Numerical study of temperature effects on jet turbulence and radiated acoustics

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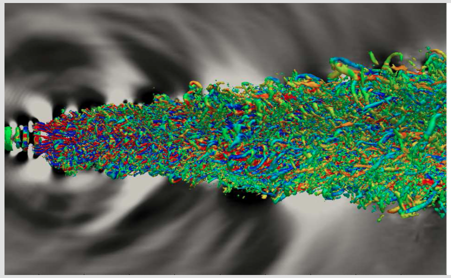
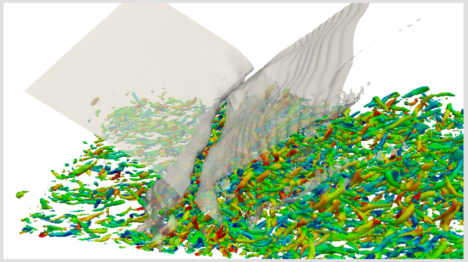
Contexte : calcul haute fidélité

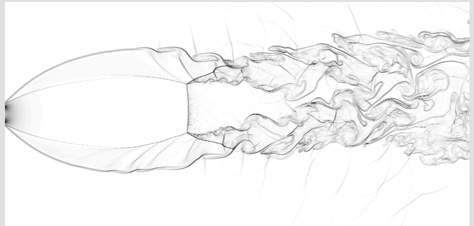
- Petit héritage numérique de Pierre à P' : quelques thèmes compressibles récents



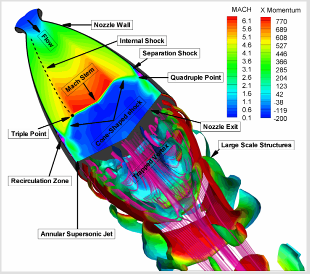
Bruit de jet subsonique
(Daviller, Comte, Jordan)



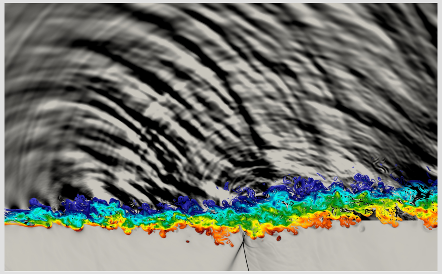
Interaction choc/couche limite
(Shahab, Lehnasch, Comte,Gatski)



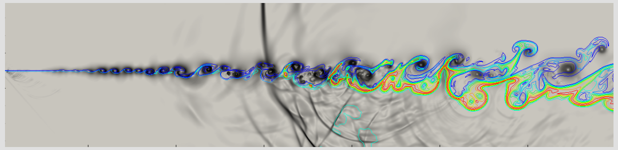
Jets fortement sous-détendus
(Buttay, Lehnasch, Mura)



Décollement en tuyère
(Shams, Lehnasch, Comte)



Interaction choc / couche de mélange
(Daviller, Lehnasch, Jordan)

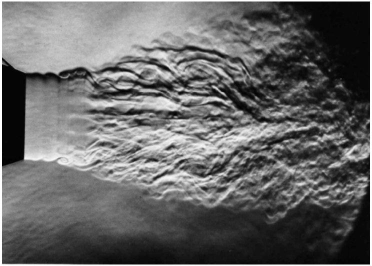


Couche de mélange réactive
(Martinez, Lehnasch, Mura)

- **NIGLO** (DNS/LES) pour la recherche fondamentale :
  - ➔ "C'est le niglo de Django, mignon mais piquant !"
  - ➔ compromis coût / précision, mais vers la précision avant tout !
  - ➔ Vers situations complexes (chocs, géométries, multiespèces réactif)

Background

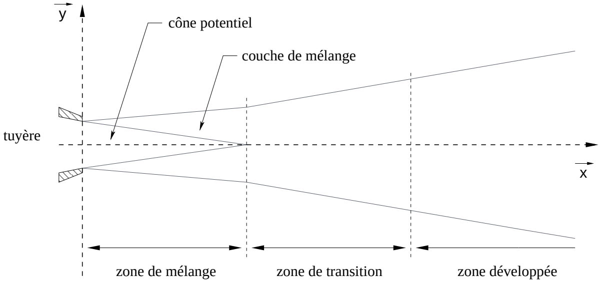
- Lighthill's theory in 1952
- Understanding of jet noise inherently tied to the understanding of turbulence in jet flows
- Real complexity of the developing turbulent flow



Bradshaw, Ferriss & Johnson (JFM 1964), from Van Dyke (1982).

- Role of coherent structures in turbulent mixing (Brown & Roshko, 1974)
- Organized structures remain present at high-Reynolds Number
- Contribution of coherent structure to the acoustic field (Mollo-Christensen et *al.*, 1960)

Background : Noise source identification



Flow regions in a subsonic jet

- 3 different regions in a turbulent jet
- Most powerful generation of sound occurs near the end of the potential core
- Coherent structures observed in the initial mixing-layer region
- First source : advection of coherent structures (Crow, 1972)
- Second source : "fine scale turbulence" (Mollo-Christensen et *al.* 1960, Tam 1998)

Background : temperature effects

- Noise from heated subsonic jet studied since the early 1970s
- Additional dipole term associated with temperature fluctuations (Fisher, 1973)
- Acoustic Mach number dependance of the temperature effect (Tanna 1977)
- Heating a jet at $M_a = U_j/c_\infty < 0.7$ increased the sound level
- Heating a jet at $M_a = U_j/c_\infty > 0.7$ decreased the radiated sound
  => SPL decrease in the high frequencies

- Mean flow results when heating jet at constant velocity (Lau, 1979) :
  => decreased the potential core length
  => increased rate of centerline velocity decay
  => increased the turbulence intensity

=> Mechanisms by which these changes is affected not yet understood.

Background : temperature effects

Bodony & Lele (2008) => “on the quieting of high-speed jets with heating”

- LES database of unheated jets ($M_j = 2$) & heated jets ($M_j = 1$) at $M_a = 1.5$
- Analysis of the sound radiated using Lighthill’s analogy (1952)

$$\frac{\partial^2 \rho'}{\partial t^2} - c_\infty^2 \frac{\partial^2 \rho'}{\partial x_i \partial x_j} \delta_{ij} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}$$

- Lighthill’s tensor :

$$T_{ij} = \rho u_i u_j + (p' - c_\infty^2 \rho')\delta_{ij} - \tau_{ij}$$

$(p' - c_\infty^2 \rho')\delta_{ij}$: entropy source term
τ_{ij} : viscous shear stress tensor (found negligible)

=> Strong anti-correlation between the the far-field contribution of the momentum and entropy terms

Temperature effects investigation

Source terms structure differences in the turbulence of heated and isothermal round jet :

- Momentum decomposition Bodony & Lele (2008) :

$$\rho u_i u_j = \overline{\rho}\,\overline{u}_i\overline{u}_j + \underbrace{\overline{\rho}(\overline{u}_i u'_j + u'_i\overline{u}_j)}_{L_1} + \underbrace{\rho'\,\overline{u}_i\overline{u}_j}_{L_2} + \underbrace{\rho'(\overline{u}_i u'_j + u'_i\overline{u}_j)}_{Q_1} + \underbrace{\overline{\rho} u'_i u'_j}_{Q_2} + \underbrace{\rho' u'_i u'_j}_{C}$$

  - $\overline{\rho}\,\overline{u}_i\overline{u}_j$: only a mean component, does not radiate sound => not considered.
  - L_1 and L_2 linear in the fluctuations
  - Q_1 and Q_2 quadratic in the fluctuations
  - C is cubic
- Entropy term : $p' - c_\infty^2 \rho'$
- Analysis based on Fourier modes decomposition in the azimuthal direction

$$q'(x, r, \theta, t) = \frac{a_0(x, r, t)}{2} + \sum_{n=1}^{N} [a_n(x, r, t)cos(n\theta) + b_n(x, r, t)sin(n\theta)]$$

=> Comparing low-order azimuthal modes of the turbulence get some insight regarding the effect of temperature on the most acoustically efficient flow scales.

Compressible LES approach : “Le code, c’est le nerf de la guerre” P. Comte 2007

Present work (NIGLO 7.0) :

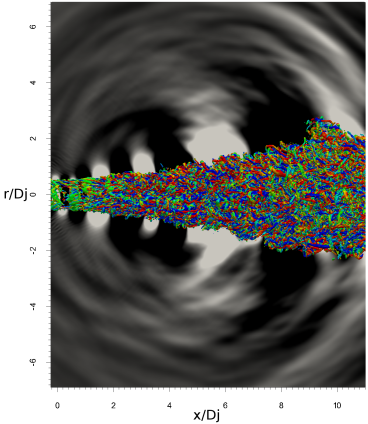
- Macro-pressure $\bar{\varpi}$ & Macro-temperature ϑ (Lesieur & Comte, 2001)
- Turbulent eddy viscosity ν_{sgs} : Filtered Structure Function model (Ducros 1996)

- Super-scalar parallelisation & optimisation (up to 4096 proc. on Babel at IDRIS)
- 4th-order explicit differencing scheme (McCormack-type)
- 3D-NSCBC non-reflective open boundary conditions (Lodato & al., 2008)
- MPI parallelisation, Domain decomposition
- Input/Output optimisation using MPI-IO library

Current version (NIGLO 9.0) :

- Scalability optimisation (up to 32768 proc. on Curie at CEA)
- High-order low dissipative scheme (4, 6, 8, DRP & Compact) & RK4
- Skew symmetric formulation
- Hybrid scheme (with WENO 3, 5 & 7 order) & Shock sensors
- Add SGS model : MSM, DSM, Vortex-streched model

Exemple : LES of single jets



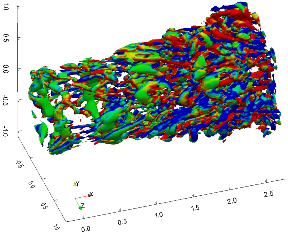
Isothermal jet : Positive $Q = 0.5(U_j/D_j)^2$ isosurfaces coloured by the streamwise vorticity $0.8 \leq \Omega_x \leq 0.8$, fluctuating pressure field $-150Pa \leq P \leq 150Pa$

	Jet 1	Jet 2
$M_j = U_j/c_j$	0.9	0.54
$M_a = U_j/c_\infty$	0.9	0.9
$Re_j = U_jD_j/\nu_j$	4×10^5	4×10^5
$D_j(m)$	0.02	0.1
T_j/T_∞	1	2.7

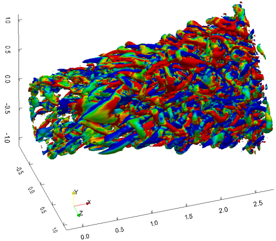
- Momentum thickness $\delta_\theta = 0.05r_o$
- $\Delta_o = r_o/32$
- $[30D_j \times 20D_j \times 20D_j]$
- $\sim 200 \times 10^6$ points
- Typicall run time : $\simeq 10$ days using 512 processor IBM Power6 (IDRIS).

Temperature effects on initial shear layer developpment

$Q = 0.5(U_j/D_j)^2 > 0$ isosurfaces coloured by the streamwise vorticity $0.8 \leq \Omega_x \leq 0.8$



$T_j/T_\infty = 1$



$T_j/T_\infty = 2.7$

Hypothesis :

=> Baroclinic torque : $\dfrac{1}{\rho^3}\vec{\nabla}\rho \times \vec{\nabla}p$

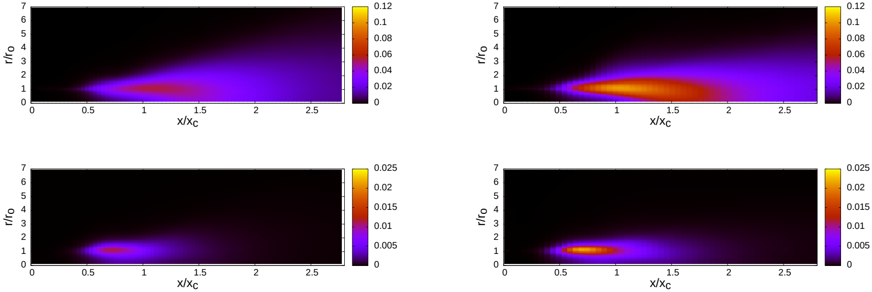
=> Should be a source of vorticity? Origin of secondary Kelvin-Helmholtz instability ?

Temperature effects in round jets : Turbulence kinetic energy & Pressure fluctuation levels

$T_j/T_\infty = 1$ $\qquad$ $T_j/T_\infty = 2.7$

$\frac{1}{2}\frac{\langle \bar{\rho} u_i' u_i' \rangle}{\rho_j U_j^2}$

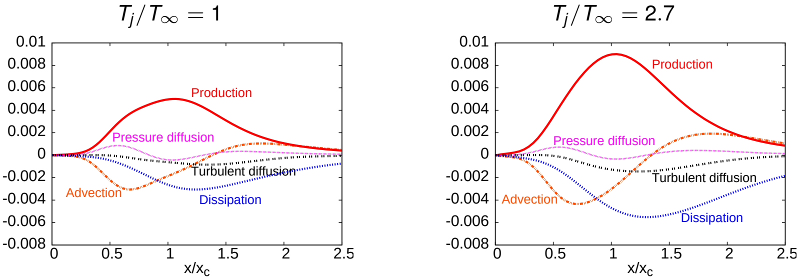
$\frac{\langle p' p' \rangle}{\rho_j^2 U_j^4}$



- Higher levels in the heated jet : effect of the time-averaged local density
  => generation of locally high levels of momentum fluctuation
  => Higher levels of local acceleration and fluctuating pressure
- tke : peak at $x/x_c = 1$, $\qquad < p'p' >$: peak at $x/x_c \simeq 0.7$
- Trend reversed with respect to the ambient conditions (acoustic analogy)

Temperature effects on tke budget

Radialy integrated turbulence kinetic energy budget normalized by $\rho_j U_j^3 / D_j$
(Axial distance normalized by jet's potential core length)

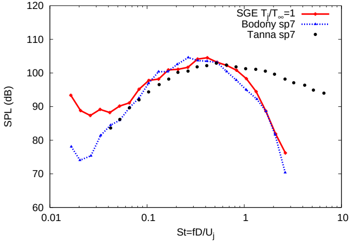


- Plotted terms close TKE budget by less than 10%
- Production initially balanced by mean transport upstream of the potential core
- Viscous & SGS dissipation act downstream of the potential core
- At $x/x_c > 1.25$ viscous dissipation is the only sink
- Higher TKE production, mechanism : baroclinic torque?

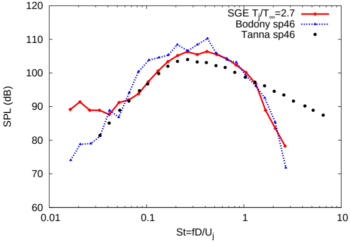
Temperature effects in round jets : Acoustic field

Far-field third-octave sound spectra at $\theta = 45^\circ$ for a point at $72D_j$ from the jet exit.

$T_j/T_\infty = 1$



$T_j/T_\infty = 2.7$

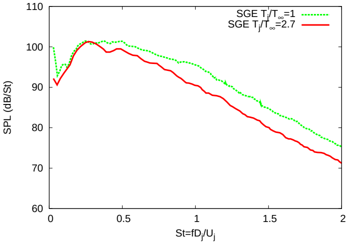


- SPL overestimated for lower frequency $St \leq 0.07$
- SPL decrease in the higher frequency $St > 1$ due to the low-pass nature of the LES, and the limited grid resolution
- SPL peak overestimated by $\sim$ 2dB in the isothermal case and by $\sim$ 5dB in the heated case.

Temperature effects in round jets : Acoustic field

Far-field sound spectra at $\theta = 35^\circ$ for a point at $7.5D_j$ from the jet exit.

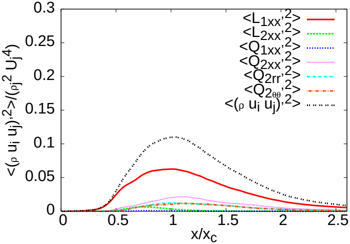
- Decrease of SPL in high frequency with heating
- SPL level in low frequency similar
- Results in agreement with experimental observations (see Tanna 1977)



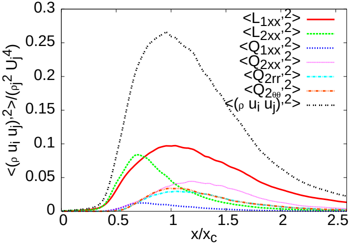
Temperature effects on Lighthill's tensor source terms on the jet lipline

$$\rho u_i u_j = \overline{\rho}\,\overline{u}_i\overline{u}_j + \underbrace{\overline{\rho}(\overline{u}_i u'_j + u'_i\overline{u}_j)}_{L_1} + \underbrace{\rho'\overline{u}_i\overline{u}_j}_{L_2} + \underbrace{\rho'(\overline{u}_i u'_j + u'_i\overline{u}_j)}_{Q_1} + \underbrace{\overline{\rho}u'_i u'_j}_{Q_2} + \underbrace{\rho' u'_i u'_j}_{C}$$

$T_j/T_\infty = 1$



$T_j/T_\infty = 2.7$

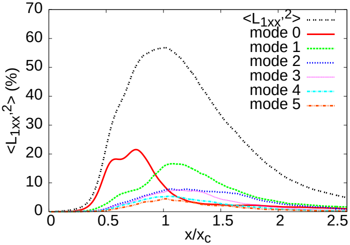


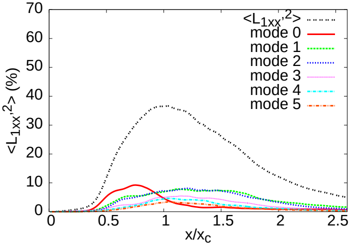
- Heated jet present higher level of momentum fluctuation
- $L_{1_{xx}}$ dominates near the potential core $x/x_c = 1$ (shear noise)
- $Q_{2_{xx}}$ dominates downstream of the potential core $x/x_c = 1.25$ (self-noise)
- Heated jet : $L_{2_{xx}}$ dominate upstream of the potential core $x/x_c = 0.7$

Temperature effects on Lighthill's tensor source terms : azimuthal structure of $L_{1_{xx}}$

$\langle L'^2_{1_{xx}} \rangle = \langle (2\bar{\rho}\bar{u}_x u'_x)'^2 \rangle$ taken on cylindrical surface with radius $r = r_o$.

$T_j / T_\infty = 1$ | $T_j / T_\infty = 2.7$





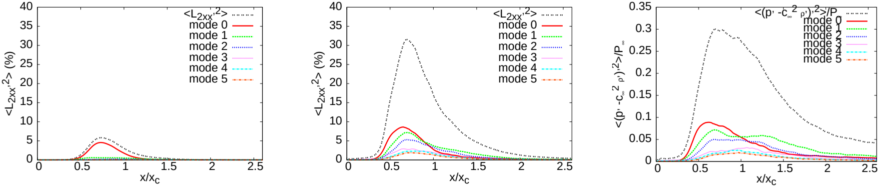
- Far-field $T_j / T_\infty = 1$: $L_{1_{xx}}$ dominates for $St < 0.5$ at 30° (Bodony & Lele , 2008)
- Axisymmetric mode $m = 0$ dominates upstream the potential core
- Helical mode $m = 1$ dominates downstream the potential core
- Relative energy of mode $m = 2$ similar to those of mode $m = 1$ in the heated case
- Isothermal case : Non-linear interaction between Fourier mode $m = 0, 1$ (Cavalieri et *al.* 2010)

Temperature effects on Lighthill's tensor source terms : azimuthal structure of $L_{2_{xx}}$ and $(p' - c_\infty \rho')$

$\langle L'^2_{2_{xx}} \rangle = \langle (\rho' \bar{u}_x \bar{u}_x)'^2 \rangle$

$T_j/T_\infty = 1$ — $T_j/T_\infty = 2.7$

$(p' - c_\infty \rho')$ — $T_j/T_\infty = 2.7$

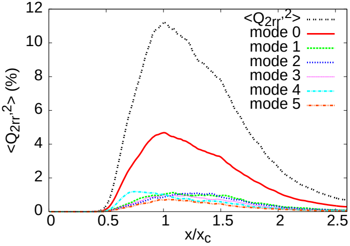


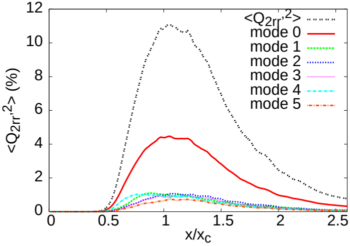
- Far-field $T_j/T_\infty = 1$: $L_{2_{xx}}$ dominates for $St \geq 0.5$ at 30° (Bodony & Lele , 2008)
- Far-field $T_j/T_\infty = 2.7$: $L_{2_{xx}}$ dominates SPL at 30° (Bodony & Lele , 2008)
- Peak location and mode ordering is similar for $L_{2_{xx}}$ and $(p' - c_\infty \rho')$
- Contributions of these two terms closely correlated to the far-field at low angles (Bodony & Lele , 2008)
- Correlation between momentum and entropy terms in the far-field causes cancellation

Temperature effects on Lighthill's tensor source terms : azimuthal structure of $Q_{2_{rr}}$

$\langle Q'^2_{2_{rr}} \rangle = \langle (\bar{\rho} u'_r u'_r)'^2 \rangle$ taken on cylindrical surface with radius $r = r_o$.

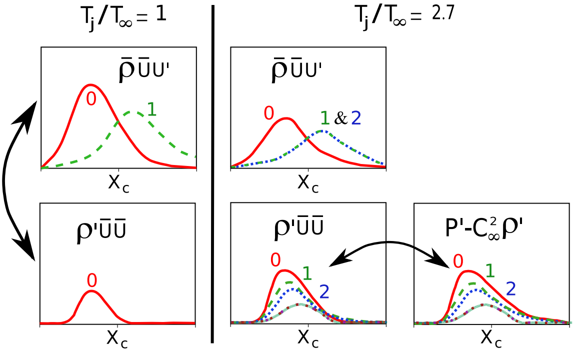
$T_j / T_\infty = 1$ $T_j / T_\infty = 2.7$





- $Q_{2_{rr}}$ dominates far-field SPL at 90° (Bodony & Lele , 2008)
- Relative energy and modal distribution similar for both jets

Temperature effects on Lighthill's tensor source terms : summary (jet's lipline $r = r_o$)



- $T_j/T_\infty = 1$: $L_{2_{xx}}$ contribution due to weak compressibility effect (velocity fluctuations)
- $T_j/T_\infty = 2.7$: $L_{2_{xx}}$ contribution due to temperature (entropy) effect
- Needs far-field prediction using acoustic analogy to complete study

Conclusion

Temperature effect on subsonic round jet :

- Performed a detailled description of the change in the near field
- Heating a jet at constant velocity increases the energy of higher Fourier mode
- Relation between linear momentum and entropy terms in the initial development of heated jet
- Increase of turbulent activity when heating a jet at constant velocity

Conclusion

Temperature effects on subsonic round jets :

- Differences in azimuthal organisation of the lowest order azimuthal modes $m = 0, 1, 2$
- Relative energy contained in modes 3,4 and 5 remains similar in the heated and isothermal flows
- Level of energy contained in mode $m = 2$
- Contribution of the highest order azimuthal mode is coherent with the increase of the turbulent activity in the heated case
- Increase of Production
- $L_{2_{xx}} = \rho' \bar{u}\bar{u}$ contribution
- Entropy contribution

Perspectives

- Numerical issues :
  => Curvilinear algorithm to include part of nozzle
  => other SGS model implementation ?
- Apply Lighthill's tensor decomposition to full domain
- Use acoustic analogy to obtain far-field prediction
- Investigate baroclinic effect in heated jet
  => Baroclinic torque should be a source of vorticity
- Apply analysis on coaxial jets databases

Thanks for your attention

Thanks to :

- P. Comte & P. Jordan