Development of High Fidelity Tools and Robust Design Approaches for Low Boom Aircraft

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Commercial Supersonic
Technology Project

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Outline

- CST Technical Challenge
- Low Boom Design Tools
  - Software Development
  - Target Generation
  - Shaping Methods
  - Uncertainty Quantification & Design
- High Fidelity Prediction Tools & Validation
  - Sonic Boom Prediction Tools
  - Inlets
  - Nozzles
- Sonic Boom Prediction Workshop
- Summary

CST Low Boom Design Tools Technical Challenge

Description: Tools and technologies enabling the design of supersonic aircraft that reduce sonic boom noise to 80 PLdB validated as ready for application in a flight demonstrator

Technical Challenge Completed on Schedule in September 2015

Tools

- Advancements in mesh adaptation, refinement, error estimation, & automation
- New and improved low boom design target generation tools and approaches
- Adjoint equation based techniques significantly impact many aspect of the development
- Powered inlet and nozzle boundary conditions for accurate simulation of propulsion flow
- Grid best practices documented for high-fidelity boom prediction

Design

- Multi-fidelity design tool integrated into improved fidelity conceptual design
- Robust designs with uncertainty considerations
- Designs completed for small airliner and flight demonstrator configurations

Validation

- Validation tests and CFD comparisons completed for full configuration and inlet flow with pressure rail and spatial averaging technique
- Validation tests and CFD comparisons completed for nozzle flow with single probe and at small scale

Tools for Low Boom Analysis & Design – Cart3D

Cart3D v1.5 with Automated Error-Estimation and Mesh Refinement

Highlights Include:

- Automatic extraction of equivalent-area distributions
- Integrated mass flow monitoring
- Integrated error-estimation for multiple outputs
- Fully integrated support for distributed memory flow solver
- Increased automation for adaptation including auto-mesh growth
- Simplified restarts with adaptation

Cart3D_Design v0.95 with Dynamic Error Control & Progressive Optimization

Highlights Include:

- Adjoint-based mesh adaptation to control error in specific outputs
- Full support for inverse design using target equivalent area distributions
- Multiple-adjoints permit native handling of aerodynamic constraints w/sensitivities
- Support for multiple, independently meshed design points
- Support for progressive optimization

Tools for Low Boom Analysis & Design - sBOOM

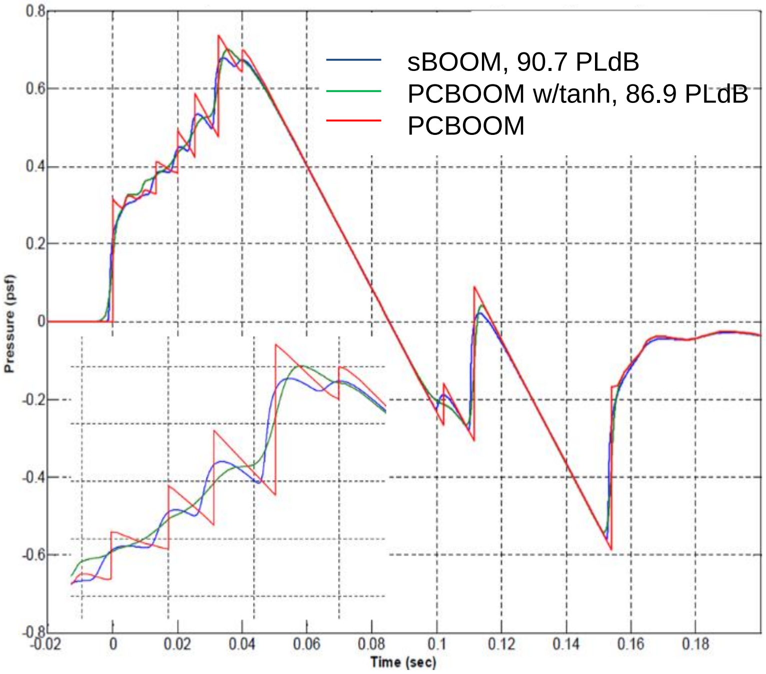
sBOOM V1 – Propagation analysis

- Based on lossy Burgers equation
- Features
    - Under-track, off-track signatures
    - Horizontally stratified winds
    - Acceleration, turn-rates, climb-rates

sBOOM V2 – Discrete-adjoint based design capability

- Ground loudness optimization
- Ground target signature matching
- Equivalent area matching
- Target equivalent area generation
- Atmospheric sensitivities - winds, temperature and humidity

Comparison of boom signatures



Significance

- High-fidelity analysis and design optimization capability
- Used in NASA, industry and academia for sonic boom propagation and design
- Demonstrated over multiple shape optimization exercises
- Adjoint sensitivities with respect to atmospheric conditions for robust design optimization

Rallabhandi, S. K., "Advanced Sonic-Boom Prediction Using the Augmented Burgers Equation", Journal of Aircraft, Vol. 48, pp: 1245-1253, 2011

Rallabhandi, S. K., Nielsen, E. J., Diskin, B., "Sonic-Boom Mitigation Through Aircraft Design and Adjoint Methodology", Journal of Aircraft, Vol. 51, pp: 502-510, 2014

Formulation of Trim-Feasible Low-Boom Targets

Objective:

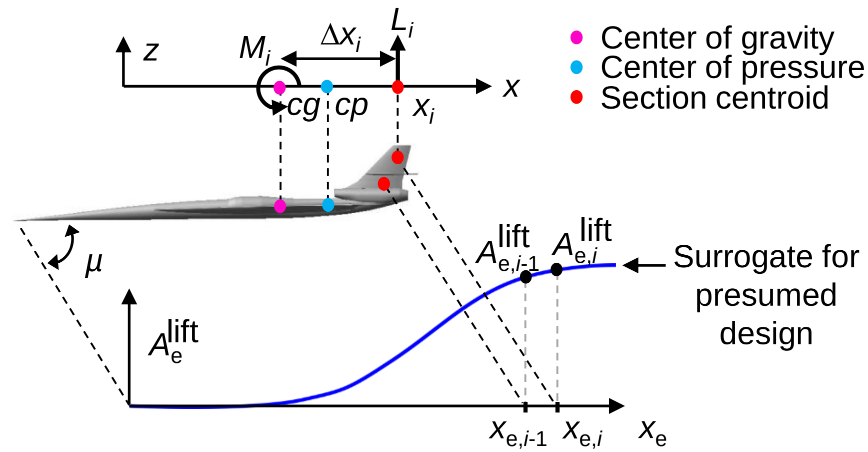
- Incorporate trim requirement into the low-boom target generation process.

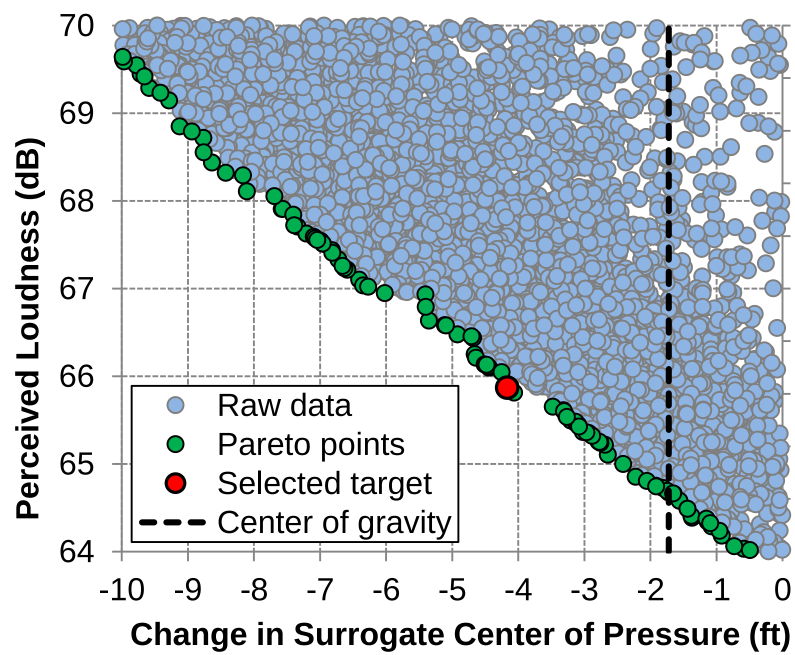
Approach:

- Trim-feasible target formulation is based on the mixed Ae design approach*.
- The change in volume distribution due to shaping of a lifting surface is assumed to be negligible.
- Lift distribution used to calculate center of pressure is approximated using a surrogate equivalent area distribution due to lift.
- New weighted optimization objective is used to generate low-boom targets.

Significance:

- Inclusion of trim requirement in the low-boom target generation is key to achieving a low-boom supersonic aircraft that can be trimmed during cruise.
- Provide a new understanding of the design space
- Avoid costly design compromises made to achieve trim of an aircraft that is already designed strictly for low-boom characteristics.





* AIAA No. 2013-2660, "Using CFD Surface Solution to Shape Sonic Boom Signatures Propagated from Off-Body Pressure." - I. Ordaz, & W. Li, AIAA Applied Aerodynamics Conference, June. 2013

AIAA No. 2014-2141, "Conceptual Design of Low-Boom Aircraft with Flight Trim Requirement." -Ordaz, I., Geiselhart, K. A., and Fenbert, J. W., AIAA Applied Aerodynamics Conference, June 2014.

Mesh-Robust Low-Boom Shaping

Objective:

- Mesh-robust, powered, under-track low-boom shape optimization of a NASA LBFD concept.

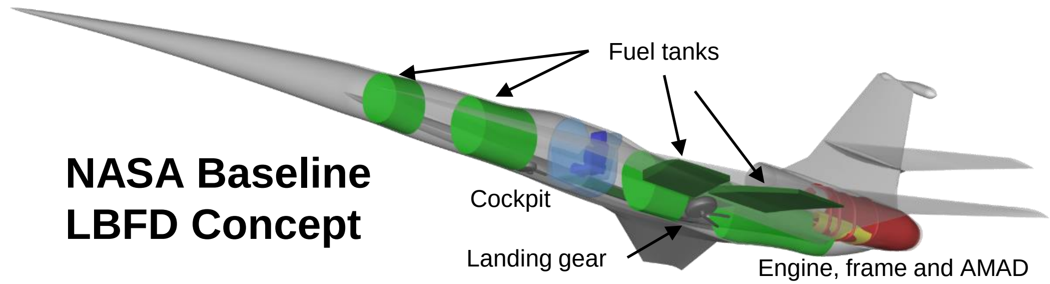
Approach:

- Apply Cart3D Adjoint Design framework and JAGUAR parametric modeler to perform gradient-driven OML shaping.
- End-stage near-field $\Delta p/p_\infty$ features inaccurately resolved using a pre-specified mesh are captured and controlled by invoking adaptive refinement at every function evaluation.

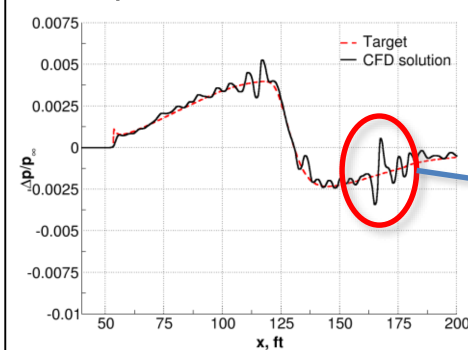
Significance:

- Shaped OML developed using this approach maintains as-designed low-boom performance under high-resolution CFD evaluation.

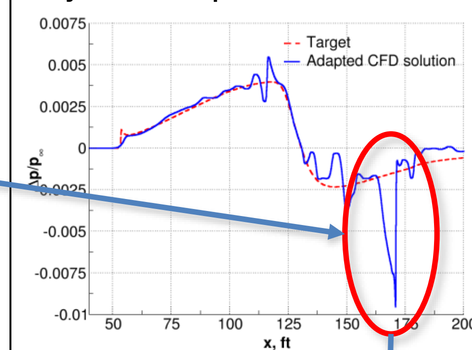
NASA Baseline LBFD Concept



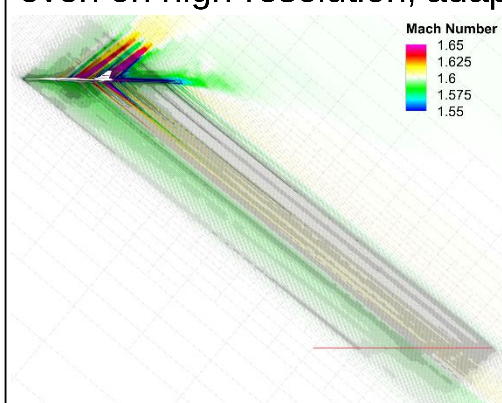
"Best practice" solution

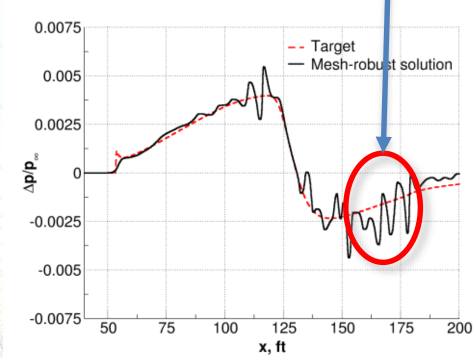


Adjoint-adapted solution



Mesh-robust design delivers consistent performance, even on high-resolution, adaptively refined mesh





Wintzer, M., Ordaz, I., and Fenbert, James W., "Under-Track CFD-Based Shape Optimization for a Low-Boom Demonstrator Concept," 33rd AIAA Applied Aerodynamics Conference (AIAA 2015-2260), June 2015.

Full Carpet Design Approach Demonstrated

Objective:

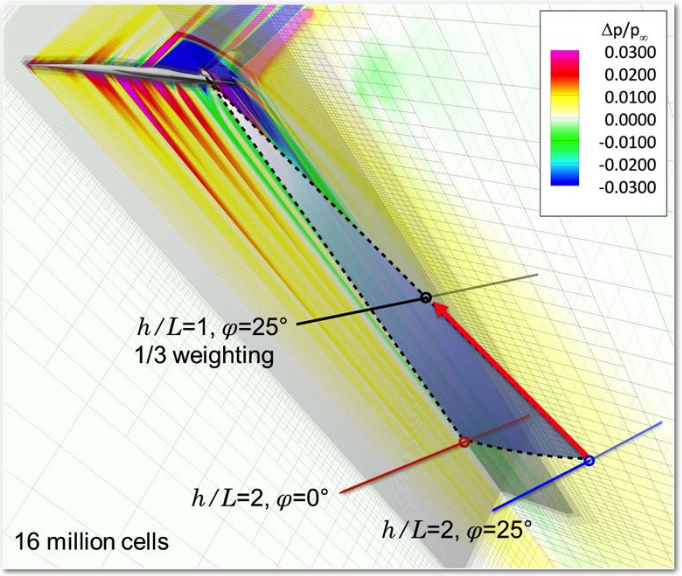
- Demonstrate a conceptual design approach to mitigate the sonic boom of a demonstrator concept across the entire boom carpet.

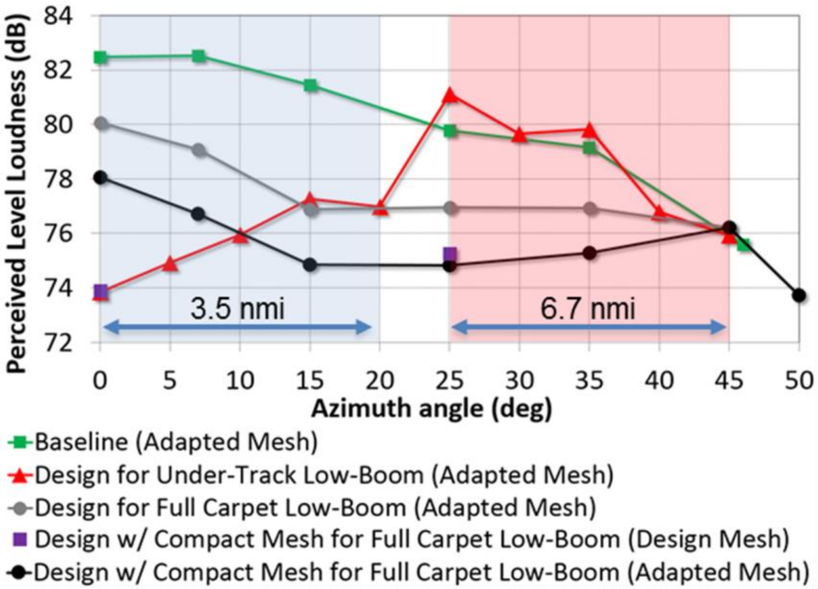
Approach:

- Performed adjoint-based inverse design to low-boom targets located at an offset distance h/L=2, and φ=0º and φ=25º.
- Maintained trim constraint through trim-feasible low-boom target at φ=0º.
- Alternate compact design mesh and off-track target position implemented to improve design response & convergence
- Sonic boom performance verified with an adapted mesh to reduce discretization error.

Significance:

- Successful development of design methodology and tools for low-boom design at off-track positions.
- Compact mesh and alternate off-track target position reduced design cycle time by half.
- Sonic boom successfully reduced across entire sonic boom carpet (up to 6 PLdB improvement).





Ordaz, I., Wintzer, M., and Rallabhandi, Sriram K., "Full-Carpet Design of a Low-Boom Demonstrator Concept," 33rd AIAA Applied Aerodynamics Conference (AIAA 2015-2261), June 2015.

Uncertainty Quantification in CFD & Boom Propagation

Objective:

- Develop a framework for efficient and accurate uncertainty quantification, sensitivity analysis and certification prediction of sonic boom configurations.

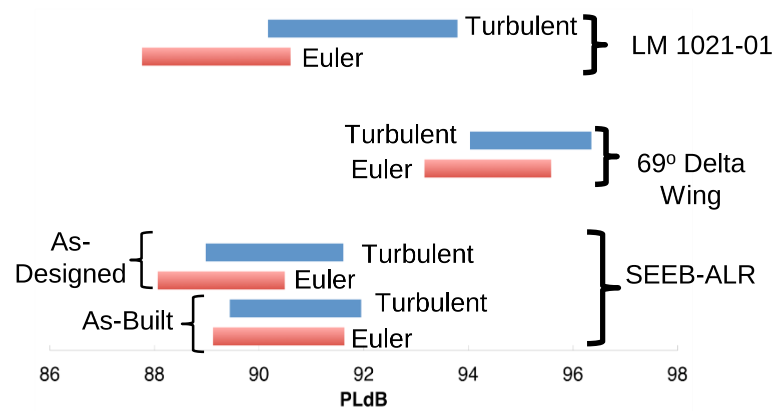
Approach:

- Identify sources of aleatory and epistemic uncertainty in sonic boom modeling and propagation.
- Implement a surrogate-based approach using non-intrusive polynomial chaos for computationally efficient uncertainty propagation.
- Use a sensitivity analysis approach based on the surrogate model to simultaneously obtain global, nonlinear sensitivity results.
- Outline a methodology and metrics for estimating ground noise uncertainty and margins for certification prediction.

Significance:

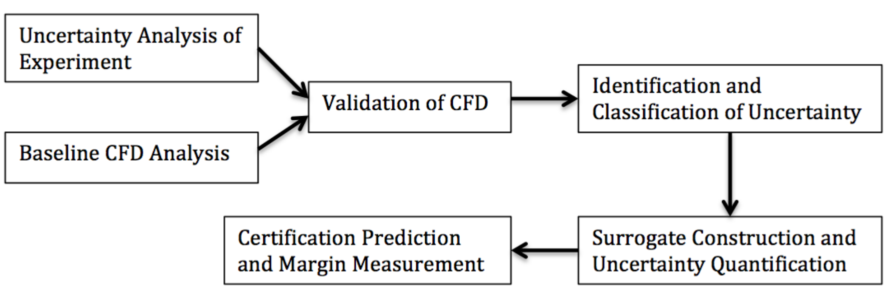
- Quantified the uncertainty in ground noise predictions for multiple configurations of interest.
- Identified key sources of uncertainty in boom propagation.

PLdB 95% Confidence Intervals



Key Fractional Contributions to PLdB Uncertainty for the LM 1021-01

Uncertain Parameter	Euler	Turbulent
Reflection Factor	33.8%	21.9%
Humidity Profile	22.7%	17.9%
Angle of Attack	39.0%	55.1%



West, T., Bretl, K., Walker, E., Pinier, J., "Sonic Boom Pressure Signature Uncertainty Calculation and Propagation to Ground Noise", AIAA 2015-1251, AIAA SciTech 2015, Kissimmee, FL, January 5-9, 2015.

Robust Design under Atmospheric Uncertainty

Objective:

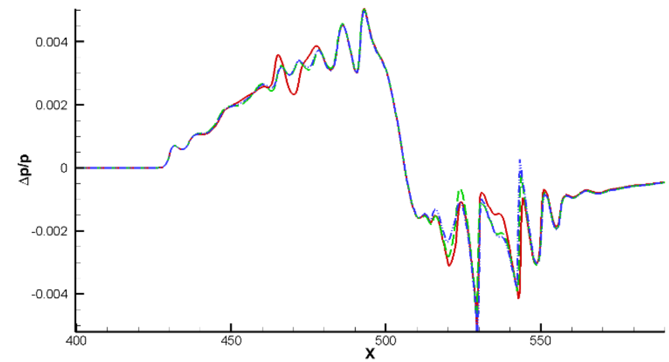
- Employ adjoint-based analysis to incorporate sensitivity to variations in winds, temperature and humidity in low boom aircraft design

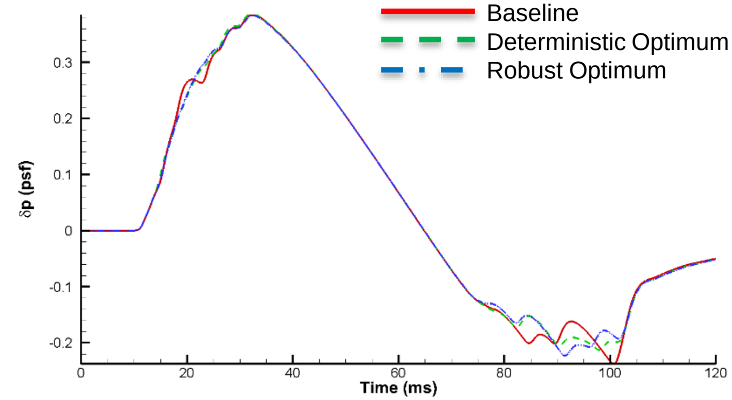
Accomplishments:

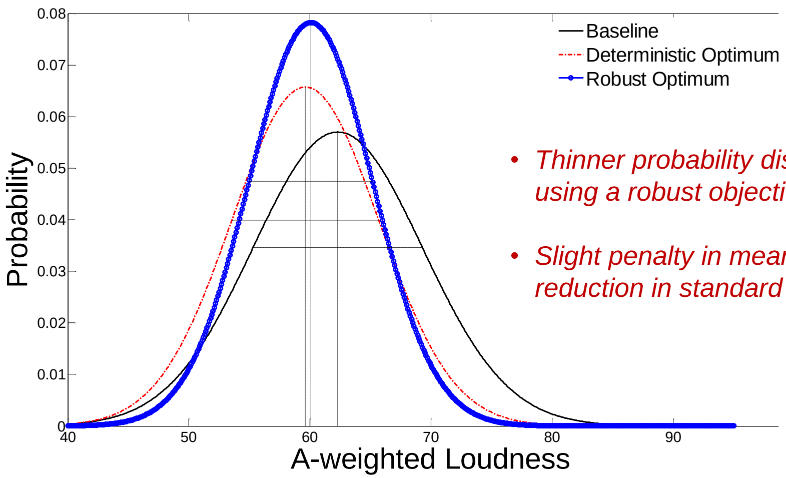
- Robust optimum near-field, ground signature and loudness very close to the deterministic optimum
- Optimization shown to maintain reasonable configuration shape
- Approximately 1.5X computational time for robust optimization compared to deterministic case

Significance:

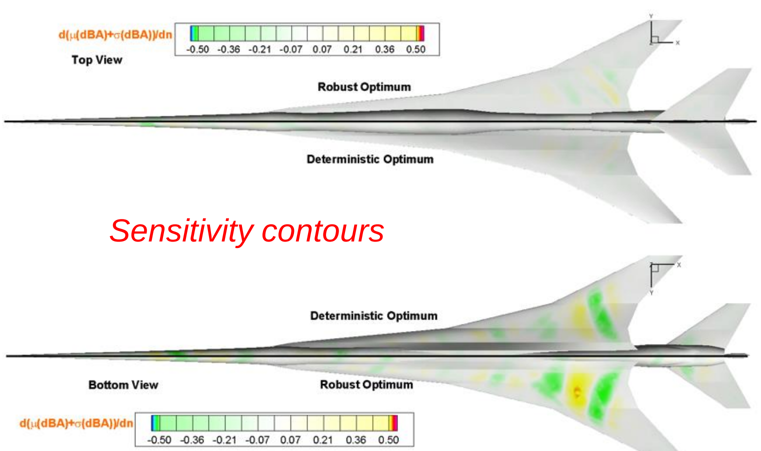
- Efficient new capability to create robust designs that inherently account for the variability in atmospheric conditions







- *Thinner probability distribution using a robust objective measure*
- *Slight penalty in mean for a reduction in standard deviation*



Rallabhandi, S. K., "Uncertainty Analysis and Robust Design of Low-Boom Concepts using Atmospheric Adjoints," 33rd AIAA Applied Aerodynamics Conference (AIAA 2015-2582), June 2015.

High-Fidelity CFD Boom Prediction Tools

Objective:

- Validate high-fidelity CFD boom prediction studies including propulsion effects (inlet & nozzle) with wind tunnel data
- Document CFD best practices

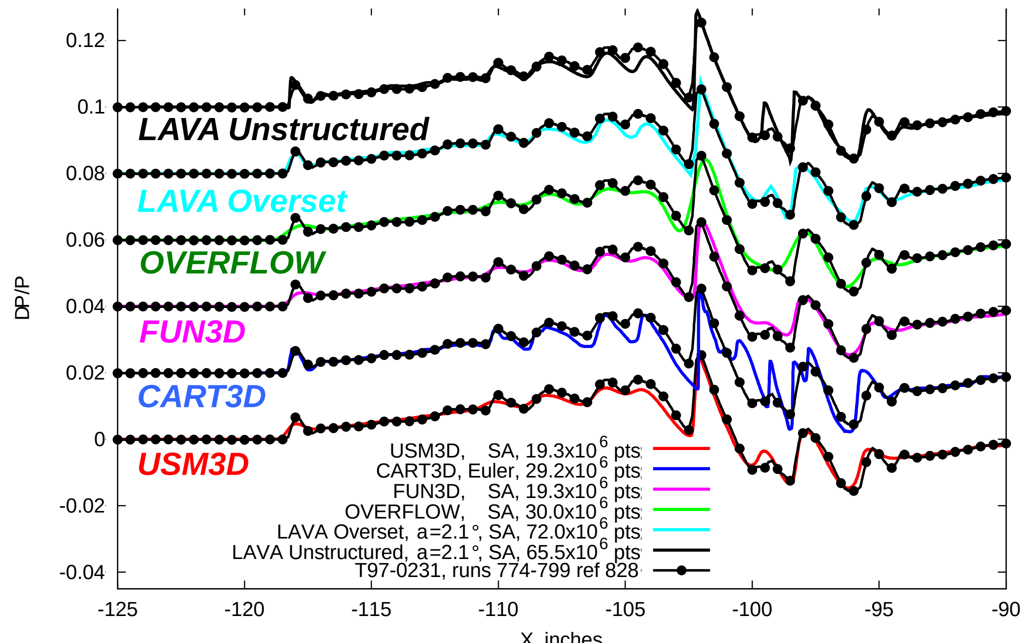
Approach:

- Validate full configurations, including propulsion effects, with wind tunnel data
- Document results and strengths/weaknesses of boom prediction tools
- Study nozzle plume PAI effects at larger scale in 1Q FY16 to further improve confidence in tools

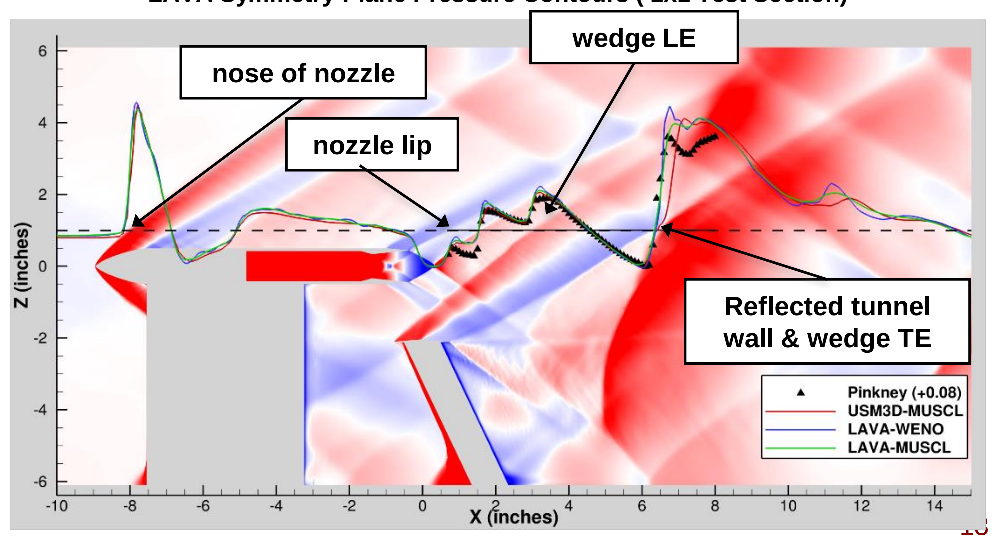
Significance:

- NASA & industry researchers have a high-fidelity tool set, validated with wind tunnel data, to support low-boom design of new supersonic transport concepts

CFD-Exp of Lockheed 1021 Wind Tunnel Model, M=1.6, α=2.3°, Re=8.1x10^6, H=20.7 in.



Computational & Experimental Signatures along Probe Traverse Overlaying LAVA Symmetry Plane Pressure Contours (1x1 Test Section)



Cliff, S., Durston, D., Elmiligui, A., Walker, E. and Carter, M., "Experimental and Computational Sonic Boom Assessment of Lockheed-Martin N+2 Low Boom Models", NASA/TP-2015-218483, January, 2015.

Durston, D., Elmiligui, A., Cliff, S., Winski, C., Carter, M. and Walker, E., "Experimental and Computational Sonic Boom Assessment of Boeing N+2 Low Boom Models", NASA/TP-2015-218482, January, 2015.

Inlet Flow Field Effects

Objective:

- Validated predicted top mounted inlet flowfield effects on sonic boom signature
- Collected experimental data on inlet performance and flow quality for top mounted low boom supersonic inlet

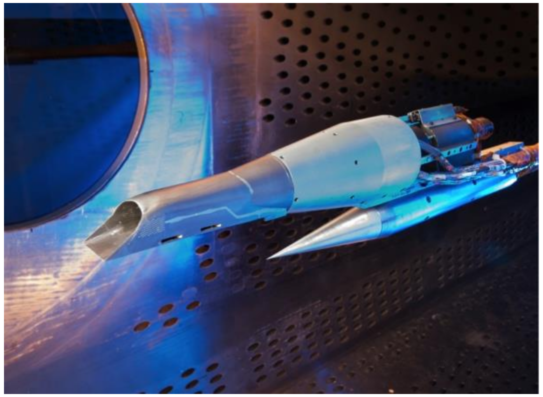
Approach:

Two entry test series to take advantage of best capabilities of NASA facilities

- GRC 8x6 Supersonic Wind Tunnel
  - Inlet performance with inlet simulator and remote control mass flow plug
- ARC 9x7 Unitary Wind Tunnel
  - Sonic boom signature data with pressure rail

Significance:

- Isolated and installed inlet performance effects data collected from Mach .25 to 1.8
- Good to Excellent recovery and flow characteristics with Mach, angle of attack and sideslip
- Low boom design shown to be robust to varying inlet flow conditions



Magee, Todd E., Fugal, Spencer R., Fink, Lawrence E., Adamson, Eric E., and Shaw, Stephen G., "System-Level Experimental Validations for Supersonic Commercial Transport Aircraft Entering Service in the 2018-2020 Time Period", NASA/CR-2015-218983, January, 2016.

Nozzle Flow and Shock-Jet Interaction Testing

Objective:

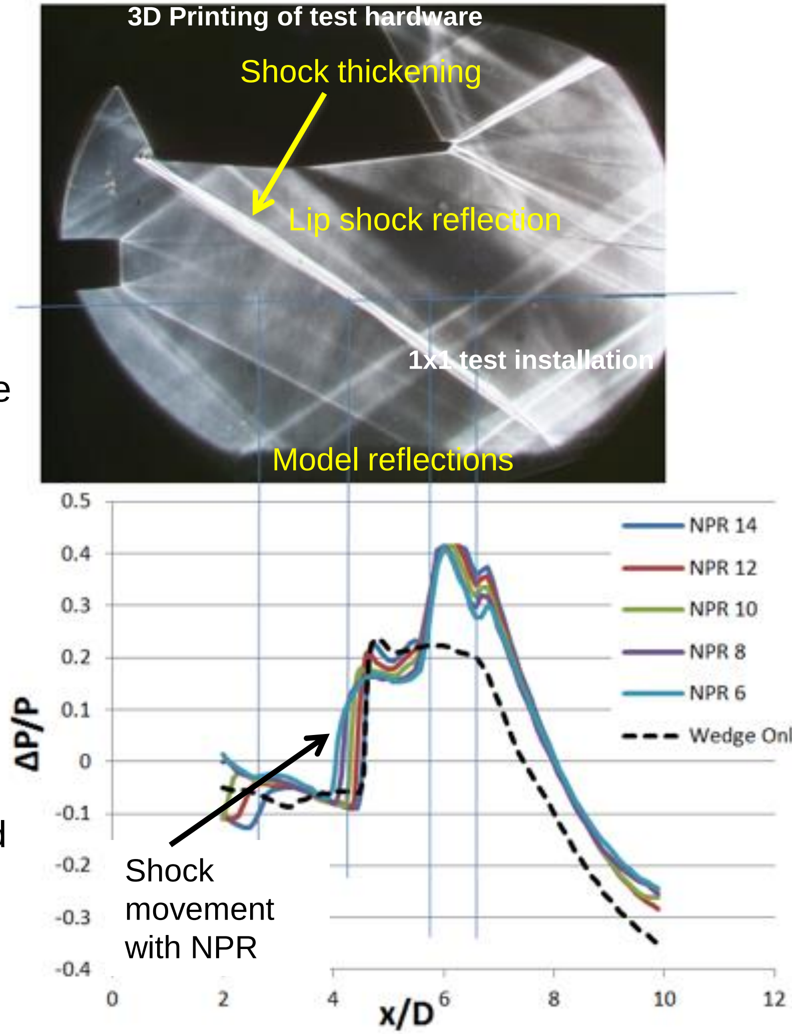
- Identify jet plume and plume-shock interactions effects with potential impact on low boom design
- Create a database for CFD tool validation

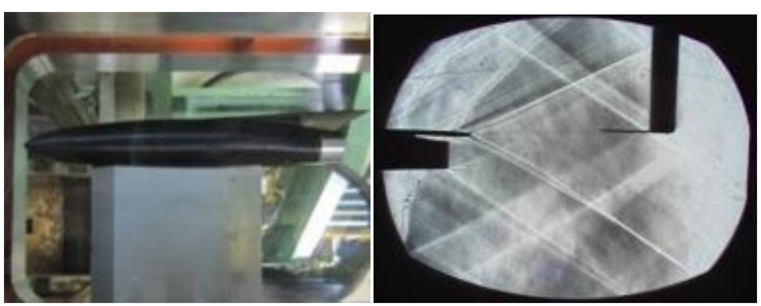
Approach:

- Test in 1ft. x 1ft. SWT at GRC
- Several shock generator and nacelle geometries
  - Included asymmetric nacelles with integrated lift surface
  - Nozzle pressure ratio varied for each case
- Static Pressure, Schlieren and PIV data collected

Significance:

- Previously unseen effects revealed
- Extensive, affordable database available to CFD team
- Some concerns with data
  - Small test section size
  - Static pressure measurement probe data was corrected based on a post-test experimental study





3-D printed Asymmetric nacelle/lifting surface and Schlieren

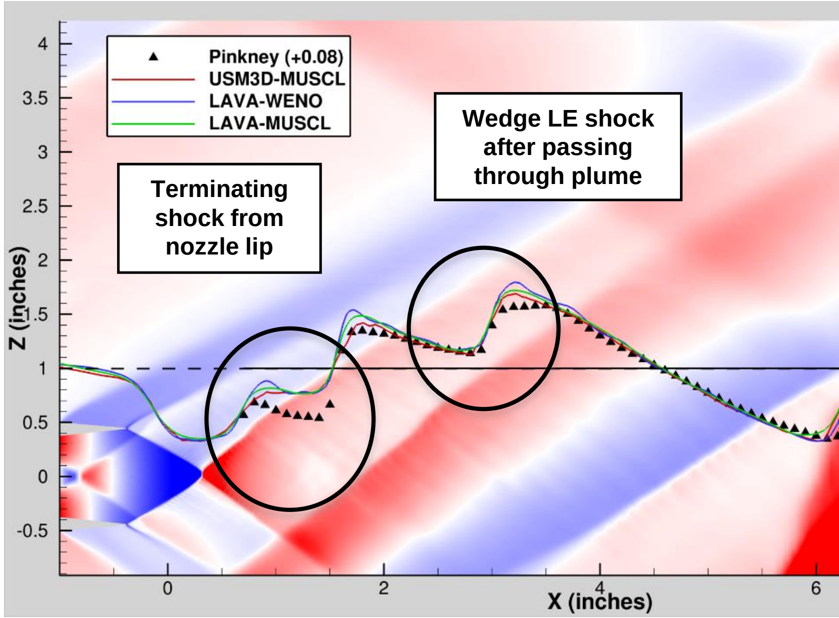
Castner, R.S., Zaman, K.Q., Fagan, A.F. and Heath, C., "Wedge Shock and Nozzle Exhaust Plume Interaction in a Supersonic Jet Flow", AIAA-2014-0232, AIAA SciTech 2014, National Harbor, MD, January 13-17, 2014.

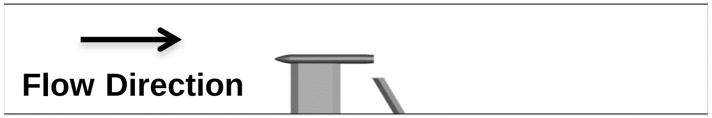
Nozzle Flow with Shock-Jet Interaction
Effect on Boom Signature

Objective:
- Develop and validate CFD capability required to accurately include nozzle flow with impinging shocks (e.g. from a horizontal tail) effect on near field and ground sonic boom signatures

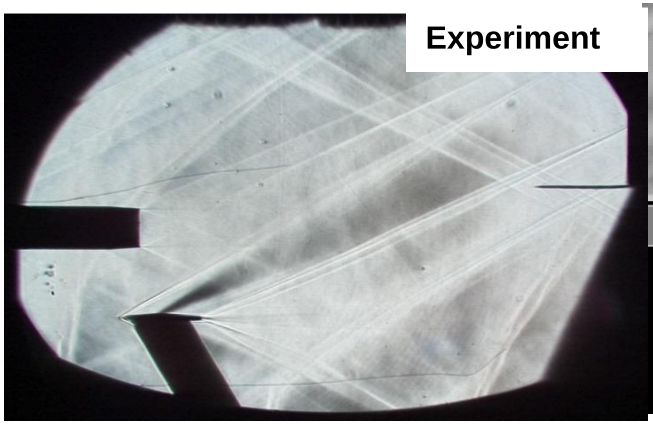
Approach:
- Corrected 1x1 data used for validation
- Due to small scale of tunnel, increased fidelity of facility model used in CFD assessment

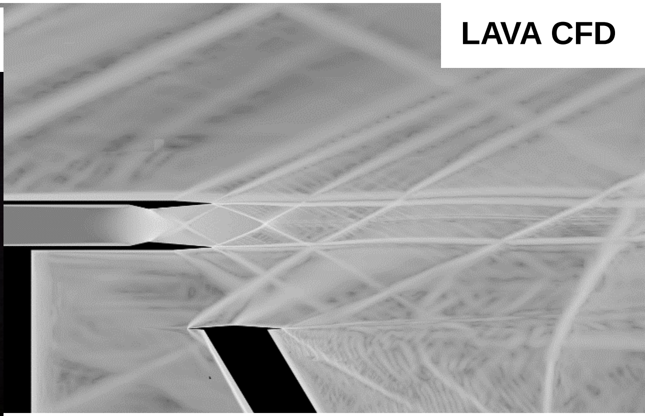
Accomplishment:
- CFD demonstrated good agreement with corrected static pressure probe data





Significance:
- High-fidelity CFD tools validated for nozzle flow and shock-jet interaction in close near field
- Importance of modeling viscous effects demonstrated



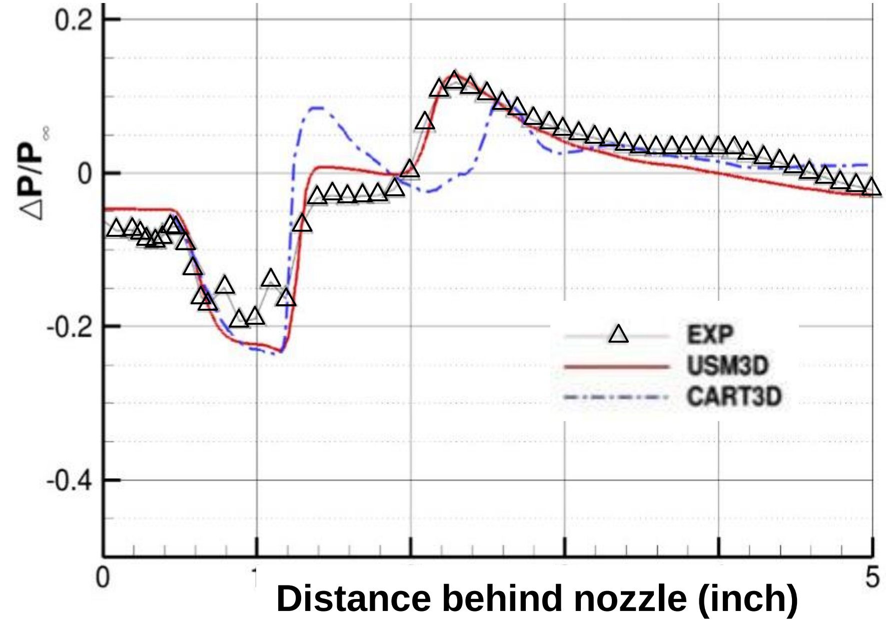


Housman, Jeffrey A. and Kiris, Cetin C., "Numerical Simulations of Shock/Plume Interaction Using Structured Overset Grids," AIAA 2015-2262, 33rd AIAA Applied Aerodynamics Conference, Dallas TX, June 2015.

Carter, M., Elmiligui, A., Nayani, S., Castner, R., Bruce, W., Inskeep, J.,"Computational and Experimental Study of Supersonic Nozzle Flow and Shock Interactions", AIAA-2015-1044, AIAA SciTech 2015, Kissimmee, FL, January 5-9, 2015.

Nozzle Flow with Aft Deck

Effect on Boom Signature



Objective:

- Develop and validate CFD capability required to accurately include nozzle flow with an aft deck effect on near field and ground sonic boom signatures

Approach:

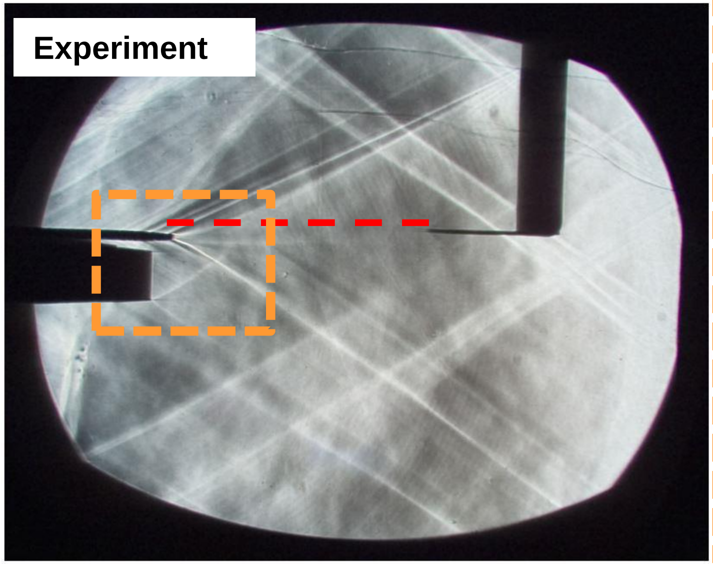
- Corrected 1x1 data used for validation
- Due to small scale of tunnel, increased fidelity of facility model used in CFD assessment

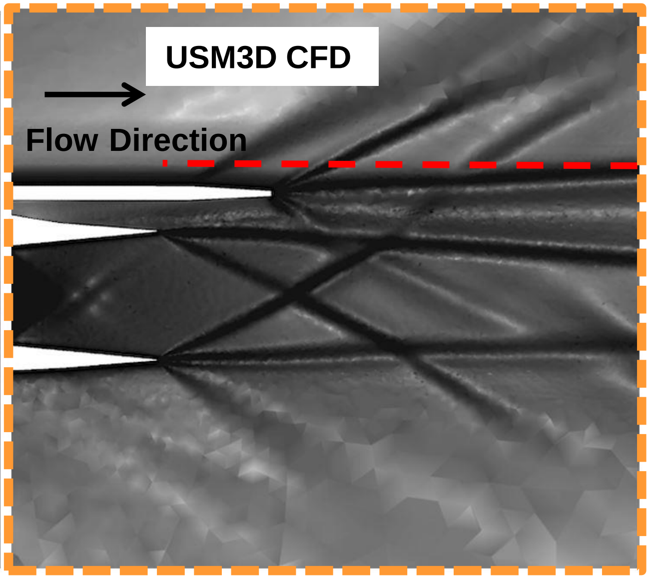
Status in FY14/15

- CFD demonstrated good agreement with corrected static pressure probe data

Significance:

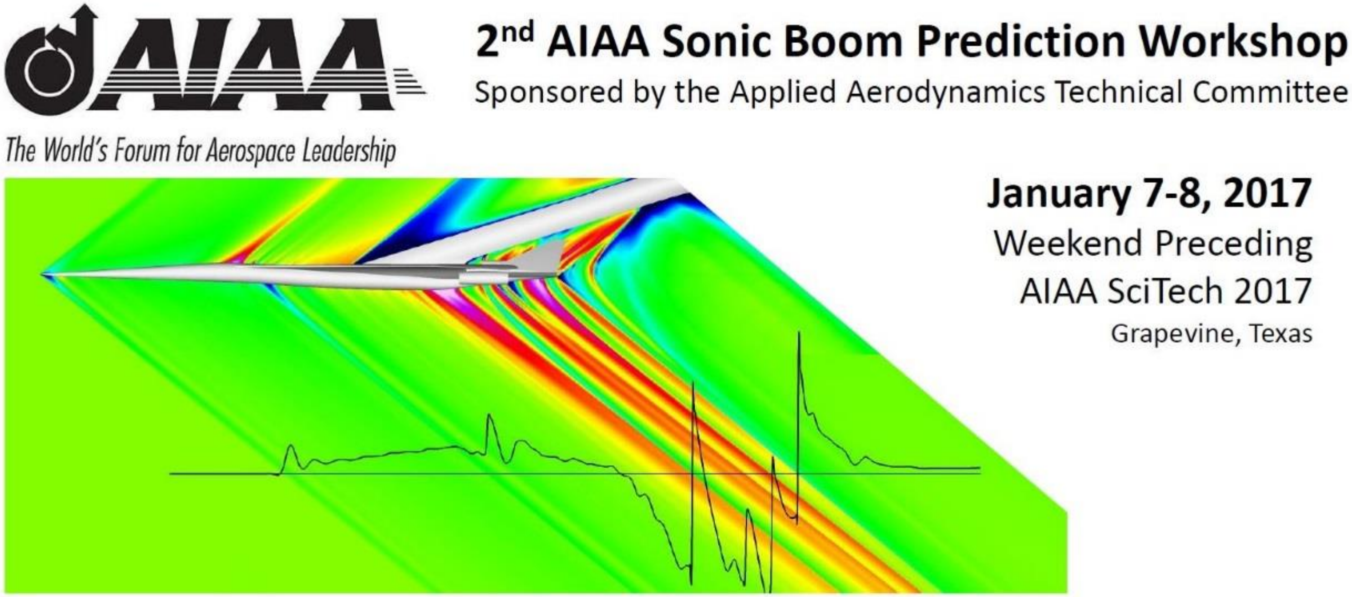
- High-fidelity CFD tools validated for nozzle flow with aft deck in close near field
- Importance of modeling viscous effects demonstrated





Walter E. Bruce, Carter, Melissa B., Elmiligui, Alaa A., Winski, Courtney S., Nayani. Sudheer, and Castner, Raymond S., "Computational and Experimental Study of Supersonic Nozzle Flow and Aft-Deck Interactions", AIAA 2016-2034, AIAA SciTech 2016, San Diego, CA, January 4-8, 2016.

2nd AIAA Sonic Boom Prediction Workshop



- Open to participants worldwide
  - 1st SBPW: 3 countries & 13 orgs submitted results; 7 countries & 24 orgs attended
  - 2nd SBPW include NOIs from: 7 countries & 16 orgs
- 1st SBPW look at simpler cases with higher shaped sonic boom levels
- 2nd SBPW will focus on more challenging lower boom designs including a required complex aircraft case and an optional powered engine case
- Propagation of near field signatures to the ground have been added to this workshop
  - Improve best practices in that critical companion analysis for sonic boom

Summary

Tools and technologies enabling the design of supersonic aircraft that reduce sonic boom noise to 80 PLdB validated as ready for application in a flight demonstrator have been developed.

Developments in tools for analysis and design include:

– Advancements in mesh adaptation, refinement, error estimation, & automation
– New and improved low boom design target generation tools and approaches
– Powered inlet and nozzle boundary conditions for accurate simulation of propulsion flow
– Grid best practices documented for high-fidelity boom prediction
– Robust designs with uncertainty considerations

Validation of CFD tools with wind tunnel tests include:

– Validation tests and CFD comparisons completed for full configuration and inlet flow with pressure rail and spatial averaging technique
– Validation tests and CFD comparisons completed for nozzle flow with single probe and at small scale

New Tech Challenge defined - Integrated Low Boom Aircraft Design (Thru FY22)

➢ Develop tools and processes applicable to a commercial supersonic low boom aircraft throughout the entire flight profile.

➢ Validated analysis techniques that support development of certification procedures for future civil aircraft

Questions?