Noise group overview
Aviation Noise

- Aircraft amongst the loudest sources of human-created noise
  - Objective: reduce noise at its source

- Multiple sources of aviation noise (propulsion, airframe)
  - Challenge: different physics/methods required

- Radiated aeroacoustic energy very small fraction of total
  - Challenge: turbulence obscures small amplitude, but acoustically important sources

- Noise spans large range of frequencies, and amplitudes
  - Challenge: First principles simulations must be very high-fidelity to be predictive → universal low-order models are needed for optimization and control
Noise group two weeks ago

• Airfoil noise
  • Sensitivity analysis and nonlinear model reduction for large-scale aeroacoustic flows (Schmid, Fosas de Pando, Lele)

• Jet noise
  • Wavepacket models
    • Data-driven approaches to understanding subsonic, turbulent jet-noise (Jordan, Colonius, Bres, Zhang, Towne, Lele)
    • Double-peaked wavepackets in supersonic jet noise (Nichols)
  • Control
    • Lattice-Boltzmann aeroacoustic study of actuated nozzle flows (Casalino, Duda, Lele)

• Combustion noise propagation
  • Noise generation and propagation in a transonic turbine stage (Papadogiannis, Wang, Moreau, O’Brien)
Noise group activities

• 15 active members
• 2 weekly group meetings so far
  • Wed. 1pm, CTR conference room
  • Well attended by external group members
  • Successful in identifying synergies between projects
• Tim Colonius’ tutorial on Jet Noise
• Multiple informal brainstorming sessions
Noise group at midterm

• Reduced order modeling for aeroacoustics
  • Sensitivity analysis and nonlinear model reduction for large-scale aeroacoustic flows \((\text{Schmid, Fosas de Pando, Lele})\)
    • Sensitivity analysis of trailing edge noise
    • Discrete Empirical Interpolation Method (DEIM) for cylinder wake
  • Data-driven approaches to understanding subsonic, turbulent jet-noise \((\text{Jordan, Colonius, Bres, Zhang, Towne, Lele})\)
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• Noise control
  • Lattice-Boltzmann aeroacoustic study of actuated nozzle flows \((\text{Casalino, Duda, Lele})\)
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Sound bites from the “noise group”

I. Methodology (sensitivity analysis, reduced-order modeling)
II. Data-Analysis I (role of wavepackets in jets)
III. Data-Analysis II (combustion noise)
IV. Simulations/simulation technique
Sensitivity analysis and nonlinear model-order reduction for large-scale aeroacoustic flows

Response behavior to physical and parametric change: sensitivity analysis

- Computation and use of adjoint information
- Efficient and effective algorithms (semi-automatized, flexible)

Low order representation of essential dynamics: model reduction

- Multiple bases for distinct dynamics
- Use of Discrete Empirical Interpolation Method (DEIM)

General framework for unsteady flow solvers
fast optimization/analysis of large-scale complex flows
Sensitivity analysis of frequency response

- General sensitivity based on
  \[ \frac{dq}{dt} = F(q) \]

- Cost functional
  \[ J = J(q) \]

- How do changes in \( q \) affect \( J \) ?

- Sensitivity of optimal frequency response
  \[ \frac{dv}{dt} = Av + f \exp(i\omega t) \]

- Maximum amplification?
  \[ G_{\text{max}} = \max \| Rf \| / \| f \| \]

- Largest singular value of the resolvent
  \[ R = (A + i\omega)^{-1} \]

- Effective techniques for unsteady flow solvers
Optimal frequency response of tonal noise in the flow around an aerofoil

Nonlinear simulation

Optimal response

NACA 0012 at 2deg
Re = 200000, M = 0.4

Sensitivity to changes in parameters?

\[ \sigma_{\text{max}}(\omega) \]

Mach number

Future plans: optimal frequency response of mixing layer past a splitter plate, sensitivity to changes in Mach number, temperature, closeness to global instability
Nonlinear model order reduction

Large scale nonlinear dynamical system

\[
\frac{d\mathbf{v}}{dt} = A\mathbf{v} + f(\mathbf{v})
\]

Reduced order system

\[
\frac{d\mathbf{\tilde{v}}}{dt} = V^H A\mathbf{\tilde{v}} + C^H f(P^T V\mathbf{\tilde{v}})
\]

- Assessment of the robustness
- Automatization
- Nested reduced-order models

Future plans: robustness analysis, reduced-order model of the dynamics of an impinging jet at M=0.8
Nonlinear reduced-order model of compressible flow past an aerofoil

Full system
$10^6$ DOF

ROM
16 DOF

abs error
~1%

NACA 0012 at zero incidence, Reynolds number (chord-based) 10000 and Mach number 0.4
Wavepackets & jet noise: **The story so far**

\[ \mathcal{L}_{\mathbf{q}}(\tilde{\mathbf{q}}) = 0 \]

Nearfield

Farfield

1 POD Mode

Linear theory

<table>
<thead>
<tr>
<th>SPL/St</th>
<th>30dB</th>
</tr>
</thead>
</table>

(d) For Cambridge LEE and Poitiers LEE experiments.
Hypothesis: unsteady base flow & jittering wavepackets

Data analysis and preliminary modelling suggest that slow mean-flow dynamics amplify acoustic radiation from wavepackets.
CTR objectives

1. Data mining of Cascade LES: wavepacket_finder.m

   - Power spectral densities,
   - Cross-spectral matrices,
   - Variable-norm POD bases.

2. Data-driven modelling:

   i. Dynamical, time-domain, approach (Linearised Euler Eqns):
      - Linear wavepackets on low-pass-filtered LES field.

   ii. Statistical, frequency-domain, approach (PSE, OWE):
      - Ensemble average of linear wavepackets on short-time mean fields.
Interactively process LES snapshot database

- Variable (pressure shown)
- Azimuthal modes (m=0 shown)
- DFT of segments in time

→ cross spectral density / POD analysis

1. wavepacket_finder.m
1. Example: POD weighted by hydrodynamic- and acoustic-fields

Weighted region for cross correlations

“Quiet wavepackets”

“Noisy wavepackets”
To whom it may concern:

It is my pleasure to provide this appraisal of Dr. Agarwal's contribution to the various fields that his research has touched. I have followed his work closely for the past 8 years and indeed I have had the good fortune to collaborate with him on a number of occasions.

Dr. Agarwal's research expertise is primarily in aeroacoustics and hydrodynamic stability, and he addresses problems in these fields by combining theoretical reasoning, model construction and analytical and/or numerical solution. The association of aeroacoustics and hydrodynamic stability is particularly pertinent for the former, as much of the underlying flow physics can be understood in the framework of stability theory. As with many of the facets of Dr. Agarwal's work, this association is not accidental: it is the result of the kind of careful thinking that characterises his research.

On studying Dr. Anurag's work, one is struck by his deep understanding of acoustics and compressible flow physics and his solid command of the mathematical tools necessary for their exploration. One appreciates a certain simplicity and elegance in the way the problems are addressed. His thinking is creative and produces studies that stand out from the crowd on account of their originality: problems are clearly identified, carefully posed in a novel manner and meticulously solved. While the models considered are simplified, their connection to the more complex 'real-life' problem they mimic is always kept in view. A good example of the foregoing qualities can be found in his recent correction and use of Goldstein's generalised acoustic analogy to study sound source mechanisms in subsonic jets; and in the subsequent follow-up study where the frequency dependence of the behaviour of the dispersion relation is considered in a simplified model flow. While Goldstein's theoretical developments are cumbersome, contain errors and are not elucidated by means of examples, Dr. Anurag's studies are correct, cleverly simplified and carefully evaluated by means of pertinent model problems.

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2. Data-driven modelling: unsteady and short-time averaged base flows

Example of short-time mean (time window ~St 0.08)

\[ U_{\text{mean}} U, \text{St}_w = 0.05 \]
Double-peaked wavepacket: original motivation

Observations of “double-peaked” wavepackets

- POD of LES data: $M_j = 1.5$ (Rodríguez et al., 2012)

- Beamforming from experiment: $M_j = 1.37$ (Nelson et al., 2013)
Global modes $\rightarrow$ Resolvent modes

Contain upstream propagating components originating from end of supersonic core

\[
\frac{\partial q}{\partial t} = Lq + f(t)
\]

\[
q_{out} = -i(L - \omega I)^{-1} q_{in} e^{i\omega t}
\]

Provide a convenient basis for computing resolvent modes
Resolvent modes (pressure norm)

1. Double-peaked wavepacket structure similar to observed in LES data
2. Optimal forcing function (input) is extended in space (vs. marching PSE)
3. Significant gain for many suboptimal modes – potential basis to capture LES data

Could intermittency-enhanced acoustics derive from sensitivity to stochastic forcing in addition to jittering instability wavepackets?
Parametric study (62 cases)

\[ M_j = 0.6, \ M_a = 1.8 \]

\[ M_j = 1.4, \ M_a = 1.4 \]

\[ M_j = 1.8, \ M_a = 1.4 \]

RANS with Thies & Tam (1996) mods. to k-ε model

Includes operating conditions for supersonic and new subsonic LES database
Next steps

• For each frequency, project LES data (M = 0.9 jet?) onto basis of optimal and sub-optimal input resolvent modes
• Determine gain from this information
• Probe physical mechanism for second peak: does it persist for all operating points?
MT1 turbine

• Full 3D high-pressure transonic stage
  (Wang et al, JCP 2014)
• High Reynolds and Mach number
• Stator-rotor interaction
• Vortex shedding
• Shock-TBL interaction
• Tip clearance flow
Indirect combustion noise: Low-frequency phenomena

Pure entropy pulsation 2KHz

Acoustic response in stator 2KHz = Indirect Noise!

DMD on T | DMD on P | ROTOR

Mid span: R=275mm
DMD analysis at inlet near plane

Work in progress:
- Outlet-plane analysis
- Composite DMD analysis
- Sparsity–promoting DMD
- Comparison with compact theory (Cumpsty and Marble 1977)
Lattice-Boltzmann prediction of M=0.9 / Tr=2.7 coaxial jet noise

Motivations

- The Lattice-Boltzmann Method is an established technology for low Mach number flows (isothermal flow assumption, M~0.4)

- LBM formulations for high Mach numbers have been proposed by Exa, based on the concept of a Hybrid LBM-PDE_Energy model (M ~0.95)

- The non-isothermal LBM formulation has been recently implemented in the beta version of PowerFLOW used in the present project.

- This is globally the first usage of a non-isothermal LBM formulation after AIAA-2014-3101, AIAA-2014-2755 and AIAA-2014-3313 all focused on jet noise prediction.
Previous work (AIAA-2014-3101)

- Accurate near field prediction (issue in the $u'$ along centerline for $M=0.98$ case)
- Shallow angle far-field noise under-predicted up to 4.5dB for and 2dB, due to downstream cup removal in the FW-H surface
Current work (1/2)
Tinney & Jordan, JFM 611, 2008 – co-axial subsonic jets

<table>
<thead>
<tr>
<th>jet</th>
<th>M</th>
<th>Ma</th>
<th>Tr</th>
</tr>
</thead>
<tbody>
<tr>
<td>primary</td>
<td>0.87</td>
<td>1.41</td>
<td>2.65</td>
</tr>
<tr>
<td>secondary</td>
<td>0.90</td>
<td>0.90</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Work plan:
- Case setup
- Coarse simulation
  - Preliminary comparisons with experiments (data provided by P. Jordan end of week 2)
- Inlet condition tuning
- Fine simulation
  - Detailed comparisons with experiments
- Investigation of a noise control device
Current work (2/2)

Coarse mesh (resolution in the plume Ds/64)

Comparison with measurements

Acoustic Mach

Temperature ratio