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Direct noise computation of a Mach 3.30 jet

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Outline

- Introduction
- Present study
  - simulation parameters
  - numerical methods
- Flow field
  - mean flow field properties
  - turbulent flow features along the shear layer
- Acoustic field
  - acoustic near field
  - acoustic far field
- Concluding remarks

Context (1)

- Vibrations at lift off on space launchers induced by acoustic waves
  - propulsive jet noise
  - blast wave
- Propulsive jets properties

  - supersonic flow: $M_e > 2$
  - not perfectly expanded: $p_e \neq p_\infty$
  - very high values of stagnation quantities: $T_r > 1000$ K and $P_r > 25$ bar

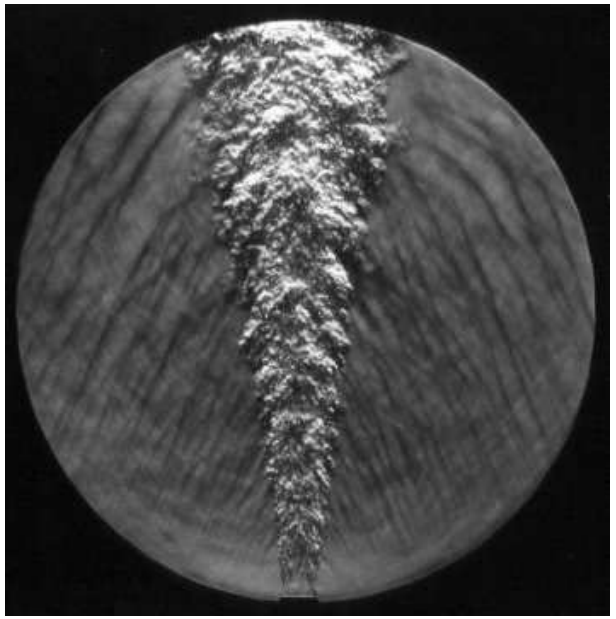
$\rightarrow$ very few experimental facilities exist for these conditions

(in France: MARTEL facility in Poitiers)

$\rightarrow$ numerical simulations difficult but now feasible

Context (2)

- **Radiation mechanisms in supersonic jets**
  - turbulent mixing noise
    Laufer *et al.*, *AIAA J.*, 1976, Panda & Seasholtz, *JFM*, 2002
  - broadband shock-associated noise
    Tam & Tanna, *JSV*, 1982, Seiner & Yu, *AIAA J.*, 1984
  - screech noise
    Powell *et al.*, *JASA*, 1992, Berland *et al.*, *PoF*, 2007
  - Mach wave radiation
    McLaughlin *et al.*, *JFM*, 1975, Tam *et al.*, *AIAA J.*, 1992



He jet at $M_e = 2$
Clemens & Paul, PoF, 1993

- **Radiation mechanisms in propulsive jets** ($M_e > 2$)
  - Mach waves are expected to be dominant
    Tam & Hu, *JFM*, 1989, Tam *et al.*, *AIAA J.*, 1992
  - contribution of other noise radiation mechanisms to be quantified

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Simulation parameters

- **Jet exit conditions**
  - exit quantities : $M_e = 3.3$, $P_e = 0.5$ bar and $T_e = 360$ K ($M_a = 3.47$)
    (stagnation temperature $T_r = 1144$ K)
  - boundary layer thickness at the nozzle exit : $\delta/r_e = 0.05$
  - maximum velocity fluctuations at the nozzle exit : $u'_{rms}/u_e = 0.3\%$

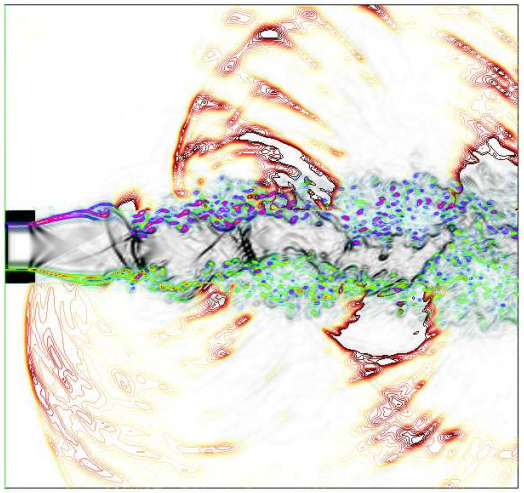
	Mach M_e	Pressure P_e	Temperature T_e	Reynolds Re
Present computation	3.30	0.50×10^5 Pa	360 K	0.94×10^5
Experiment*	3.27	0.51×10^5 Pa	359 K	17.5×10^5

* Varnier & Gély, *RT 112/3643, 1998*

- **LES numerical parameters**
  - cylindrical mesh : $n_r \times n_z \times n_\theta = 256 \times 840 \times 128 = 28 \times 10^6$ points
  - CPU time : 500 hours on a NEC SX-8 (120,000 iterations)
- **Far-field wave extrapolation**
  - LES data are propagated to $r = 80 r_e$ from the nozzle exit
  - full non linear Euler equations are solved on a grid containing 210×10^6points
- **Cut-off Strouhal number and simulation time**
  - $St_c \approx 1.4$; $T = 540 T_c = 540 D_e/U_e$

Numerical approach

- **Direct Noise Computation**
  - aerodynamic and acoustic fields are solved simultaneously using Navier-Stokes equations
  - successful applications to subsonic and supersonic jets



Berland, Bogey & Bailly
Phys. of Fluids, 2007

- **Large-Eddy Simulation based on Relaxation-Filtering**
  Bogey & Bailly, *J. Fluid Mech.*, 2009, 626
- **In-house finite-difference solver**
  - low-dissipation and low-dispersion schemes
    Bogey & Bailly, *J. Comput. Phys.*, 2004, 194(1)
    Berland, Marsden, Bogey & Bailly, *J. Comput. Phys.*, 2007, 224
  - non-reflective boundary conditions and sponge zone
    Bogey & Bailly, *Acta Acustica*, 2002, 88(4)
  - adaptative and conservative shock-capturing method
    Bogey, de Cacqueray & Bailly, *J. Comput. Phys.*, 2009, 228(5)

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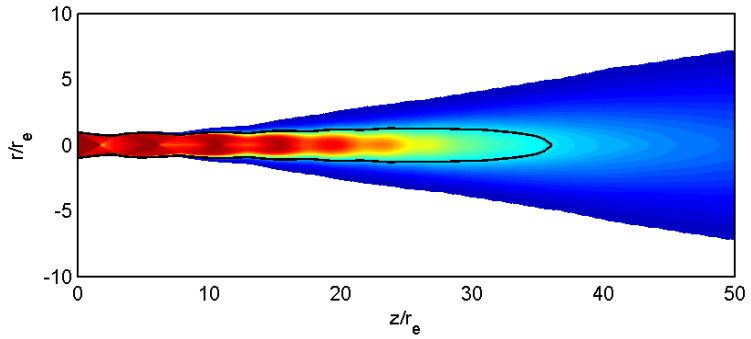
Mean flow field properties

- **Mean axial velocity**

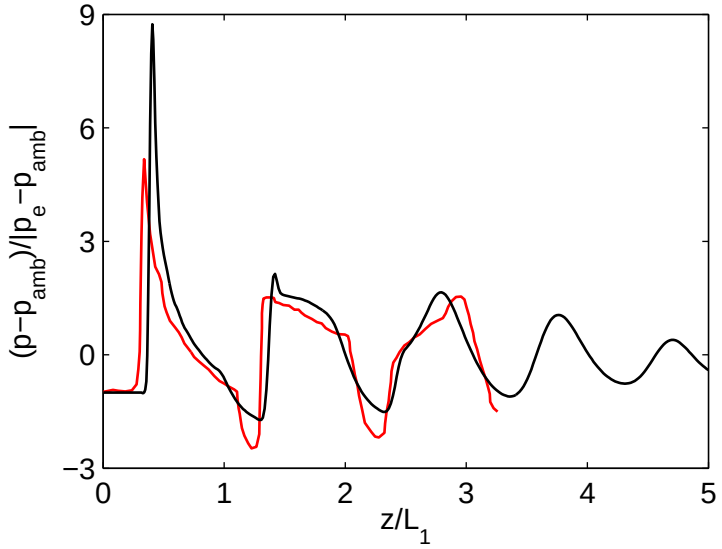


– **sonic core :** $L_s = 36r_e$

– **potential core :** $L_c = 20r_e$

– **MARTEL exp. :** $L_s = 50r_e$ **and** $L_c = 24r_e$

- **Centerline mean static pressure**



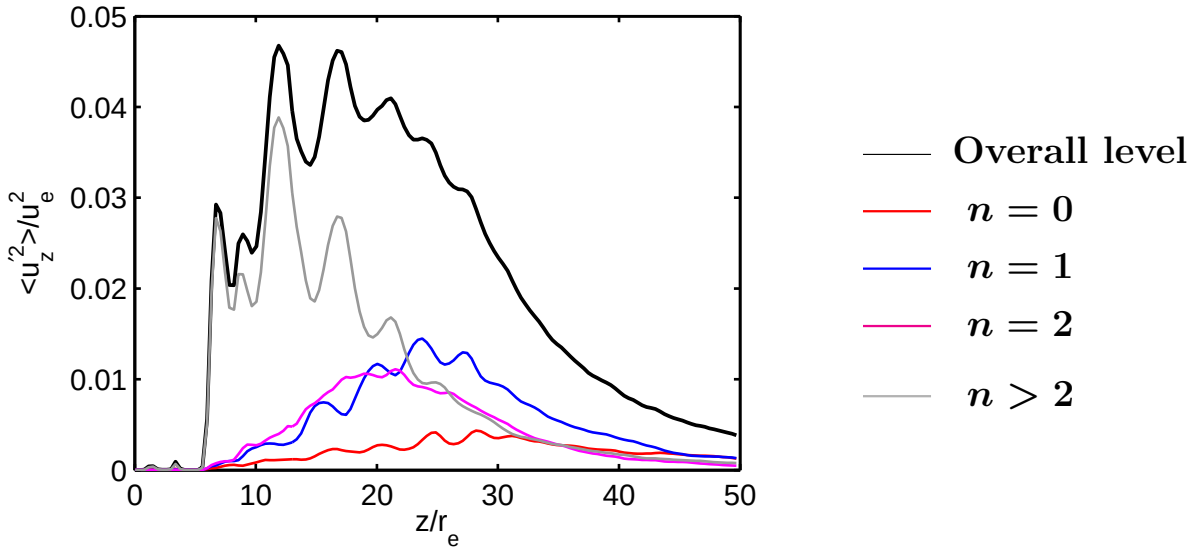
	M_e	M_j	L_1	$\lvert p_e - p_{amb}\rvert$
Present LES	3.3	2.83	$4.6r_e$	0.5×10^5 Pa
N & S⋆	2	1.82	$3r_e$	0.2×10^5 Pa

vspace/3cm ⋆ Norum & Seiner, *NASA TM 84521, 1982*

→ **the shape of the first three shocks agrees reasonably well with experimental data (with proper scaling)**

Turbulent flow (1)

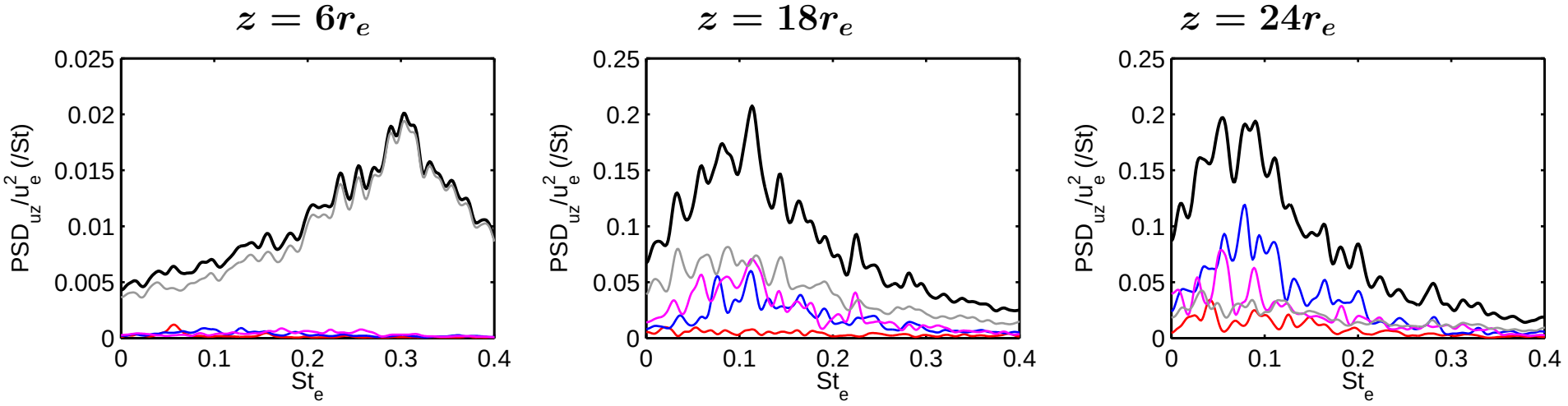
- **Longitudinal turbulent fluctuations and azimuthal decomposition along $r = r_j$**



  - **before the end of the potential core: $(z < 20r_e)$**
    - **$\rightarrow$ azimuthal modes $n > 2$ dominate**
    - **$\rightarrow$ contribution of modes $n = 0$, $n = 1$ and $n = 2$ increases with axial distance**
    - **$\rightarrow$ mode $n = 0$ has a low contribution**
  - **after the end of the potential core: $(z > 20r_e)$**
    - **$\rightarrow$ mode $n = 1$ dominates**

Turbulent flow (2)

- **Frequency analysis of modal components of u'_z at $z = 6$, 18 and 24, for $r = r_j$**

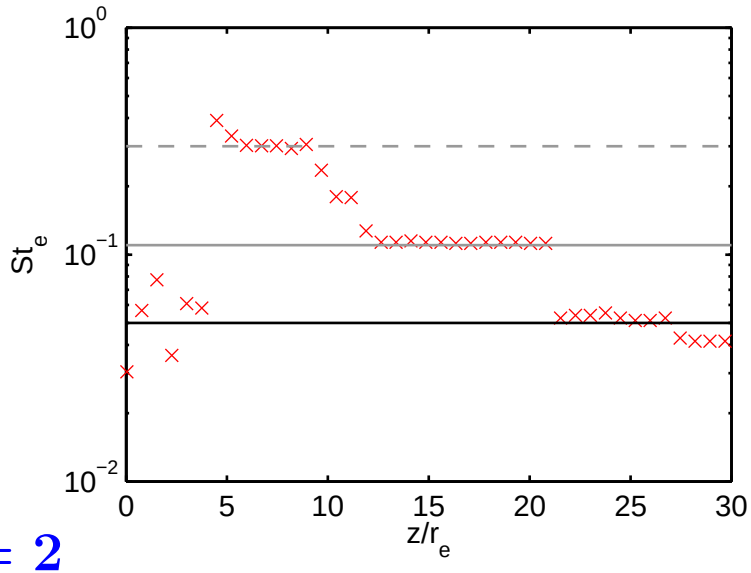


— Overall level, — $n = 0$, — $n = 1$, — $n = 2$ and — $n > 2$

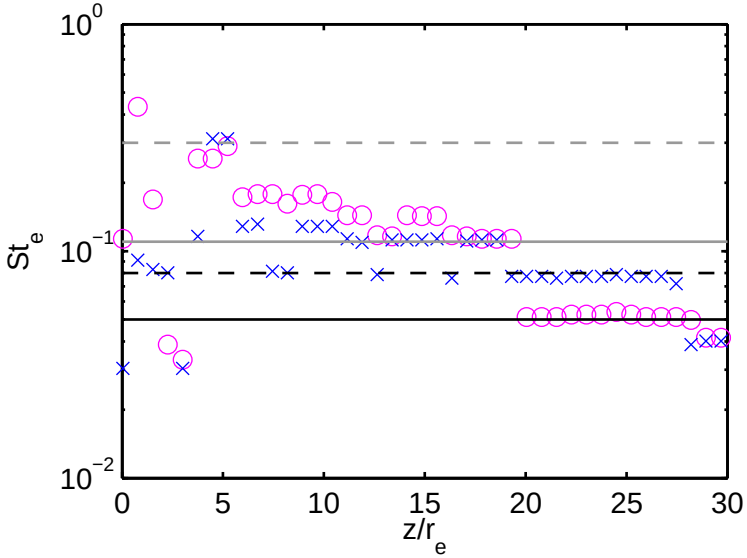
- $z = 6r_e$: connections between the peak at $St_e = 0.3$ and higher order modes
- $z = 18r_e$: peaks at $St_e = 0.08$, 0.11 and 0.22
- $z = 24r_e$:
  - → peaks at $St_e = 0.05$, 0.08, 0.09 and 0.11
  - → the peak at $St_e = 0.08$ seems connected to mode $n = 1$
  - → mode $n = 0$ emerges with a maximum at $St_e = 0.04$

Turbulent flow (3)

- **Peak Strouhal numbers of u'_z at $r = r_j$**
  - before the end of the potential core ($z < 20r_e$)
    → peaks at $St_e = 0.3$ and $St_e = 0.11$
    → connected to a change of shock motion
  - after the end of the potential core ($z > 20r_e$)
    peaks at $St_e = 0.05$



- **Peak Strouhal numbers of modes $n = 1$ and $n = 2$**
  - before the end of the potential core ($z < 20r_e$)
    → peaks between $St_e = 0.1$ and $St_e = 0.17$
    → peaks at $St_e = 0.08$ for $n = 1$
    are also noticed
  - after the end of the potential core ($z > 20r_e$)
    → peaks at $St_e = 0.05$ for mode $n = 2$
    → peaks at $St_e = 0.08$ for mode $n = 1$



x n=1, o n=2

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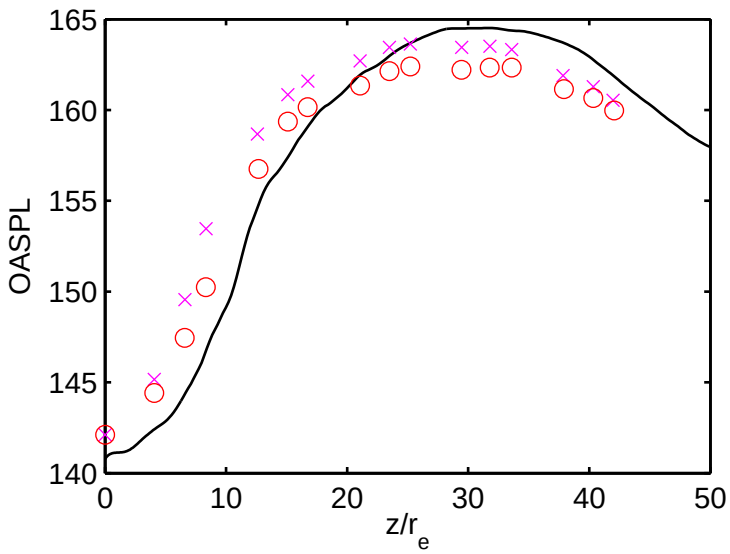
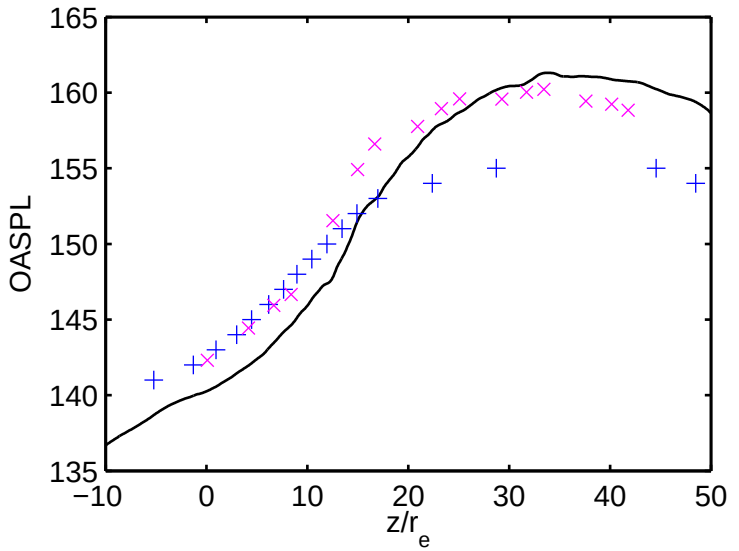
Near field OASPL

- **Overall pressure levels at $r = 9.5r_e$**
  - measurements of Greska *et al.*:
    present LES $M_e = 3.3$ $M_j = 2.83$ $M_a = 3.5$
    Greska exp. $M_e = 2$ $M_j = 2$ $M_a = 3$
    (* AIAA Paper 2008-3026)
  - maximum of OASPL around $z = 30r_e$
  - rapid growth between $z = 7r_e$ and $z = 20r_e$



× $r = 8r_e$ and o $r = 10r_e$

- **Overall pressure levels at $r = 16r_e$**
  - measurements of Greska *et al.* and V&G
    AIAA Paper 2008-3026
    Varnier & Gély, ONERA, RT 112/3643
  - 5dB difference between V&G and Greska
    (effect of Reynolds number, nozzle exit conditions or reservoir conditions?)



× Greska *et al.* and + V&G

→ good agreement between computation and experiments

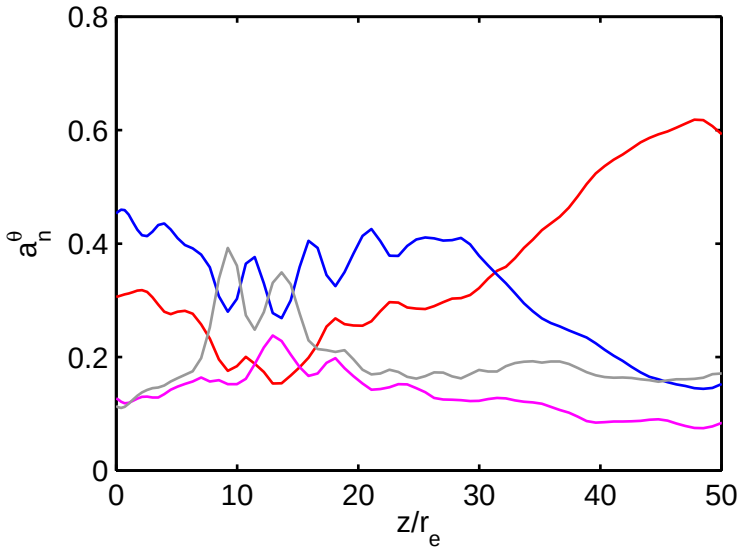
Acoustic near field at 9.5 radii (1)

- **Azimuthal decomposition**
  - **azimuthal cross-correlation functions:**

$$R^{\theta}(\delta\theta) = \frac{< p'(\theta)p'(\theta+\delta\theta) >}{< p'^2(\theta) >^{1/2} < p'^2(\theta+\delta\theta) >^{1/2}}$$

  - **Fourier sum:**

$$R^{\theta}(\delta\theta) = \sum_{n=0}^{\infty} a_n^{\theta} \cos(n\delta\theta)$$



$\rightarrow$ modes $n = 0$ and $n = 1$ are predominant

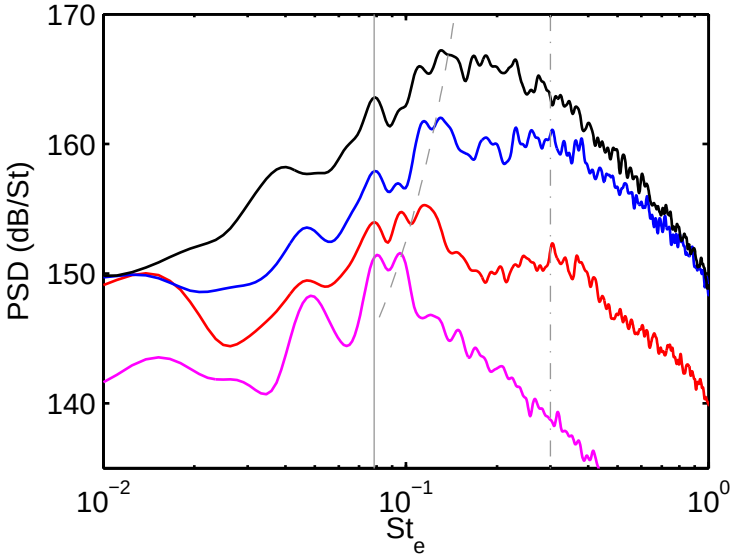
$\rightarrow$ the acoustic field is less correlated between $z = 7r_e$ and $z = 16r_e$

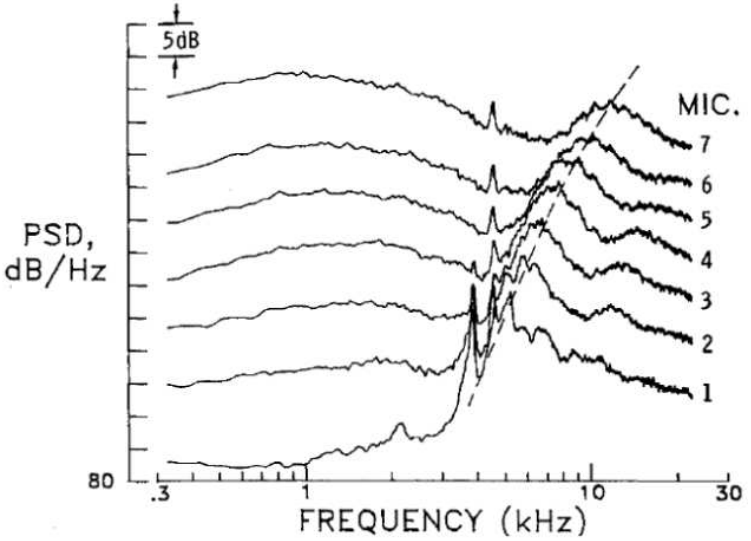
$n = 0$, $n = 1$, $n = 2$ and $n > 2$

Acoustic near field at 9.5 radii (2)

- Acoustic spectra between $z = 0$ and $z = 20r_e$

$z = 0$
$z = 10r_e$
$z = 15r_e$
$z = 20r_e$





Seiner & Yu, *AIAA J.*, 1984
$M_e = 1.45$
$p_e/p_{amb} = 0.79$

– upstream propagating shock-associated noise (Tam *et al.*, *JSV*, 1986)

$$St_{up} = \frac{2r_e u_c/u_e}{L_{shock}(1 + M_c)} = 0.079$$

– low-frequency component observed at $St_e = 0.05$

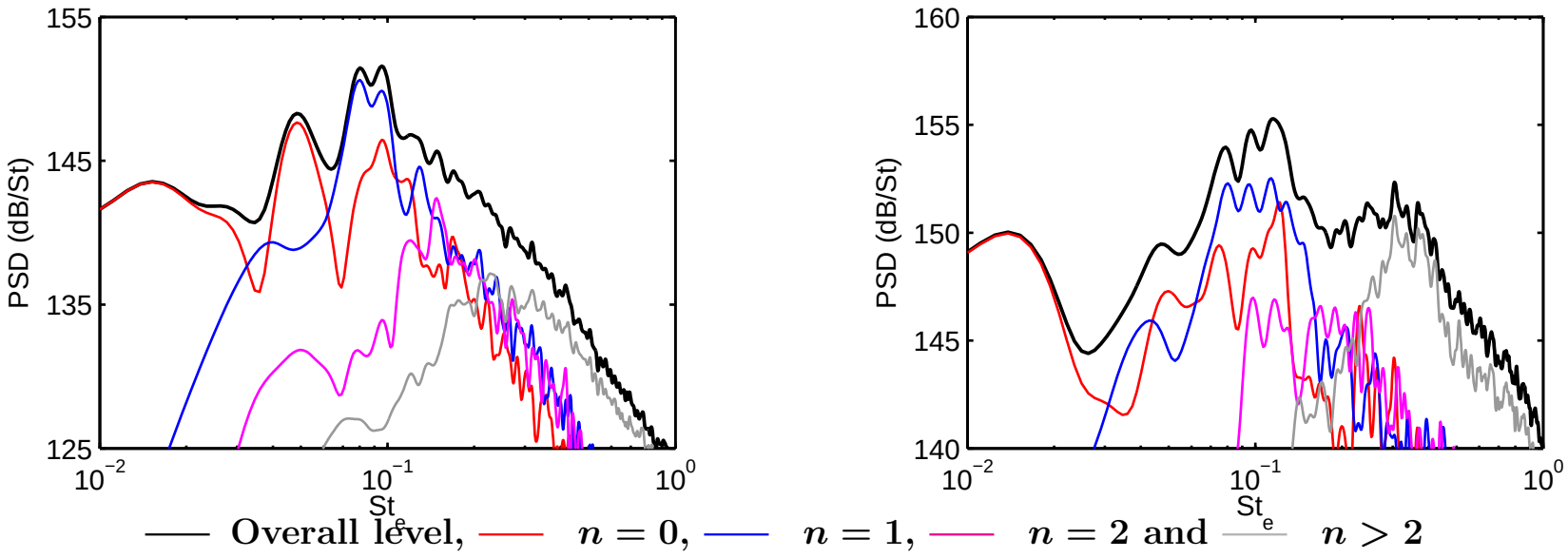
– 'high-frequency' broadband noise around $St_e = 0.3$

– broadband spectra at $z = 20r_e$

– a qualitative agreement is noticed with near-field measurements by Seiner & Yu for the moving peak

Acoustic near field at 9.5 radii (3)

- **Azimuthal decomposition at $z = 0$ and $z = 10r_e$**

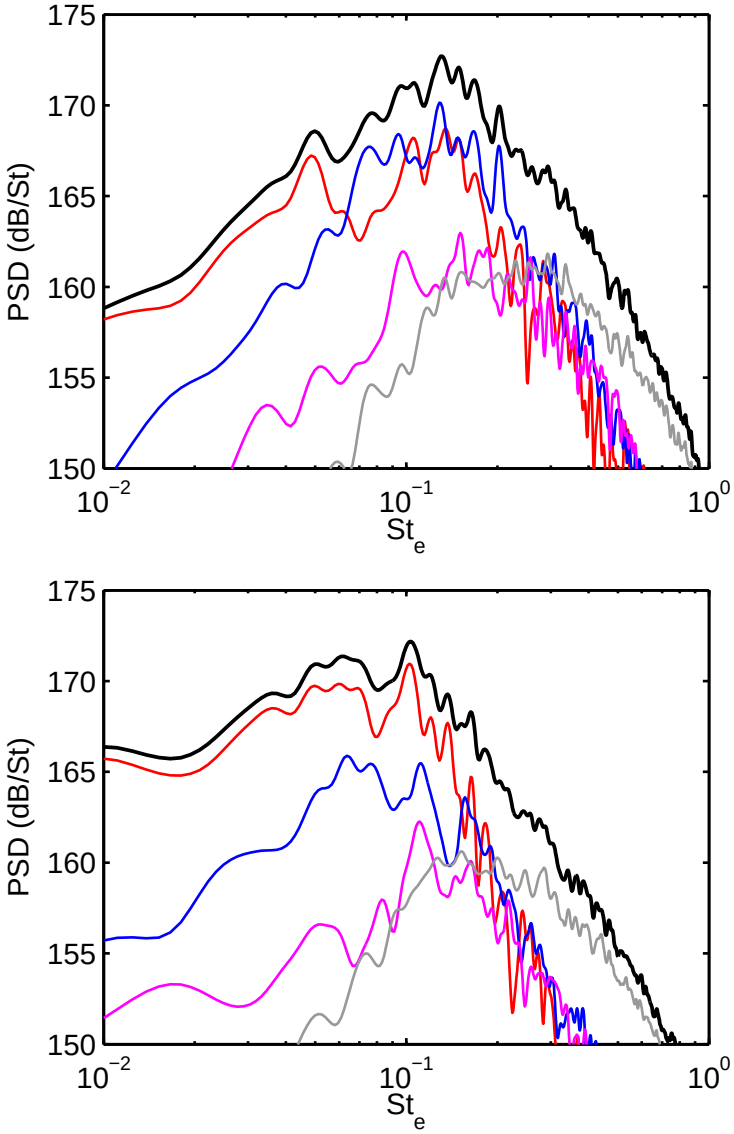


– modes $n = 0$ and $n = 1$ dominate for low frequencies
  → peak at $St_e = 0.05$ associated with mode $n = 0$
  → peak at $St_e = 0.08$ associated with mode $n = 1$

– at $z = 10r_e$, the broadband noise centered at $St_e = 0.3$ is linked to azimuthal modes higher than 2

Acoustic near field at 9.5 radii (4)

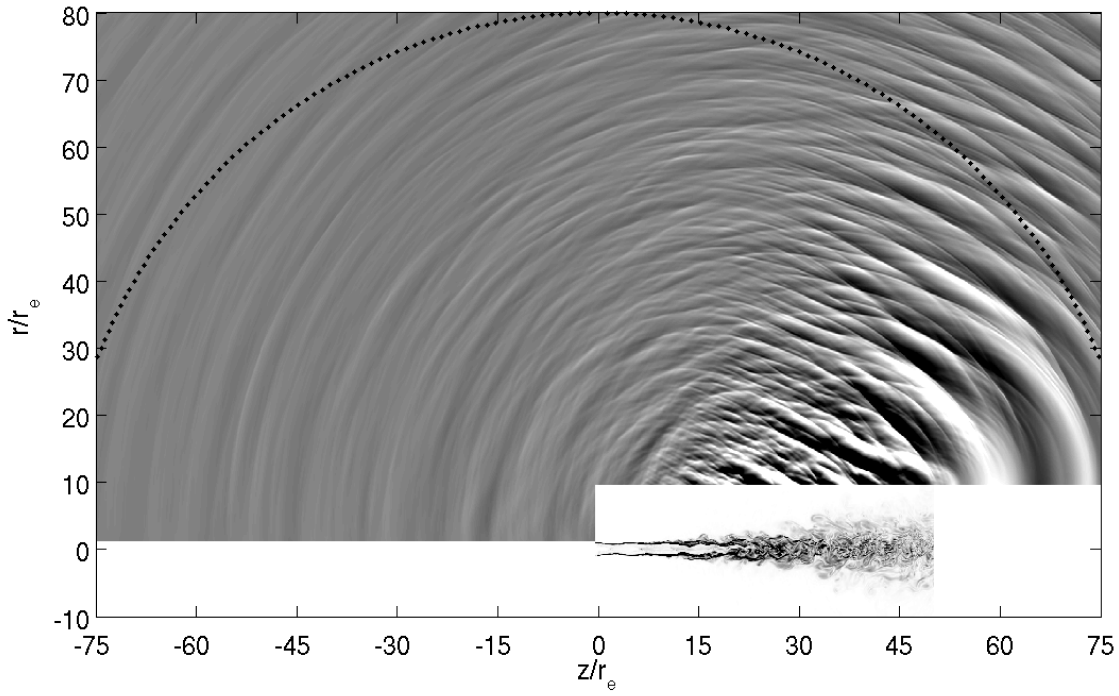
- **Azimuthal decomposition at $z = 30r_e$**
  - $z = 30r_e$ corresponds to the maximum of the OASPL
  - modes $n = 0$ and $n = 1$ dominate
  - the maximum at $St_e = 0.13$ is linked to mode $n = 1$
  - a peak at $St_e = 0.05$ is linked to mode $n = 0$
- **Azimuthal decomposition at $z = 40r_e$**
  - mode $n = 0$ dominates
  - two peaks at: $St_e \approx 0.055$ and $St_e = 0.1$ (axial velocity fluctuations after end of potential core: $St_e = 0.05$



—— Overall level, —— $n = 0$, —— $n = 1$, —— $n = 2$ and —— $n > 2$

Acoustic far field (1)

- **Acoustic far field**

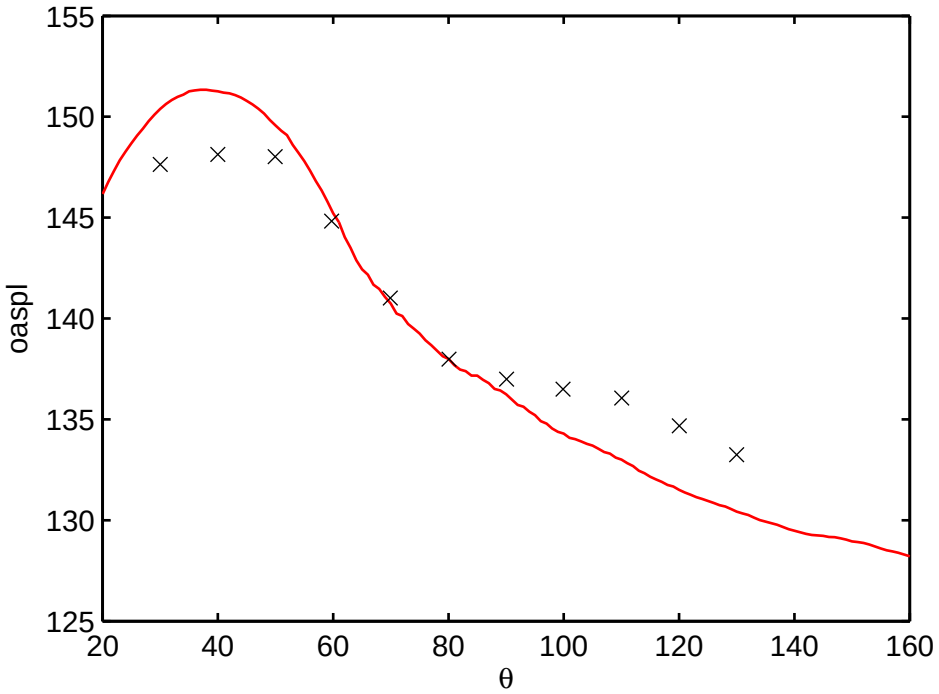


  - acoustic waves are propagated to a distance of 80 radii, starting from a control surface located at $r = 9.5r_e$
  - full (non linear) Euler equations are solved
  - same numerical methods are used including the shock-capturing procedure

Mach wave radiation apparent for $\theta = 60°$ (very close to expected value $cos\theta = 1/M_c$)

Acoustic far field (2)

- **Far field SPL compared to experimental data**



present computation

× Martel data, X. Robin

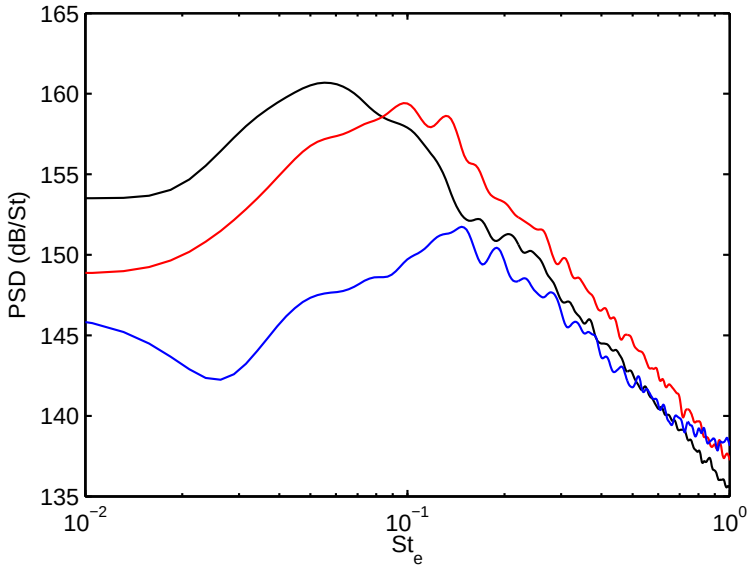
– **good agreement with experimental data**

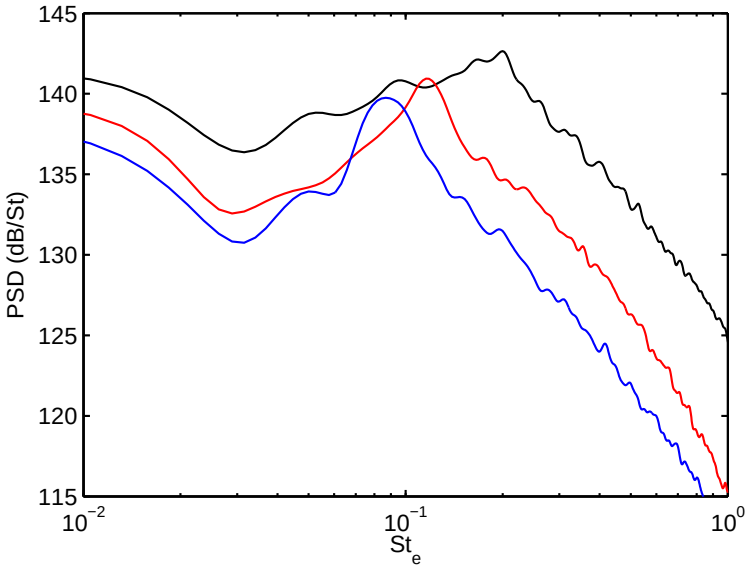
– **peak SPL 3-4 dB higher than measurements**

– **note that V&G (Martel) near field data already 5 dB lower than Greska (in downstream direction), and that operating conditions are not fully comparable**

Acoustic spectra

- **Acoustic spectra**





—— $\theta = 30°$, —— $\theta = 45°$, —— $\theta = 60°$

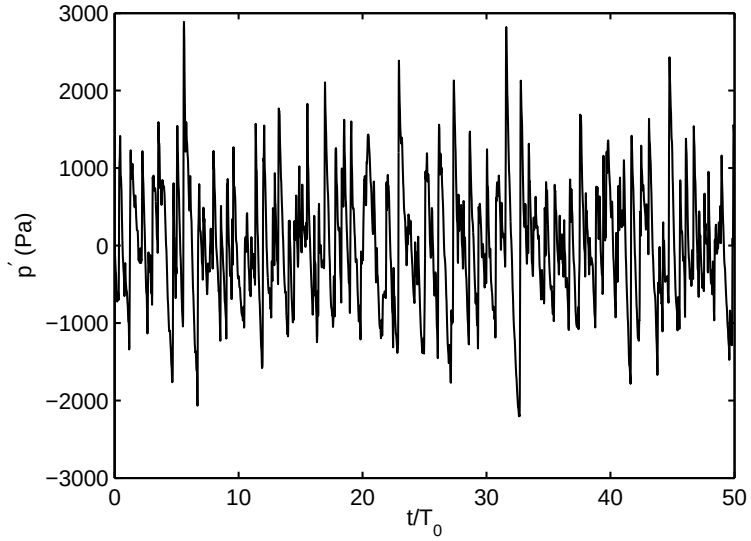
—— $\theta = 90°$, —— $\theta = 120°$, —— $\theta = 150°$

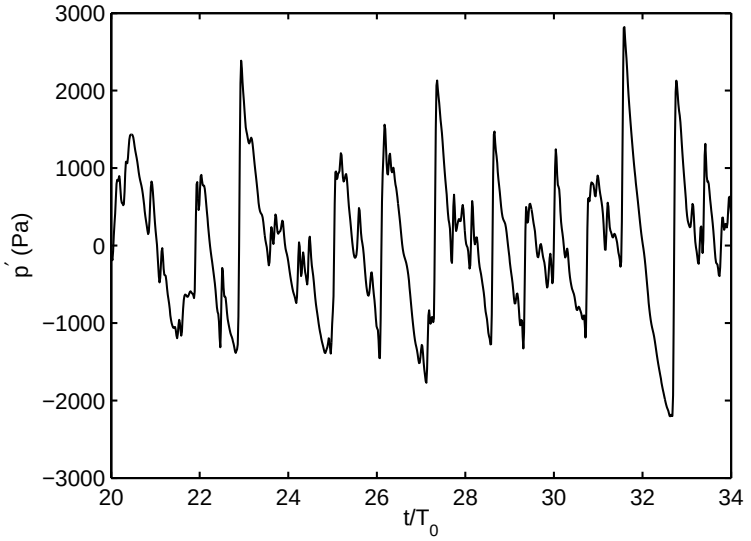
– **evidence of shock associated noise in the rear arc**
  ($St_e = .09$ & $.12$ for $\theta = 150°$ & $120°$)

– **nothing special at Mach wave radiation angle**
  (slight reinforcement of high frequencies?)

Mach wave radiation

- **Time evolution of acoustic pressure in Mach wave direction**

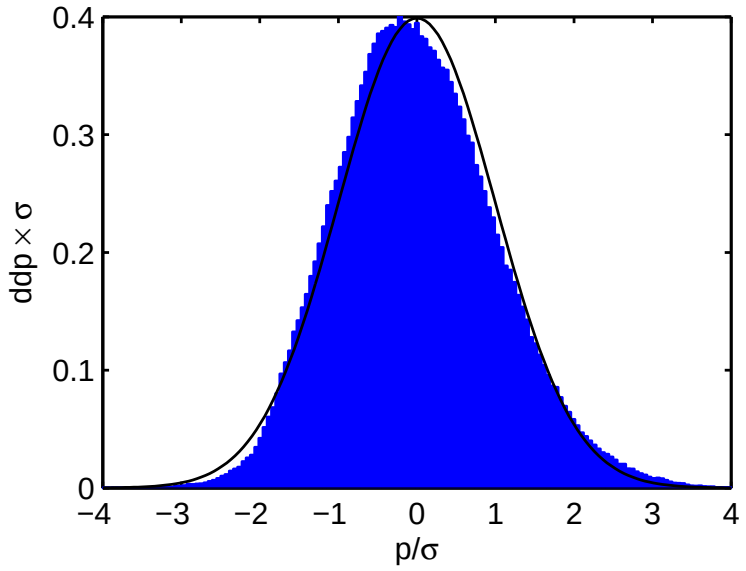




  - positive peaks generally larger than negative ones
  - consequence: non-gaussian, skewed pdf
  - indication of "'crackle"' component?

Mach wave radiation (2)

- Pdf of pressure signal



—— Gaussian distribution

– skewness factor $k = \frac{\overline{p^3}}{(\overline{p^2})^{3/2}} \approx 0.4-0.45$

– value somewhat lower than in experiments (crakle detectable for $k > .3$); measured values up to $k = .8$.

– however skewness tends to be lower for very high velocity jets as well as the contribution of Mach waves to overall noise level in the peak radiation angle (see *Krothapalli & al., AIAA paper 2003-1200*)

Concluding remarks

- **Aerodynamic field**
  - good qualitative agreement with the few experimental data available
  - spectra of turbulent fluctuations exhibit low frequency peaks which may be associated to shock motion

- **Acoustic field**
  - good agreement with experimental data for the near-field OASPL
  - acoustic near field dominated by modes $n = 0$ and $n = 1$
  - good agreement also with experimental data for far-field directivity. Apparent overestimation of level in the direction of maximum radiation.
  - shock-associated noise identified in upstream arc
  - 'crackle' component present in the direction of Mach wave radiation

Concluding remarks

- **Future work**
  - **more detailed investigation of Mach wave component and relation to crackle**
  - **azimuthal decomposition of far-field pressure and search for a link with turbulent fluctuations**

  - **a second computation is currently running, with exit conditions comparable to recent Martel experiments (exit temperature $T_e = 750K$).**
    Detailed comparison of directivity and spectra to come!