The role of direct numerical simulations in understanding and controlling jet and airfoil noise

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Turbulence is nonlinear process with wide range of scales

Computational cost: turbulence

\[ N^{3D} \propto Re_t^3 \]

Computational cost: aeroacoustics

\[ N_{tot} \propto Re_t^3/M^4 \]

Implication: for every doubling of Re

\[ \rightarrow \sim 11 \text{ times more numerical operations} \]

(efficient algorithm)
Meeting the challenge

Orszag & Patterson (1972)

→ CDC 7600 with 36MFLOPs

Cost per GFLOPs:
1984: $33Million
2013: $0.12
2015: $0.08

Expect that in 12-15 years, we can do 1000 x more

NVIDIA Kepler K80: 1,870 GFLOPs
→ 52,000 x more!
Jet Noise


Motivation:

Understand noise generation mechanisms in jets

Use phased-array + source breakdown technique on DNS data

Long-term impact:

Reduction of jet noise
• Early experimental work: jets in flight conditions quieter than same jets in static environment (Crighton et al., 1976; Tanna & Morris, 1977)

• Power spectral density (PSD) for co-flowing jet at 90° scales with $(u_{CL} - u_{co})^5 u_{CL}^3$

• **Question**: does this velocity scaling apply to overall PSD only or also to different frequency ranges and individual azimuthal modes

• Implication for noise reduction techniques in which azimuthal modes exploited

• Obtain physical insight using high-fidelity simulations
Jet noise

Radiated Sound:

Low-frequency sound
(highly directional)

High-frequency sound
(radiating in all directions)
(e.g. Tam, 1991, Viswanathan, 2002)

To capture all mechanisms:
• Simulation must include nozzle
• Flow inside nozzle turbulent

Initial findings indicate strong nozzle-based sources over all $St_D$
(Sandberg et al., AIAA 2012-2613)

Sound generated by:

1. Large-scale structures
2. Breakdown of potential core
3. Fine-scale turbulence in shear layer
4. Scattering process at sharp corner

DNS of this set-up performed
(Sandberg et al., 2011)
Reduce internal noise sources

1. Passive control in form of an acoustic liner
   - Acoustic energy converted into heat through viscous/thermal diffusion
   - Characterized by an acoustic nominal Impedance

   **Model** by time-domain impedance boundary condition based on a mass-spring-damper analogy
   Tam & Auriault, 1996
   JSV, Olivetti, Tester, Sandberg, 2015

2. Modify inflow turbulence generation \( (u'_i=0, \ m=0) \)

   **Additional DNS** (Sandberg & Tester, 2014):
   - New inflow turbulence BC succeeds in reducing internal noise source of \( m=0 \)
   - Acoustic liner reduces internal noise in \( m>0 \)
Jet noise

- Illustrates fully developed turbulent pipe flow exiting nozzle
- Initial shear layers of jet turbulent

**density gradient**

- M8c2L

Both cases $\lambda \approx 4$.

- M45c1L
- ‘Clean’ noise field – no interference from BCs (levels ±10^{-4})
- Main source: near-nozzle region
- Upstream radiating noise from nozzle lip visible (at lower ampl.)

- M8c2L shows stronger directivity, with main radiation θ=40°
- For M45c1L, identification of jet noise difficult?
  ➔ Use phased-array technique
– Phased array technique code: uses far-field cross-spectral density data, processed by applying non-linear least squares algorithm

– Parameterized source model used to determine spectrum source levels at each angle, or ‘source breakdown’
  – in current work 1 jet + 2 nozzle sources

– Technique around for many years, application to DNS/LES data often prevented by combination of:
  1) lack of far-field data
  2) lack of sufficient record length

– Here, polar array of virtual microphones at r/D=20, spacing 0.5 degrees

– Record length (>350 time units) permits number of averages for cross-spectral density to be of order 100 with filter separation of St=0.1
Mach-scaling – \( \text{St}_D=1, \theta=90^\circ \)

PSD scaled by \((1-u_{co}/u_{CL})^5\), to account for co-flow, plotted over \(M_{CL}\)

→ Expect to see \(M^8\) scaling

- Scaling obtained from DNS shows \(M^5\) behaviour – other sources present, ie nozzle-based

- Scaling from jet source only, extracted using AFINDS shows expected \(M^8\) behaviour

**Encouraging result:**

1) AFINDS able to extract jet noise component from overall acoustic field
2) Series of DNS solutions capturing the expected physics
Not clear: does M-scaling also apply to individual modes?

\( m=0: \)
- similar to total noise field
- DNS close to \( M^5 \) scaling
- AFINDS jet noise closer to \( M^8 \)
\( \rightarrow \) total noise field at low \( M \), \( m>0 \) contributions cause deviation

\( m=1: \)
- for higher \( M \), DNS close to \( M^8 \)
\( \rightarrow \) liner BC removes internal noise, jet noise dominates
- At lower \( M \), AFINDS required to extract jet noise \( \rightarrow M^8 \)

\( m=3: \)
- DNS even closer to \( M^8 \)
\( \rightarrow \) liner working even better
- AFINDS jet noise \( \rightarrow M^8 \)

Key result: all azimuthal modes show same M scaling
Motivation:
*Understanding of airfoil self-noise generation, testing of TE noise theories*

Long-term impact:
*Quieter aircraft, propulsion systems, wind turbines, cooling fans, etc*
• Coordinate system $x_1, x_2, x_3$, scaled with semi-chord $b$
• Plate coordinate system $y_1, y_3$, scaled with semi-chord $b$
• Plate with zero thickness assumed semi-infinite
  $\rightarrow$ leading edge not considered
• Integration of sources over a finite length $-2 \leq y_1 \leq 0$
Amiet’s classical result for far-field spectrum (at $x_3=0$)

$$S_{pp}(x, \omega) = \left( \frac{\omega M x_2}{2 \pi \sigma^2} \right)^2 \mathcal{L}(x_1, K_x) l_{x_3}(\omega) S_{qq}(\omega, 0)$$

• Key elements:
  - Surface pressure jump function – relating total pressure field to incident pressure field
  - Spanwise correlation length:
    $$l_{x_3}(\omega) = \frac{1}{S_{qq}(\omega, 0)} \int_0^{\infty} S_{qq}(\omega, x_3) \, dx_3 = 2.1 U_c/\omega$$
  - ‘Frozen’ turbulence spectrum:
    $$S_{qq}(\omega, 0) = \frac{\delta_1}{2} 1 \times 10^{-5} / (1 + \tilde{\omega} + 0.217 \tilde{\omega}^2 + 0.00562 \tilde{\omega}^4)$$
    \[0.1 < \tilde{\omega} < 20\]
    \[\delta_1 = 0.094 Re_c^{-1/5}\]

Use DNS data to test assumptions made by Amiet
To use DNS for assessment of TE noise models:

→ chose set-up that replicates assumption in model derivations

- top side: TE noise superposed with noise of B-L and inflow
- bottom side: TE noise only

Key advantage of DNS with turbulent B-L on one side only

Contours of dilatation
(JFM, Sandberg & Sandham, 2008)
Simulation of turbulent B-L on one side only $\rightarrow$ allows computation of $p_i$

Total pressure on top surface: $p_{top} = p_i + p_s$

Total pressure on bottom surface: $p_{bot} = -p_s$

Use Amiet’s surface pressure jump function: $\Delta p_i = H_D p_i$

Simultaneously:

$$p_i = p_{top} + p_{bot}$$

$$\Delta p_i = p_{top} - p_{bot} \quad \text{from DNS}$$

Amiet’s surface pressure jump function accurately predicts $\Delta p_i$
Perform the same analysis for data from NACA-0012 case at Re=50,000

(FTaC, Sandberg, 2015)

Amiet’s surface pressure jump function accurately predicts $\Delta p_t$
Testing Amiet’s TE noise theory

‘Frozen’ turbulence spectrum

Model spectrum in Amiet’s theory

Empirical model for $l_y$ accurate

Spanwise correlation length

DNS at trailing edge

Model spectrum in Amiet’s theory

Spectrum not ‘frozen’

DNS upstream of TE

DNS at trailing edge
\( \text{Re}_C = 50,000; \ M = 0.4 \)

C-type grid:

Zonal CBC

Total: \( 170 \cdot 10^6 \) points

Contours of dilatation - inset of spanwise vorticity

- anti-symmetric radiation
  → additional noise sources

(JFM, Jones, Sandberg & Sandham, 2008)
• Turbulence is observed to ‘self sustain’

• Linear stability analysis of time-averaged flowfield
  → shows no Absolute Instability

What is the mechanism behind the self sustaining turbulence observed?

Experiment 1:

Investigate response of unsteady 2D flow to 3D perturbations

Perturb airfoil boundary layer with $w$-fluctuations in the form of a white noise ‘strip’, amplitude $\sim 1 \times 10^{-8}$

Perturbations can either decay in time at airfoil, or grow in time (CI/AI)
**Mechanism 1:**

1) **exponential growth in braid region**

- Vorticity stretching in braid region provides inviscid growth mechanism
- Similar to hyperbolic (mode B) and elliptic (mode A) instabilities in wakes

2) **upstream flow during shedding cycle**

Lines indicate negative $u$-velocity

Strong reverse flow (0.77$U_e$)
Mechanism 2:

Use time-averaged flowfield as initial condition for 2D simulation

- Force Navier-Stokes eqns to maintain initial condition
- Determine response of baseflow to small perturbation

- Acoustic feedback loop comprised of four stages:
  A: Convective growth of B.L disturbances
  B: Acoustic scattering of disturbances at T.E
  C: Upstream wave propagation
  D: Boundary layer receptivity

\[ \text{RHS}_{\text{store}} = \frac{\partial q}{\partial t} \bigg|_{t=0} \]

For all subsequent iterations:

\[ \frac{\partial q}{\partial t} = \text{RHS} - \text{RHS}_{\text{store}} \]

If no perturbation added, simulation maintains initial condition indefinitely

(JFM, Jones, Sandberg & Sandham, 2011)
For most practical applications TE noise mechanism will dominate

→ Airfoil noise reduction measures must address TE noise mechanism

**Modification known to reduce TE noise-intensity:**

Geometric modification of trailing-edge, e.g. sawtooth/sine-wave (Howe, 1991)

→ Significant noise-reductions possible
  (e.g. 2-3dB in Oerlemans et al. 2008)

→ Modification of hydrodynamic behaviour near trailing-edge?
  → Exact mechanism not yet known

→ Use DNS to study flow in vicinity of serrations
NACA-0012 airfoil at $Re_C = 50,000$ and $5 \, ^\circ$ incidence
— Also study effect of serrations on low-frequency tonal noise
— TE geometry modelled with immersed boundary technique
— Use similar grid to previous study without TE modifications (Jones et al. 2008)

Flat plate extension to trailing edge
— Motivation: Evaluate effect on TE noise avoiding bluntness-related effects

• Run equivalent straight TE case for comparison
Pressure power spectra, recorded at $(x,y) = (0.5, \pm 1.0)$

- Above the airfoil:
  - TE noise + additional noise sources
  - Amplitude greater than that observed below the airfoil for $St>5$

- Below the airfoil:
  - TE noise only

Serrations have no effect on additional noise sources (expected)

Serrations have significant effect on TE noise for $St>5$
  - $3-10\text{dB}$ reduction
Low-Re Airfoil Noise - Reduction

$\frac{1}{3}$ octave averaged

**Straight**

$f = 3.37$
- TE noise only
- Noise reduction not expected (Howe)

$f = 7.75$
- Most amplified instability waves
- Noise reduction exp.

$f = 11.2$
- Additional noise sources dominant

**Serrated**

Additional upstream pointing lobe
Outlook for airfoil DNS

DNS Flow Conditions:
Re_c = 150,000
M = 0.25

DNS without tripping
- Interference/multiple sources
- Larger amplitude acoustic waves

DNS with IMBM tripping
- Transition noise?
- Less turbulence in wake

Inclusion of wind tunnel installation
Consider compliant TE for noise reduction
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