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)
1 Motivation & objectives

2 Numerical Tools : code NIGLO

3 Temperature effects

4 Conclusion
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

- 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
  $\Rightarrow$ SPL decrease in the high frequencies

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

$\Rightarrow$ Mechanisms by which these changes is affected not yet understood.
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
$
\tau_{ij}$ : viscous shear stress tensor (found negligible)

=> Strong anti-correlation between the the far-field contribution of the momentum and entropy terms
Source terms structure differences in the turbulence of heated and isothermal round jet:

- Momentum decomposition Bodony & Lele (2008):
  \[
  \rho u_i u_j = \overline{\rho u_i u_j} + \rho (\overline{u_i u_j'} + u_i' u_j) + \rho' (\overline{u_i u_j'} + u_i' u_j) + \rho u_i' u_j' + \rho' u_i' u_j'
  \]
  \[\text{L}_1 \]
  \[\text{L}_2 \]
  \[\text{Q}_1 \]
  \[\text{Q}_2 \]
  \[\text{C} \]

- \(\overline{\rho u_i u_j}\): only a mean component, does not radiate sound => not considered.
- \(\text{L}_1\) and \(\text{L}_2\) linear in the fluctuations
- \(\text{Q}_1\) and \(\text{Q}_2\) quadratic in the fluctuations
- \(\text{C}\) 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 $\bar{\omega}$ & Macro-temperature $\bar{\theta}$ (Lesieur & Comte, 2001)
- Turbulent eddy viscosity $\nu_{sgs}$: 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-stretched 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 $-150 \text{Pa} \leq P \leq 150 \text{Pa}$

<table>
<thead>
<tr>
<th></th>
<th>Jet 1</th>
<th>Jet 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_j = U_j/c_j$</td>
<td>0.9</td>
<td>0.54</td>
</tr>
<tr>
<td>$M_a = U_j/c_\infty$</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>$Re_j = U_jD_j/\nu_j$</td>
<td>$4 \times 10^5$</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td>$D_j(m)$</td>
<td>0.02</td>
<td>0.1</td>
</tr>
<tr>
<td>$T_j/T_\infty$</td>
<td>1</td>
<td>2.7</td>
</tr>
</tbody>
</table>

- 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
- Typical run time : $\sim 10$ days using 512 processor IBM Power6 (IDRIS).
Temperature effects on initial shear layer development

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

Hypothesis:
=> Baroclinic torque: \[ \frac{1}{\rho^3} \vec{\nabla} \rho \times \vec{\nabla} \rho \]
=> Should be a source of vorticity? Origin of secondary Kelvin-Helmholtz instability?
Temperature effects in round jets: Turbulence kinetic energy & Pressure fluctuation levels

\[ T_j / T_\infty = 1 \]

\[ T_j / T_\infty = 2.7 \]

Higher levels in the heated jet: effect of the time-averaged local density
\[ \frac{1}{2} \frac{\langle \bar{\rho} u'_i u'_i \rangle}{\rho_j U_j^2} \]

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

- Generation of locally high levels of momentum fluctuation
- Higher levels of local acceleration and fluctuating pressure
- \( \text{tke} \): peak at \( x / x_c = 1 \), \( \langle p' p' \rangle \): peak at \( x / x_c \approx 0.7 \)
- Trend reversed with respect to the ambient conditions (acoustic analogy)
Temperature effects on the budget

Radially integrated turbulence kinetic energy budget normalized by $\frac{\rho_j U_j^3}{D_j}$

(Axial distance normalized by jet’s potential core length)

$T_j/T_\infty = 1$

$T_j/T_\infty = 2.7$

- 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 $\sim 2$dB in the isothermal case and by $\sim 5$dB 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

\[
\rho u_i u_j = \bar{\rho} \bar{u}_i \bar{u}_j + \bar{\rho}(\bar{u}_i u'_j + u'_i \bar{u}_j) + \rho' \bar{u}_i \bar{u}_j + \rho'(\bar{u}_i u'_j + u'_i \bar{u}_j) + \rho u'_i u'_j + \rho' u'_i u'_j
\]

\[
T_j / T_\infty = 1
\]

\[
T_j / T_\infty = 2.7
\]

- Heated jet present higher level of momentum fluctuation
- \(L_{1xx}\) dominates near the potential core \(x/x_c = 1\) (shear noise)
- \(Q_{2xx}\) dominates downstream of the potential core \(x/x_c = 1.25\) (self-noise)
- Heated jet: \(L_{2xx}\) dominate upstream of the potential core \(x/x_c = 0.7\)
Temperature effects on Lighthill’s tensor source terms: azimuthal structure of $L_{1,xx}$

$$\langle L_{1,xx}^2 \rangle = \langle (2 \bar{\rho} \bar{u}_x u'_x)^2 \rangle$$ taken on cylindrical surface with radius $r = r_0$.

**Far-field $T_j/T_\infty = 1$:** $L_{1,xx}$ dominates for $St < 0.5$ at $30^\circ$ (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 $L_{2,xx}^2$ and $(\rho' - c_{\infty} \rho')$

$$\langle L_{2,xx}^2 \rangle = \langle (\rho' \bar{u}_x \bar{u}_x)^{\prime 2} \rangle$$

$T_j / T_{\infty} = 1$

Far-field $T_j / T_{\infty} = 1$ : $L_{2,xx}^2$ dominates for $St \geq 0.5$ at $30^\circ$ (Bodony & Lele, 2008)

Far-field $T_j / T_{\infty} = 2.7$ : $L_{2,xx}^2$ dominates SPL at $30^\circ$ (Bodony & Lele, 2008)

Peak location and mode ordering is similar for $L_{2,xx}^2$ and $(\rho' - c_{\infty} \rho')$

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 $Q_{2rr}$**

\[ \langle Q_{2rr}^2 \rangle = \langle (\bar{\rho}u'_r u'_r)^2 \rangle \text{ taken on cylindrical surface with radius } r = r_o. \]

- $Q_{2rr}$ dominates far-field SPL at $90^\circ$ (Bodony & Lele, 2008)
- Relative energy and modal distribution similar for both jets
Temperature effects on Lighthill’s tensor source terms: summary (jet’s plume line $r = r_0$)

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

- Performed a detailed 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
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
- \( L_{2xx} = \rho' \bar{u} \bar{u} \) contribution
- Entropy contribution
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