Adjoint-based Mesh Adaptation for the Sonic Boom Signature Loudness

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Introduction and Motivation

- Commercial supersonic flight overland requires overcoming sonic boom annoyance

- Sonic boom prediction involves:
  - CFD simulation (Inviscid or viscous) near the aircraft to generate an off-body pressure waveform termed as “near-field”
  - Atmospheric propagation where the pressure disturbances are modeled as they reach the ground
    - Possibly under prevailing atmospheric conditions including winds
    - Standard atmosphere assumed as U.S. Standard Atmosphere (1976) with guidance on humidity profiles
  - Noise analysis
    - Frequency spectrum (1/3-octave frequency bands)
    - Multiple metrics: Perceived Level (PL) and A-weighted Sound Exposure Level (ASEL) is used in this study
Introduction and Motivation

\[ S_t = S_m + F(\Sigma S - S_m) \]

\[ PL = 32 + 9 \log_2(S_t) \]


Introduction and Motivation

- Perceived level (PL) is the generally accepted quantitative measure of sonic boom
  - Decibels are logarithmic
  - CFD mesh and atmospheric propagation sampling requirements increase as signals get quieter
  - Specialized boom meshes (INFLATE\textsuperscript{1}, MCAP\textsuperscript{2}, Boom Grid\textsuperscript{3}) may or may not be sufficient
  - Adjoint-based mesh adaptation offers a way to generate suitable meshes for the output being optimized
- PL metric not amenable to differentiation
- A-weighted Sound Exposure Level (ASEL) has been shown to be well correlated\textsuperscript{4} with PL for outdoor sonic booms

FUN3D
http://fun3d.larc.nasa.gov

- Established as a research code in late 1980s; now supports numerous internal and external efforts across the speed range
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows
- General dynamic mesh capability: any combination of rigid / overset / morphing grids, including 6-DOF effects
- Aeroelastic modeling using mode shapes, full FEM, CC, etc.
- Constrained / multipoint adjoint-based design, mesh adaptation
- Distributed development team using agile/extreme software practices including 24/7 regression, performance testing
- Capabilities fully integrated, online documentation, training videos, tutorials
sBOOM

- Propagation based on lossy Burgers equation
- **Features**
  - Under-track, off-track signatures, Horizontally stratified winds, Acceleration, turn-rates, climb-rates
  - **Adjoint-based design capability**
    - Near-field dp/p matching
    - Ground loudness optimization/ Target/ EA matching
    - Target equivalent area generation
    - Atmospheric sensitivities

**Recent sBOOM enhancements**
- Boom focusing calculations, interfacing with non-linear Tricomi solver

sBOOM is under active development. Contact Sriram.Rallabhandi@nasa.gov or Lori.Ozoroski@nasa.gov to get a copy of sBOOM.
FUN3D-sBOOM Coupling

• Input to sBOOM is represented by a transformation (T) that maps CFD solution to the desired pressure distribution

\[ p_0 = T(Q, X) \]

• Lagrangian

\[ L(D, Q, X, \Lambda_f, \Lambda_g, \Lambda_b) = J + [\Lambda_g]^T G + [\Lambda_f]^T R + [\Lambda_b]^T (p_0 - T) \]

• System of adjoint equations

\[
\begin{align*}
\left[ \frac{dJ}{dp_0} \right]^T + \Lambda_b &= 0, \\
\left[ \frac{\partial R}{\partial Q} \right]^T \Lambda_f - \left[ \frac{\partial T}{\partial Q} \right]^T \Lambda_b &= 0, \\
\left[ \frac{\partial G}{\partial X} \right]^T \Lambda_g + \left[ \frac{\partial R}{\partial X} \right]^T \Lambda_f - \left[ \frac{\partial T}{\partial X} \right]^T \Lambda_b &= 0.
\end{align*}
\]

• Desired sensitivity derivatives

\[ \frac{\partial L}{\partial D} = [\Lambda_g]^T \frac{\partial G}{\partial D} + [\Lambda_f]^T \frac{\partial R}{\partial D} \]

• Current state-of-the-art: Integral of quadratic pressure deviation functional

$$f = \int_I \left( \frac{p - p_\infty}{p_\infty} \right)^2 dl.$$  

• Near-field pressure waveform is a heuristic of ground loudness
RESULTS
Case 1: 2D Diamond Airfoil

- When enough mesh was provided, dpp adaptation and ASEL adaptation gave identical results
  - Constraining the mesh to differentiate the schemes

- Meshes
  - More refinement in the wake for ASEL adaptation
  - Regions above the geometry also refined in ASEL adaptation
  - Refined farther into the domain with ASEL adaptation
Case 1: 2D Diamond Airfoil

- Remaining error drops three orders of magnitude for ASEL adaptation, and 2 orders for dpp
- Minor differences observed in loudness convergence
Case 2: Airfoil with Complex Flow-field

- 2D case with a complex flow-field that can produce low boom
- Used supersonic small perturbation theory to inverse design airfoil
Case2: Effect of Mesh

- dpp Adaptation - Coarse
- dpp Adaptation - Refined
- ASEL Adaptation - Coarse
- ASEL Adaptation - Refined
Case 2: Cell Size Projection During Adaptation

- **dpp Adaptation**
  - After 5 cycles
  - After 20 cycles

- **ASEL Adaptation**
  - After 5 cycles
  - After 20 cycles
Case 2: Moderate Mesh

The graph shows the variation of $\delta p/P$ and $d(\delta p/P)$ along the X-axis (in feet). The lines represent different simulations or conditions:
- **Red line**: dpp_Adaptation_40
- **Blue line**: ASEL_Adaptation_40
- **Green line**: Adjoint_Gradient_40

The graph illustrates the detailed comparison and analysis of these conditions across different X-values.
Case 2: Error Convergence and Signatures

Coarse Mesh

Medium Mesh

Fine Mesh
Case3: Axi-Symmetric Body of Revolution

- For a 3D case, the overall adaptation behavior is similar
  - Higher refinement in aft and above the body for dpp adaptation
  - Different from the 2D case before
Case 3: Axi-Symmetric Body of Revolution

- Loudness convergence is achieved earlier with smaller meshes for ASEL adaptation
Case3: Axi-Symmetric Body of Revolution

- dpp adaptation picks up on shocks sooner than ASEL adaptation
- ASEL adaptation quickly “catches-up” to dpp adaptation
- First two shocks are better resolved using ASEL adaptation with smaller overall meshes
Case 4: Low Boom Concept

- A low-boom demonstrator concept analyzed via mesh adaptation
- 8 adaptation cycles were run, to achieve loudness convergence
- ASEL from dp/p adaptation is within 0.5 dB, but not converged on the loudness scale
- With the same mesh growth guidance, ASEL adaptation has slightly larger mesh starting from adaptation cycle = 4
- Mesh size increased from 31M nodes to ~240M nodes
Case 4: Low Boom Concept

- Differences observed in the near-field pressure waveform
- ASEL adaptation captures the smaller peaks better, while dp/p resolves the larger shocks crisply
- Ground signatures visually similar
  - ASEL build-up shows steeper shocks of ASEL adaptation compared to dp/p adaptation
  - Proximity of loudness from ASEL adaptation to baseline is fortuitous
Summary/Conclusions

- Demonstrated adjoint-based mesh adaptation for sonic boom loudness on multiple cases
- Current state-of-the-art for mesh adaptation is an off-body pressure functional, a heuristic or surrogate of low boom
- Using ASEL-based adaptation implicitly weighs regions of the pressure waveform based on their importance to loudness metrics
  - If detailed information is known of the underlying concept, dp/p adaptation may impose weights along the sensor accordingly
- More work is needed to show applicability in 3D simulations over realistic concepts
- ASEL adaptation may be used in conjunction with dp/p adaptation
Future Work

• Future Work
  • Leverage FUN3D development toward simultaneous mesh adaptation and design to generate suitable adapted meshes during design for minimizing sonic boom
  • During ASEL adaptation, sBOOM grid is fixed i.e. sBOOM does not contribute to the error to drive adaptation.
    • Enhance sBOOM to work with non-uniform grids and contribute towards adaptation error correction
  • Use ASEL sensitivities as weights to drive \( \frac{dp}{p} \) adaptation
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Questions?
BACKUP-SLIDES
Case 2: Refined Mesh
Case 3: Axi-Symmetric Body of Revolution

- Result from ASEL adaptation has higher front loudness compared to dpp adaptation
Case 3: Error Convergence

![Graph showing error convergence with respect to mesh nodes. The y-axis represents remaining error on a logarithmic scale, and the x-axis represents mesh nodes ranging from 10^6 to 10^7. Two curves are shown: dpp_Adaptation and ASEL_Adaptation. The dpp_Adaptation curve starts higher and decreases more sharply compared to ASEL_Adaptation.]