structure of hydrodynamic nearfield



x-t structure of hydrodynamic nearfield



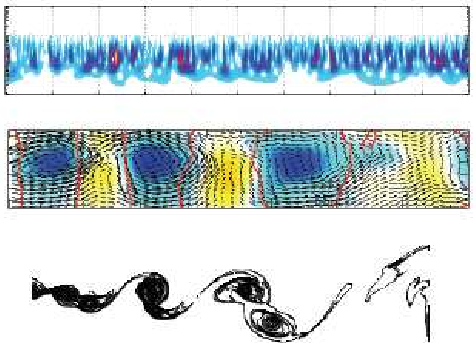
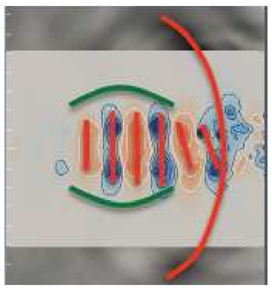
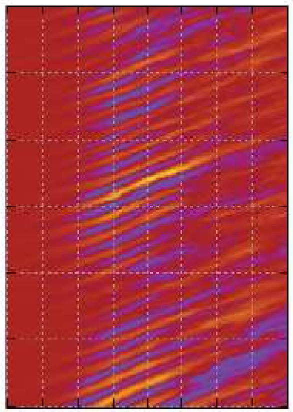
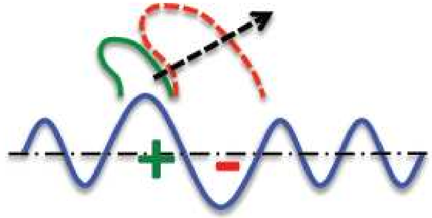
What all those studies showed

1. We repeatedly see evidence---numerical, experimental and theoretical--- supporting the contention that the flow dynamics which underpin jet noise are *less complex than Navier-Stokes dynamics*

2. We repeatedly see evidence suggesting that the *sound production mechanism* (acoustic dynamics) associated with these flow dynamics can be understood by means of a *retarded-potential mechanism* (students of compressible turbulence often have difficulty believing this),

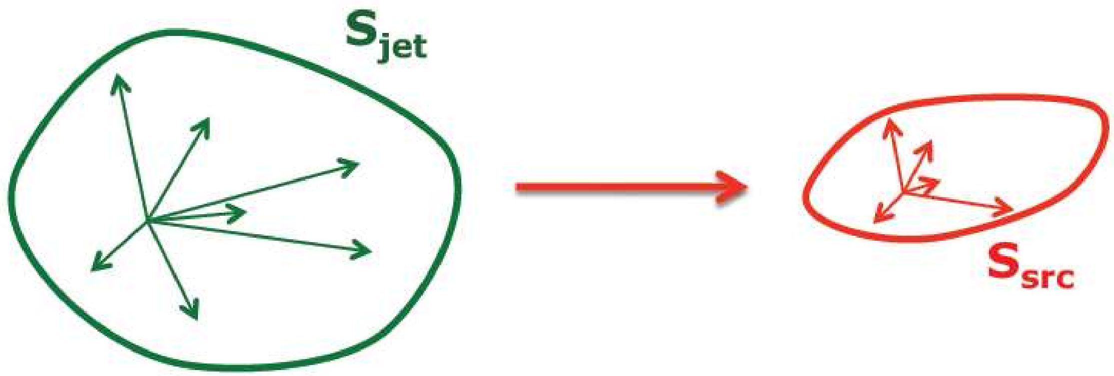
3. Low-angle sound production appears to be driven by a *wavepacket mechanism;* as Mollo-Christensen (1968) suggested: 'a semi-infinite antenna for sound',

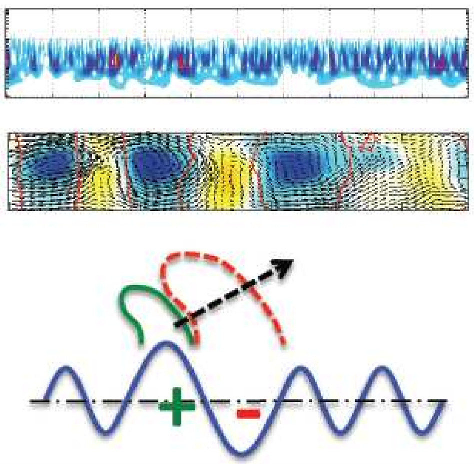
4. *The intermittent dancing of the wavepacket* looks to be a most important source feature.

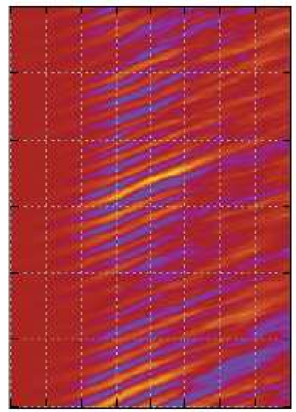
Where are we headed now?

...to search for the reduced-order dynamic law: - EU project ORINOCO
- ANR Chair of excellence TUCOROM (B. Noack)





$$\overset{?}{C(\overline{U}, m_1)}\frac{dm_0}{dt} = \overset{?}{f}(m_0)$$



8. Control of jet noise

PHYSICS OF FLUIDS **20**, 101519 (2008)

Subsonic jet noise reduction by fluidic control: The interaction region and the global effect

E. Laurendeau, P. Jordan, J. P. Bonnet,[a] J. Delville, P. Parnaudeau, and E. Lamballais
LEA Laboratoire d'Études Aérodynamiques, University of Poitiers, ENSMA, CNRS, 43 rue de l'aérodrome, F-86036 Poitiers cedex, France

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Von Karman Lecture Series 2009-02

Control of jet noise

Peter Jordan
Laboratoire d'Etudes Aérodynamiques, UMR-CNRS-6609,
Université de Poitiers, ENSMA, France

6 March 2009

Extremum-seeking optimisation of fluidic jet-noise control

R. Maury[1], M. Koenig[1], L. Cattafesta[2], P. Jordan[1], J. Delville[1] and J-P. Bonnet[1]

[1]Institut Pprime, CNRS-Université de Poitiers-ENSMA, UPR 3346, Département Fluides, Thermique, Combustion, CEAT, Poitiers, FRANCE
[2]MAE Department, University of Florida, Gainesville, FL, USA

49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition

Jet noise control using unsteady converging microjets

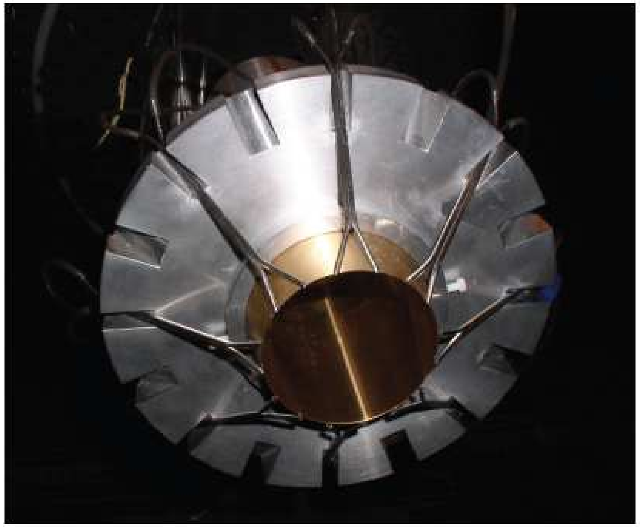
R. Maury* L. Gomes* & P. Jordan* & J. Delville* & J.-P. Bonnet*

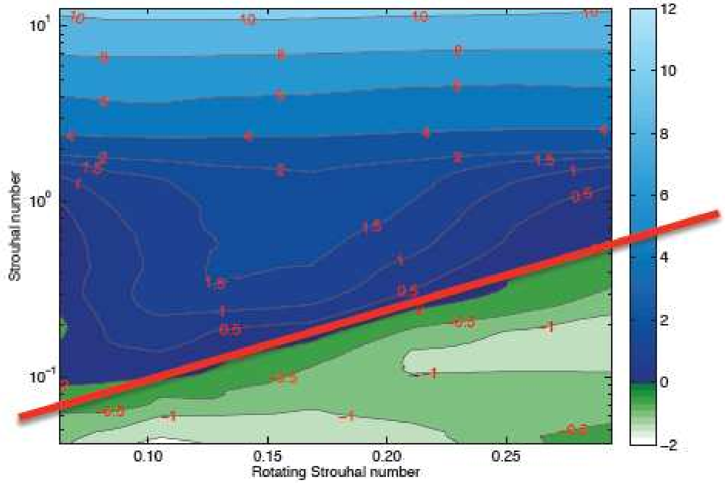
49th AIAA Aerospace Sciences Meeting

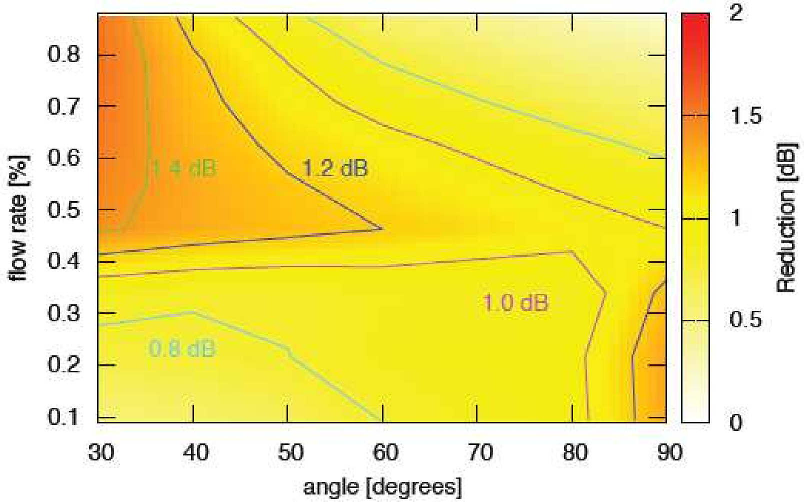
Jet noise control by a fluidic injection via a rotating plug

M. Koenig*†, P. Jordan*, Y. Gervais* & J. Julliard†

7. Control of jet noise







Thanks for your attention