Minimizing Sonic Boom Through Simulation-Based Design: The X-59 Airplane

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Motivation

Overcoming the Barrier to Overland Supersonic Flight

• Vision for Commercial Supersonic Flight is a future where fast air travel is available to a broad spectrum of the traveling public
• Biggest challenge is sonic boom
  - Civil supersonic flight operations are prohibited over many parts of the world
  - Currently, U.S. law prohibits flight in excess of Mach 1 overland
• Supersonic En-Route Noise standard is required
  - Must be accepted internationally (ICAO, FAA, EASA, TCCA)
• Additional barriers include airport noise, high-altitude emissions, efficiency, and many more
Sonic Boom Physics

Sound heard

Sound generated

Ray Path

Acoustic Frame of Reference

Mach > 1

Aerodynamic Frame of Reference

Acoustic Propagation

Sound heard

$\mu = \sin^{-1} \left( \frac{1}{\text{Mach}} \right)$

Mach = 1 $\rightarrow$ 767 mph or 1,235 km/h (at sea level)

Goals

- Simulation-based analysis must reliably predict ground noise
- Simulation-based design must reliably determine aircraft shape to minimize ground noise
Sonic Boom Noise

Boom sound characteristics are a function of the ground pressure signature

- Classical signatures are N-waves

- Low-boom designs exploit shaped signatures
  - Strategy is to increase rise time, decrease amplitude, increase duration and smooth recovery
  - Requires designing aircraft with nearfield signatures that do not coalesce into N-waves
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Sonic boom characterization requires prediction of the primary boom carpet

- Influenced by several factors, some with significant uncertainties

- Aircraft shape and operating conditions
- Atmospheric conditions (wind, temperature, humidity)
- Local terrain
- Additional factors
  - Aircraft acceleration and maneuvers, focus booms
  - Secondary boom carpets
Low-Boom Flight Demonstration

- NASA mission to support development of an En-Route noise standard
  - Aircraft is a supersonic-acoustic-signature-generator with characteristics representative of a commercial supersonic transport
- Design Mach number is 1.4
- Design sonic boom sound level is 75 PLdB (Perceived Level)
  - Roughly a factor of eight quieter than the boom generated by Concorde
  - Near ambient noise level of a city
  - Similar to a rumble from a distant thunderstorm
- Goal is to perform multiple overflights of representative communities and climate across the US to collect noise response data
- Deliver community response data to ICAO
X-59 Aircraft

Configuration C612
- MDGW: 24,300 lbs
- Fuel (Std Day): 7,500 lbs
- Payload: 600 lbs
- Design Mach: 1.4
- Loudness: <75 PLdB
- Engine: 1xF414-GE-100
- Landing Gear: F-16 Blk25 NLG, F-16 Blk25 MLG

Control Surfaces
- Aileron: 12.9 sq ft/+35/-25 deg
- Flap: 12.4 sq ft/+30/-3 deg
- Stabilator: 39.9 sq ft/+20/-15 deg
- Rudder: 8.5 sq ft/+25/-25 deg
- T-tail: 6.8 sq ft/+10/-0 deg

Static ground line (0.7° nose-up)
- 7' 10'' Wheel track
- 96' 8'' Overall length

Turning:
- 55.8° Turnover Fwd CG

Dimensions:
- Wing span: 29' 6''
- Overall height: 14'
- Tipback:
  - Fwd CG: 23.9°
  - Aft CG: 11.8°
- Wheelbase: 17' 6''
- Fuselage strike: 9.2''

www.nasa.gov/aero/x-59-quesst-overview
Role of High-Fidelity Simulations and HPC

• High-fidelity CFD simulations are a major contributor to X-59
  - All aspects of aerodynamic design and acoustic analysis
  - Wind-tunnel hardware verification and test support
  - Uncertainty quantification
• Ongoing pre-test analysis to support acoustic validation flights
• Near-real-time prediction capability for community test planning
• Suite of new prediction tools for certification of supersonic aircraft
Sonic Boom Analysis

Nearfield
- 3D effects (aircraft shape and plume)
  - Use CFD

Propagation
- Atmospheric variability
- Absorption
  - Use Ray Tracing and quasi-1D PDE
Core Solver: Cart3D

Meshing
- Multilevel embedded-boundary Cartesian mesh
  - Cut-cells at boundary
  - Handles arbitrarily complex vehicle shapes

Flow Solver
- Inviscid flow assumption (Euler equations)
- Second-order spatial and temporal discretization
  - Fully conservative finite-volume method
  - Dual time-stepping for unsteady flows
- Calorically perfect and equilibrium gas models
- Runge-Kutta time marching with multigrid acceleration
Core Solver: Cart3D

Error Estimation and Goal-Oriented Mesh Adaptation

- Mesh automatically refined in locations with most impact on user selected outputs (pressure signatures, lift, drag, moments, …)
- Method of adjoint weighted residuals
- Used for every simulation

Adaptation Convergence History

Near-body region of adapted mesh around LBFD aircraft for pressure sensor output ($C_p$ contours)
Parallel Performance

Excellent scalability through use of domain decomposition based on space-filling curves

OpenMP and MPI fully supported

HECC Supercomputing Systems

Cascade Lake Engineering Workstation

- Intel(R) Xeon(R) Gold 6252 CPU
- 2 sockets, 24 physical cores per socket
- Hyper-Threading and TurboBoost ON
- icc, version 19.0.4.243
Example Results

1. Nearfield Flow Solutions
2. Nearfield Signatures
3. Ground Signatures
4. Ground Noise Level
Schlieren Flow Visualization

Photographs from flight tests in the Supersonic Corridor near Armstrong Flight Research Center

- Schlieren photographs are a well-established experimental technique
  - Visualization of density gradients, excellent for shocks
- New capability in Air-to-Air Background Oriented Schlieren (AirBOS) imaging
  - Allows schlieren imagery of aircraft in flight
  - Emerging technique for validating simulations through comparison with computational schlierens
Flight-Matching Computation

Cart3D Simulation

Computational schlieren

Flight Test

Mach number = 1.05
Angle of Attack = 1.15°
T-38 Aircraft

AirBOS image
Photographed 2,000 feet from the aircraft
Shock-Shock Interactions

Supersonic Formation Flight

Mach number = 1.05
Angle of Attack = 1.15°
T-38 Aircraft

Preliminary work toward flight-matching simulations and future acoustic validation flights
Computational schlieren
- Dark lines are shockwaves
- White regions are expansions
- Perspective projection

Mach number = 1.05
Angle of Attack = 1.15°
T-38 Aircraft (wingtip separation ~13°)
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Challenging simulations:
• Fine geometric detail (probes, vortex generators, flaps, ailerons, stabilator, t-tail, ...)
• Many secondary-air systems, in addition to the main engine
• Requires accurate prediction of a complex system of shockwaves far from the aircraft in addition to standard aerodynamic performance coefficients
Shockwaves at Cruise

Computational schlieren
- Dark lines are shockwaves
- White regions are expansions
- Perspective projection

- Significant influence of nozzle exhaust
- Shaped pressure signature below aircraft

Mach number = 1.4
Angle of Attack = 2.05°
Nearfield Pressure Signature

\[ \frac{h}{L} = 1 \]  
(\approx 30m)

\[ \frac{h}{L} = 2 \]  
(\approx 60m)

\[ \frac{h}{L} = 3 \]  
(\approx 90m)

Coefficient of pressure on mid-plane
- White: freestream
- Yellow-Red: above freestream
- Blue: below freestream

Mach number = 1.4
Angle of Attack = 2.05°

Nearbody refinement in streamwise and crossflow directions:
- Typical mesh size 50 million cells
- Fine mesh size 100–500 million cells
Nearfield Pressure Signature

Nominal Conditions
Mach=1.4, $\alpha=2.05^\circ$

Uncertainty Quantification

Normed PDF

Distance

10% Quantiles

1.4
1.5

Mach Number Uncertainty

Low uncertainty region

Error Estimate

Nearfield Pressure Signature

Distance along sensor

Nominal Conditions

Mach=1.4,
$\alpha=2.05^\circ$

Uncertainty Quantification

Local Discretization

Error Estimates
Nearfield Pressure Cylinders

• Recall that goal is to compute the boom carpet on the ground
  - This requires computation of the nearfield pressure cylinder, not just the on-track signature

\[
\frac{\Delta p}{p_\infty}
\]

Pressure signatures at different off-track angles

Example nearfield pressure cylinders below the aircraft

• Adaptively refined mesh for many sensor locations
  - In practice, we take full advantage of mesh alignment
  - Separate into several cases with sensors at similar off-track angles
Atmospheric Propagation and Ground Signatures

- Propagate nearfield signature through atmosphere to ground
- Numerical analysis via sBOOM:
  1. Ray tracing (path and arrival time)
  2. Quasi-1D propagation (signature morphology)
    - Includes relaxation loses, stratification, spreading and non-linear propagation
Sonic Boom Carpet

Altitude (~10 miles)

Track Width (70+ miles!)

\( \phi = \text{off-track angle} \)

cutoff angle

Convert ground waveform to level of noise for each off-track angle up to cutoff

• Perceived level (PLdB) is the primary metric
• ASEL, BSEL & CSEL also used

Noise target is 75 PLdB

• Current design is quieter than target over the full carpet
• Holds for most atmospheric conditions

Ground noise

Noise Metric (dB)

Off-Track Angle (deg)
Importance of High-End Computing

Challenges of simulating low-boom aircraft

- Propagation of weak shocks over several aircraft lengths
  ‣ Difficult to reap benefits of advanced higher-order schemes
  ‣ Highly susceptible to attenuation by discretization error
- Wide range of scales: complex flow & aircraft geometry
  ‣ Large grids even with adaptive mesh refinement
- Many engineering cases
  ‣ Operating conditions, flaps, ailerons, stabilator, T-tail, engine settings
  ‣ Fast turn-around critical (4—8 hours per case)
  ‣ Each case fits on 1—4 nodes, but may need several 100 nodes to fill databases efficiently
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