AMS Seminar

Computational Simulations of a Mach 0.745 Transonic Truss-Braced Wing Design

AIAA-2020-1649

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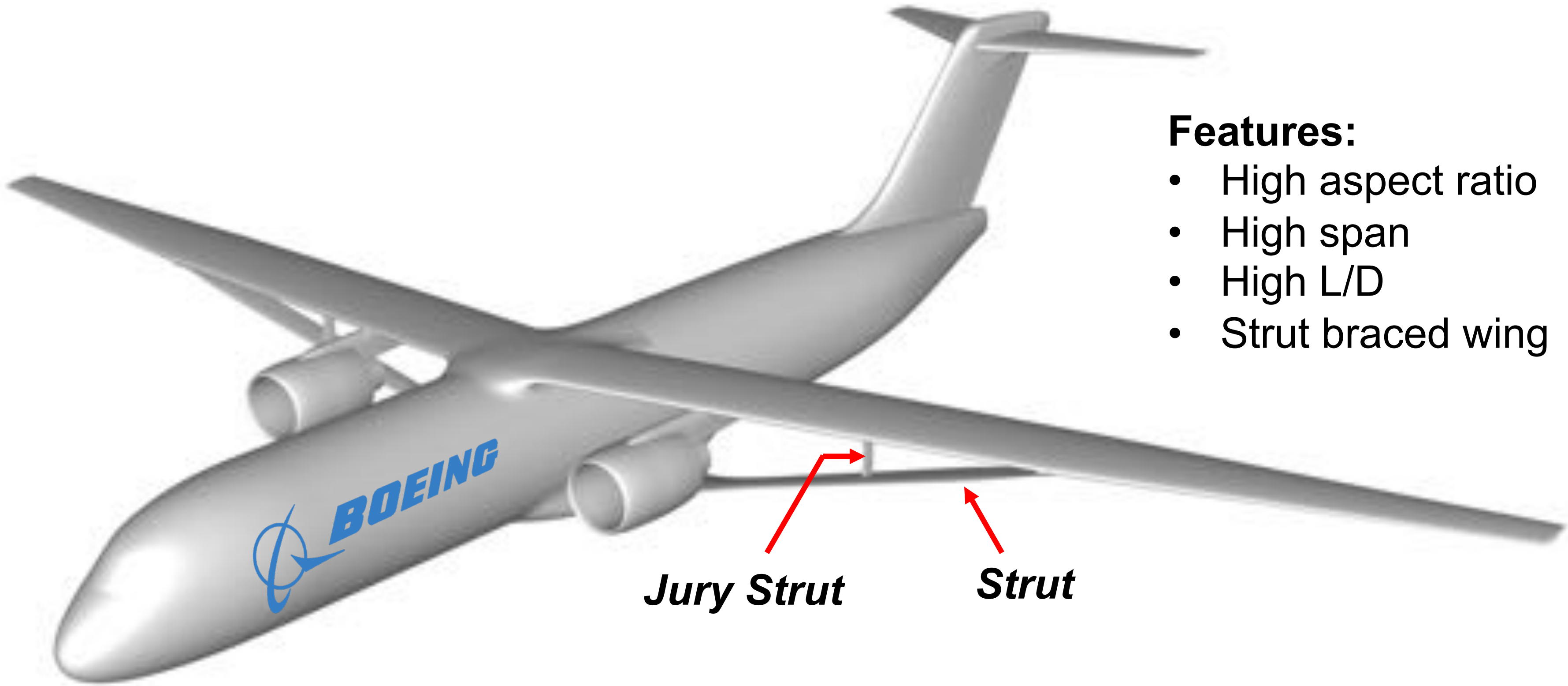
Outline

- Introduction / Objectives
- Computational Methods
  - Codes
  - Modeling Procedure
- Verification Process
  - Grid Refinement Study
  - Verification on Flight Geometry
- Validation with Wind Tunnel Data
  - Free Air
  - Wind Tunnel
  - Geometry Sensitivity Study
- Summary

Introduction



Features:
- High aspect ratio
- High span
- High L/D
- Strut braced wing

Boeing Transonic Truss-Braced Wing (TTBW)

Mach 0.745 Variant

Objectives

- Establish best practices for NASA CFD codes for Transonic Truss-Braced Wing-like configurations.
  - Utilize two grid paradigms
    - Structured Curvilinear with overset
    - Unstructured mixed-element

- Perform validation study of CFD results compared to TTBW wind tunnel experiments.

Description of NASA CFD Codes

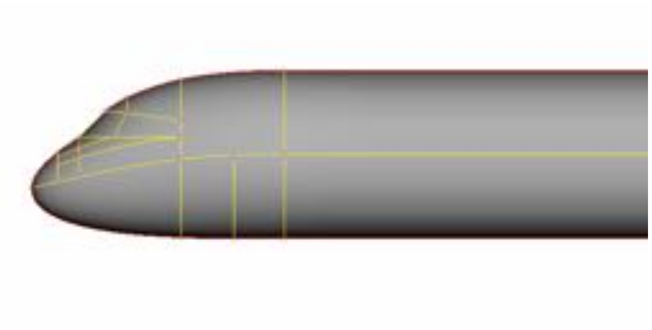
Launch Ascent and Vehicle Aerodynamics (LAVA)

- Vertex-based RANS
- 2nd order finite difference formulation
- Koren limiter
- Structured curvilinear overlapping grids
- Spalart-Allmaras turbulence model
  - Rotation / Curvature Correction (RC)
  - Quadratic Constitutive Relationship (QCR2000)

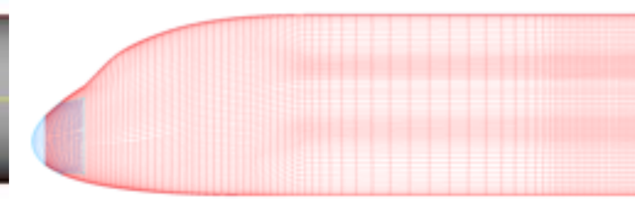
USM3D from TetrUSS (Tetrahedral Unstructured Software System)

- Cell-centered RANS
- 2nd order finite volume formulation
- No limiter
- Mixed-element unstructured meshes
- Spalart-Allmaras turbulence model
  - With and without QCR2000

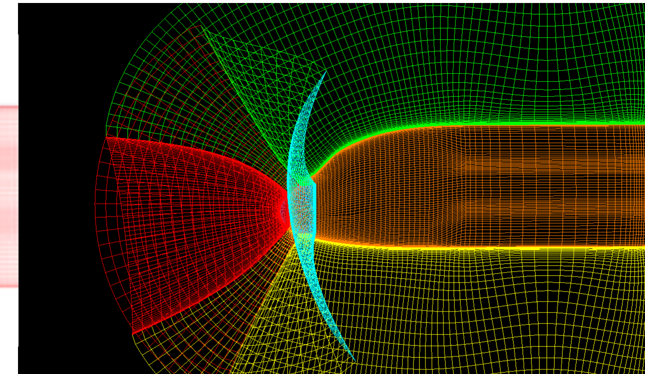
Structured Overset Grid Generation



1. Geometry clean up and preparation using ANSA



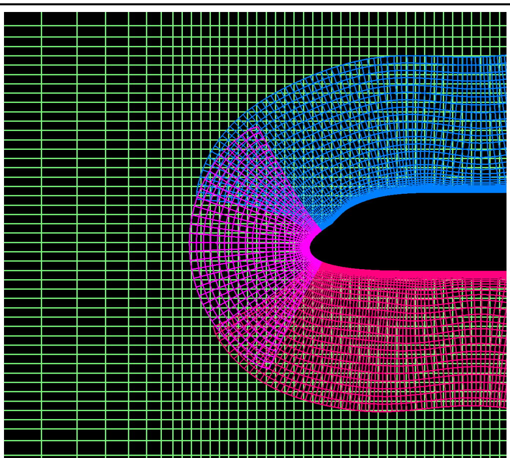
2. Surface mesh generation using Pointwise



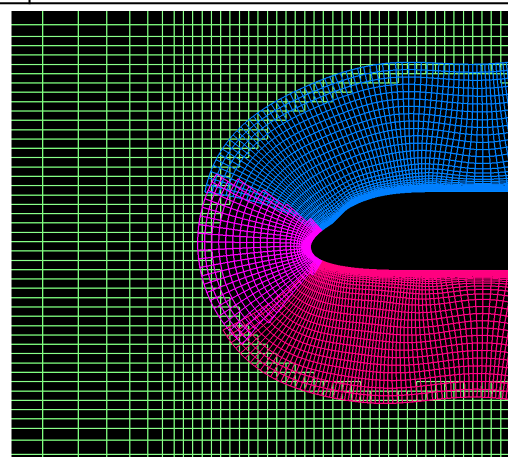
3. Volume mesh generation using Chimera Grid Tools (CGT)

- Maintaining a $y^+ \leq 1$
- Double fringe
- Consistent first layer spacing across all viscous walls
- Half model with symmetry plane

Other Guidelines



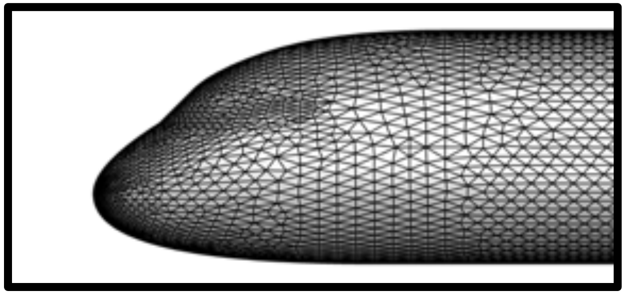
4. Domain Connectivity using DCF Module of OVERFLOW



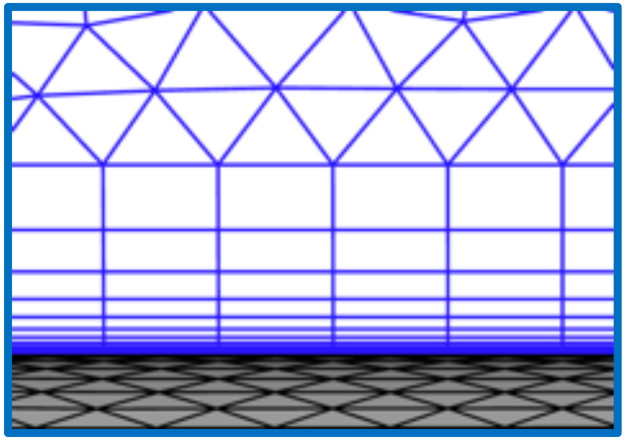
5. Minimized overlap regions between grid using LAVA MIHC

Unstructured Mixed-Element Grid Generation

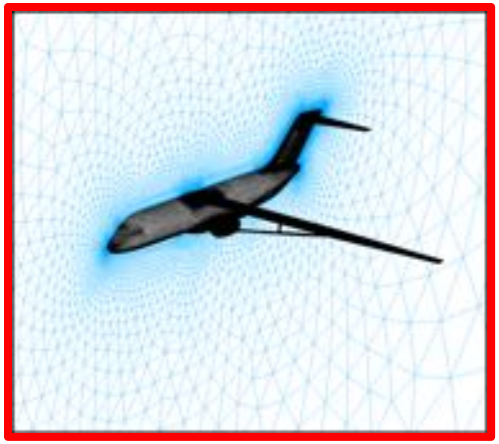
1. IGES CAD imported into Heldenmesh
2. Generate triangulated surface mesh



3. Adjust first layer height to $y^+ \approx 1$. First cell centroid of approximately $y^+ = 0.5$.
4. Cell to cell growth rate of 11-14%
5. Mixed-element mesh with 32 layers of prismatic cells for the boundary layer
6. Pyramidal cell transition to tetrahedral meshes in the outer grid

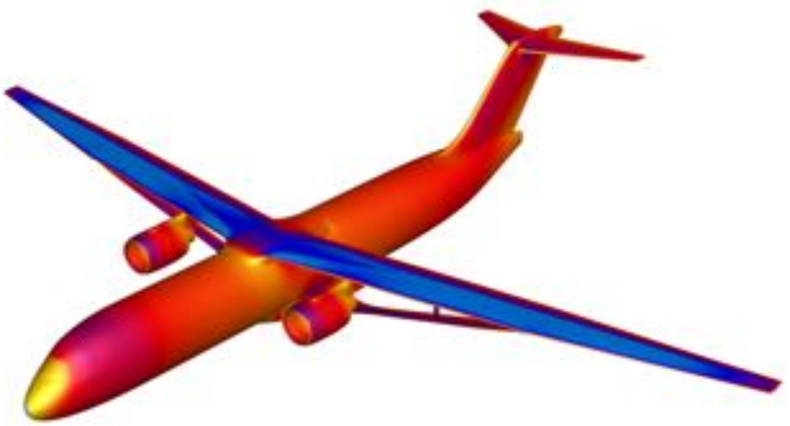


7. Half Model with Symmetry Plane



Verification and Code to Code Comparison

- Code to code comparison was done to remove sensitivity to grid type from the simulation, quantify the uncertainty, and help diagnose cause of discrepancies with experimental results



USM3D Sample Simulation

LAVA

- Grid convergence study
- Angle of attack effect on grid convergence
- Flux discretization effect on grid convergence
- Wake grid
- Angle of Attack sweep with best practices

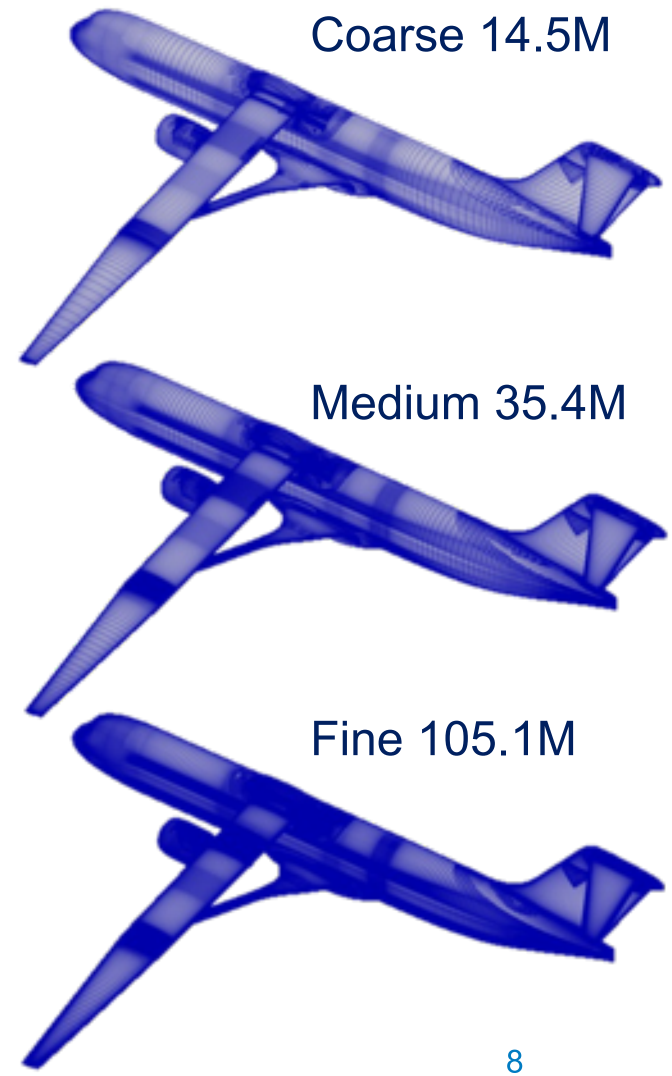
USM3D

- Grid convergence study
- Angle of attack effect on grid convergence
- SA vs SA-QCR2000
- Angle of Attack sweep with best practices

Structured Overset Grid Refinement Process

- A scale factor (*SF*) is used for each refinement level
  - 3 Refinement Levels created.
  - Coarse (*SF*=1), Medium (*SF*=1.4), Fine (*SF*=2.0)
- Surface grids are refined in Pointwise using script
  - Edge spacing scaled by inverse of *SF*
  - Number of points scaled by *SF*
- Scripts used to generate volume grids with CGT have *SF* built-in to account for any refinement level

Resulting Volume Grids



Unstructured Mixed-Element Grid Refinement Process

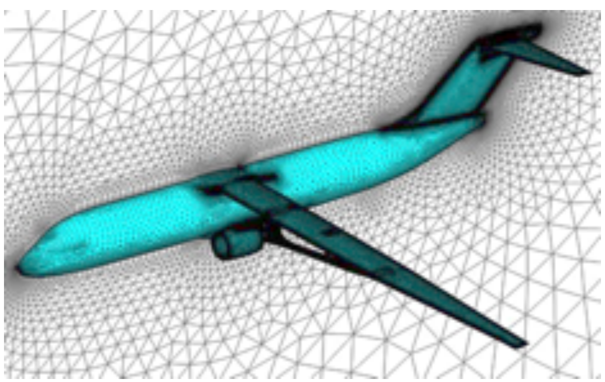
- Three refinement levels are created.
  - Coarse, Medium, Fine

- Mesh refinement and coarsening using Heldenmesh

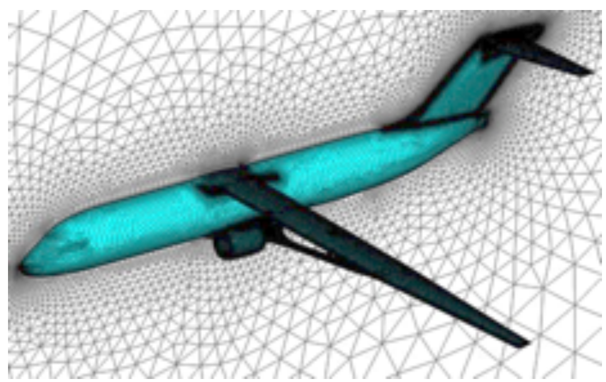
- Grid sourcing scaled by approximately $1/\sqrt{2}$ and $\sqrt{2}$ to obtain finer and coarser meshes

- Scaling of $1/\sqrt{2}$ and $\sqrt{2}$ applied to surface mesh, viscous layers, and volume mesh.

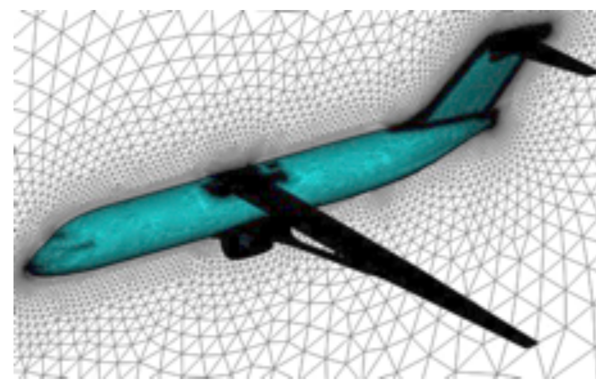
Coarse 18.5M



Medium 31.3M

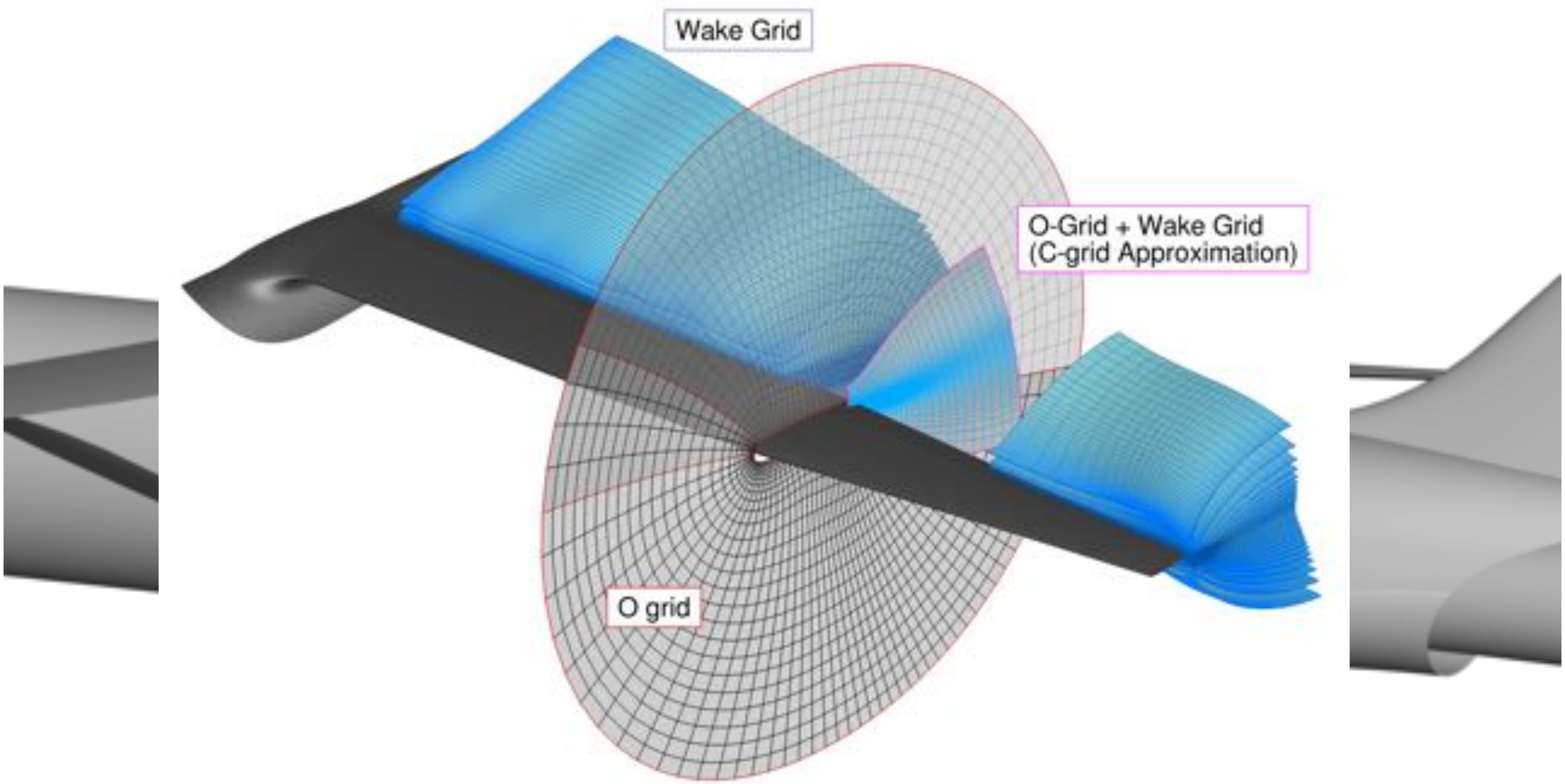


Fine 59.4M



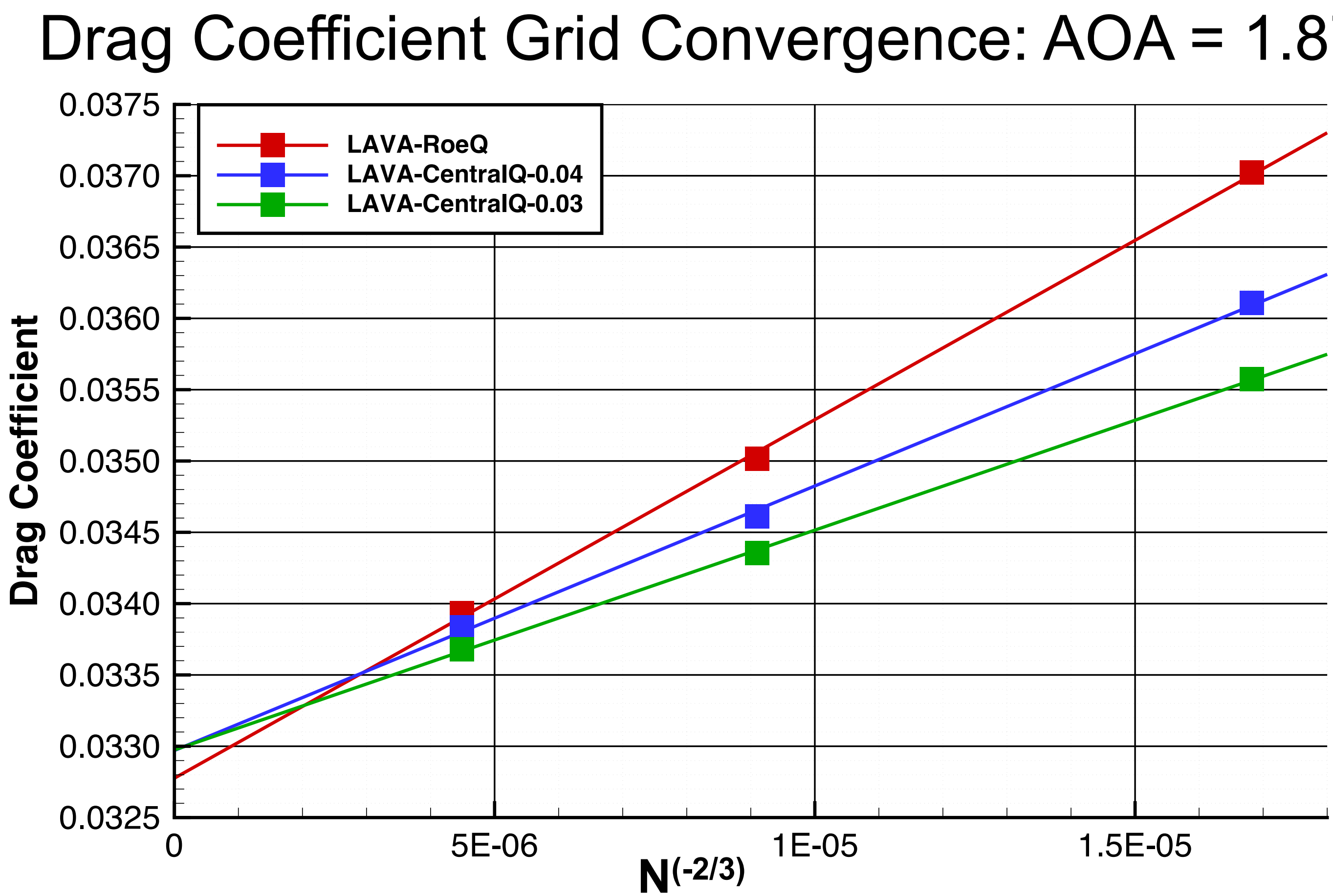
Wake Mesh

- Approximates C-Grid Topology
- Improves the capture of the wing wake



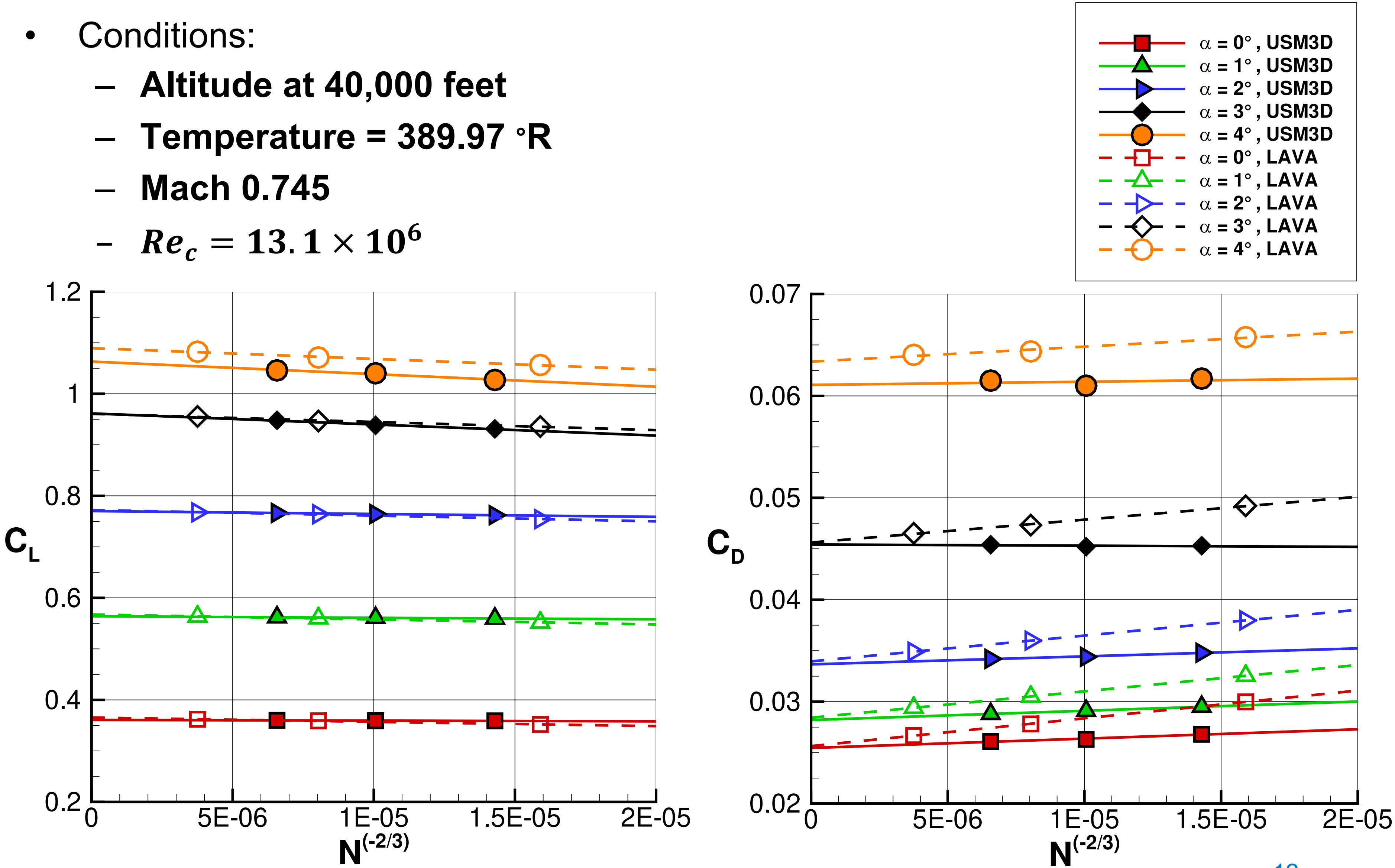
Flux Discretization Scheme

- For evaluating convergence, the loads of the 3 different grid levels are plotted against $N^{-2/3}$.
- Linear fit used to evaluate asymptotic convergence and estimate the load value for infinitely refined grid



Grid Convergence Comparison - LAVA and USM3D

- Conditions:
  - **Altitude at 40,000 feet**
  - **Temperature = 389.97 °R**
  - **Mach 0.745**
  - $Re_c = 13.1 \times 10^6$



Grid Convergence Comparison - LAVA and USM3D

Comparison of loads at $\alpha = 2^{\circ}$

LAVA SA-RC-QCR2000

Refinement Level	Nodes (Million)	C_L	C_D	C_m
Coarse	14.5	0.7543	0.03798	-0.1097
Medium	36.4	0.7640	0.03599	-0.1184
Fine	105.1	0.7677	0.03490	-0.1246
Asymptote	∞	0.7732	0.03375	-0.1297

USM3D SA-QCR2000

Refinement Level	Cells (Million)	C_L	C_D	C_m
Coarse	18.5	0.7621	0.03480	-0.1278
Medium	31.3	0.7643	0.03439	-0.1285
Fine	59.4	0.7665	0.03421	-0.1298
Asymptote	∞	0.7702	0.03367	-0.1313

Difference between codes

C_L	C_D	C_m
0.39%	0.8 Counts	-1.23%

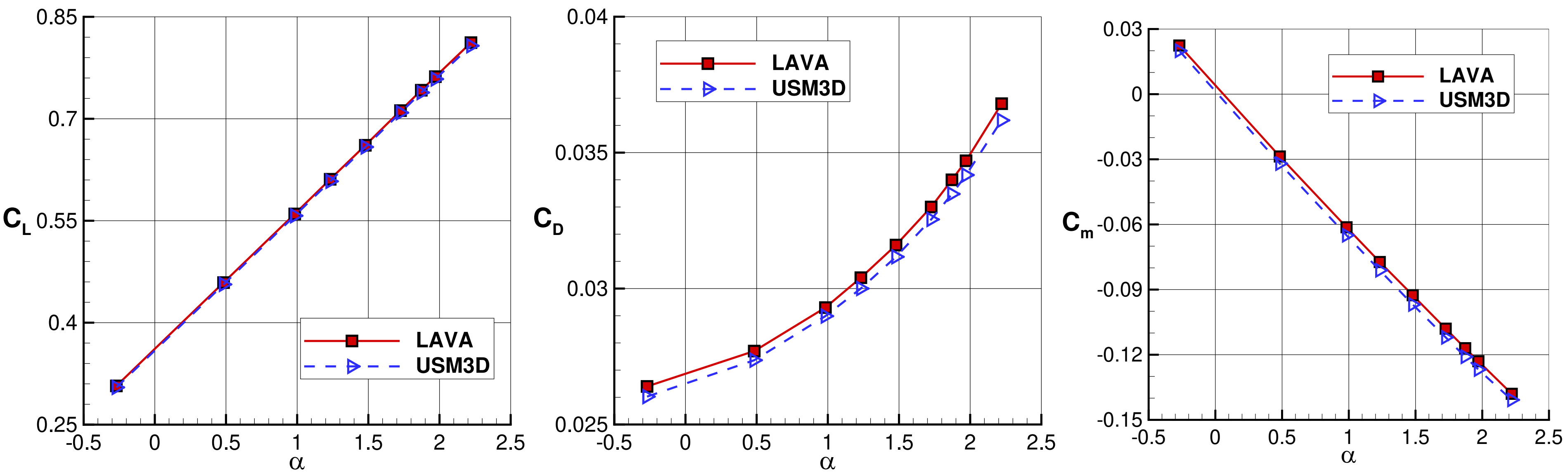
Difference using only Coarse and Medium data points to find Asymptote

C_L	C_D	C_m
0.76%	22.7 Counts	-1.16%

Difference using only Medium and Fine data points to find Asymptote

C_L	C_D	C_m
-0.057%	-3.3 Counts	-1.23 %

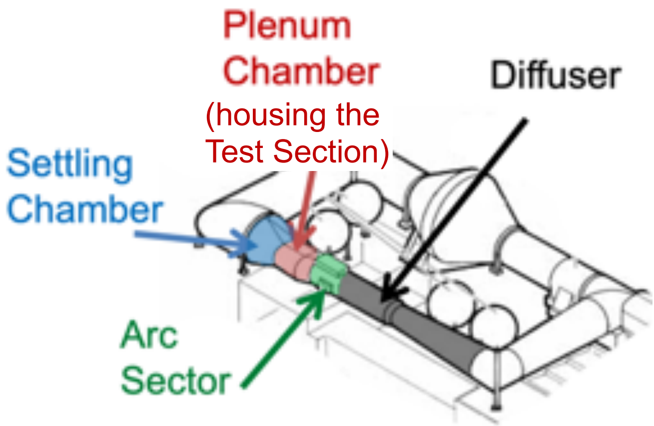
Code to Code Comparison – AOA Sweep



- LAVA SA-RC-QCR compared with USM3D SA-QCR
- The code to code comparison at flight conditions was successful in verifying the codes would arrive at a similar solution
- Throughout the sweep C_L varied by **0.38-0.73%**, C_D by **2.4 to 6.1** counts
  - Slight shift in C_m due to drag differences

Wind Tunnel Test - Background

- A 4.5% scale model was built to be tested in the NASA Ames Unitary Plan 11-foot Transonic Wind Tunnel (TWT).

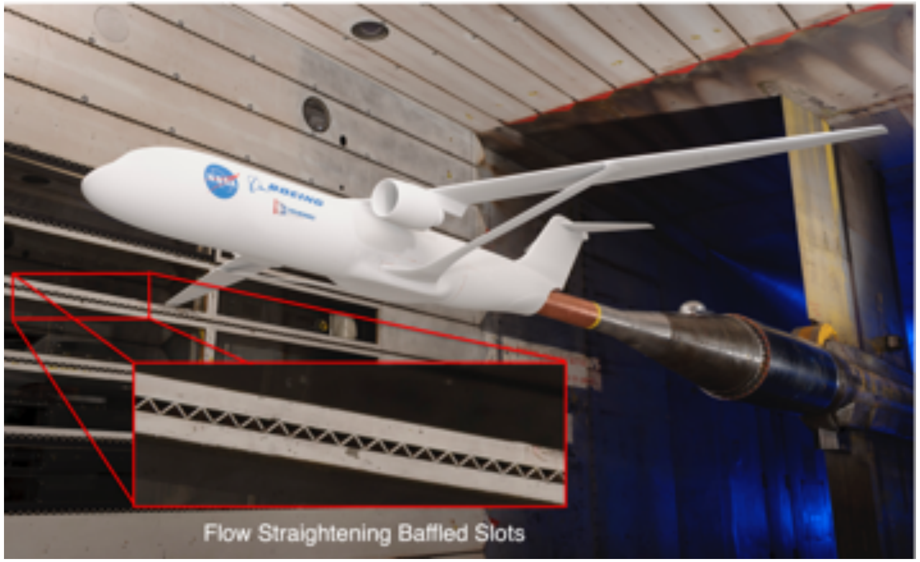


Schematic of 11ft TWT
Courtesy of NASA

NASA Ames Unitary Plan Wind Tunnels
Courtesy of NASA

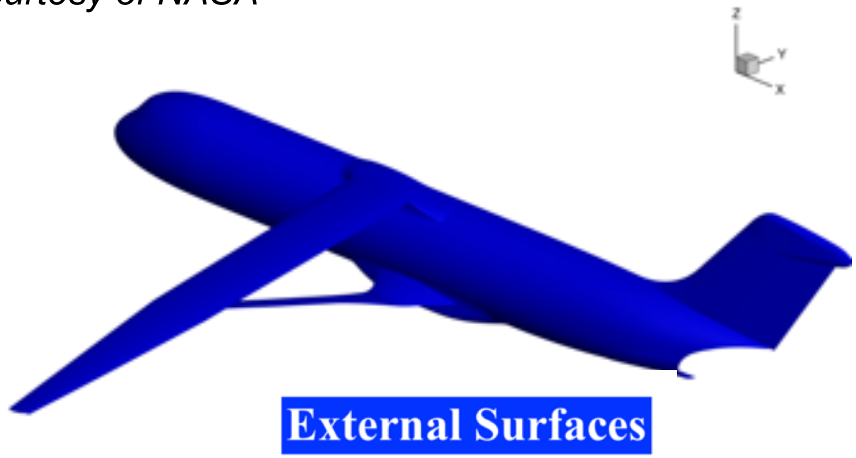
- The 11-ft TWT is a closed-circuit fixed-geometry tunnel composed of a settling chamber, a ventilated test section enclosed by a plenum, an arc sector to actuate the model, and a diffuser.

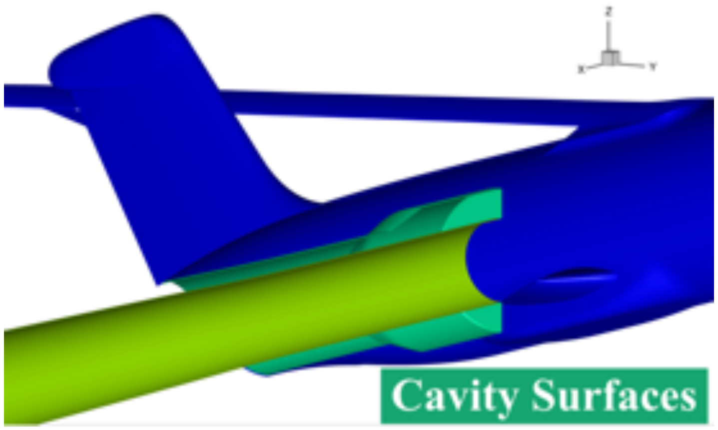
Experimental Conditions and Data



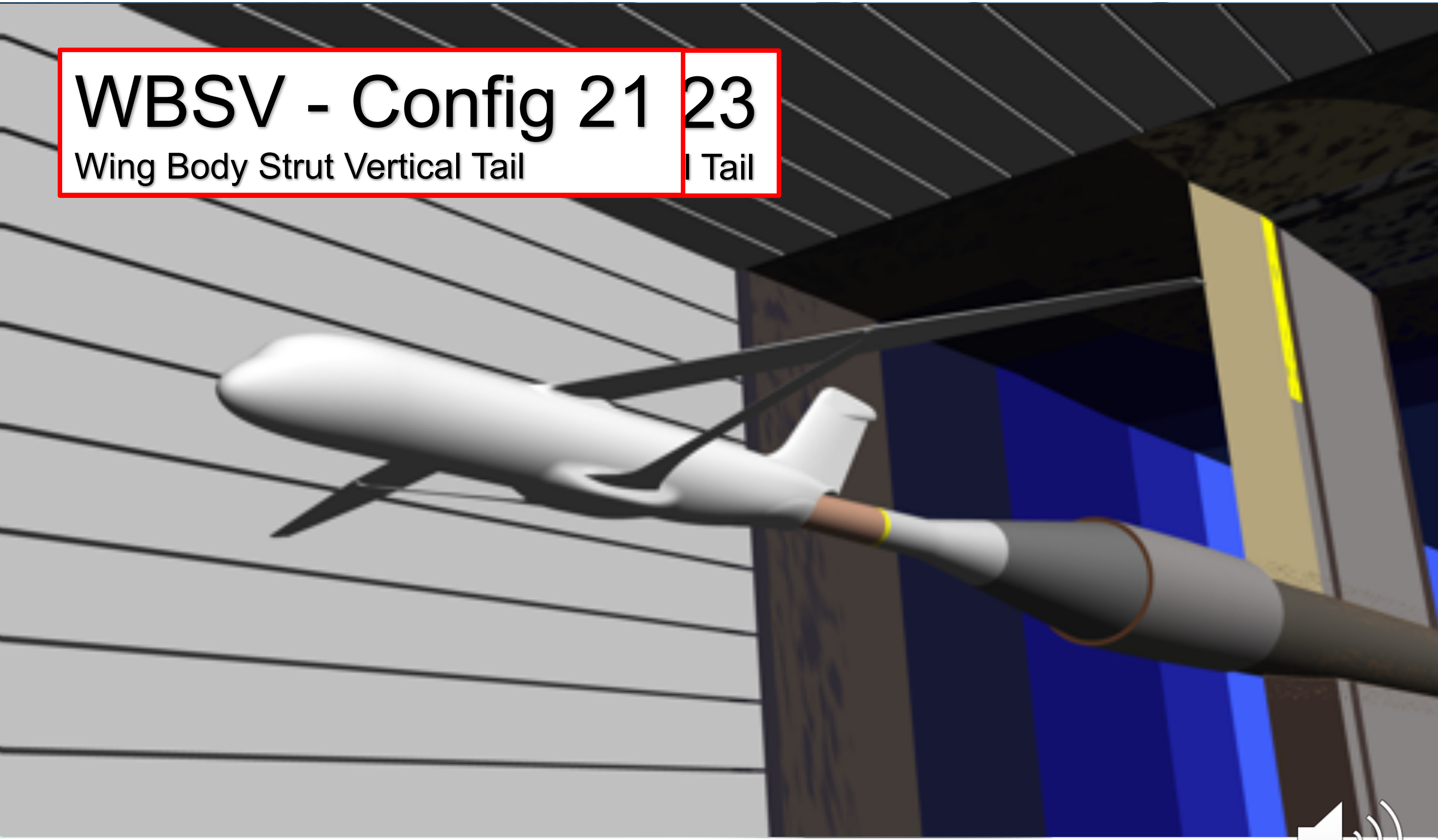
Mach 0.745 TTBW installed in 11ft TWT
Courtesy of NASA

- **Wind Tunnel Data**:
  - Raw data (Uncorrected)
  - Cavity Correction
    - Accounts normal and axial forces and pitching moment inside of cavity where sting attaches to fuselage
  - All corrections (Corrected)
    - Approximates free air condition





Computational Geometry



Validation with Experimental Data

LAVA

- Grid convergence studies
- Free-air simulations
  - WBSV
  - WBSNPV
- Slotted-wall wind tunnel simulations
  - 2nd Order Steady Rans
  - Mixed Order Steady Rans
  - 1st Order Unsteady Rans
- Simplified wind tunnel
  - Inviscid Channel
  - Viscous Wall Wind Tunnel
- Porous Wall
  - Full Body
  - Half Body
- Sensitivity to Geometry Corrections
  - Twisted Wing
  - Trailing Edge

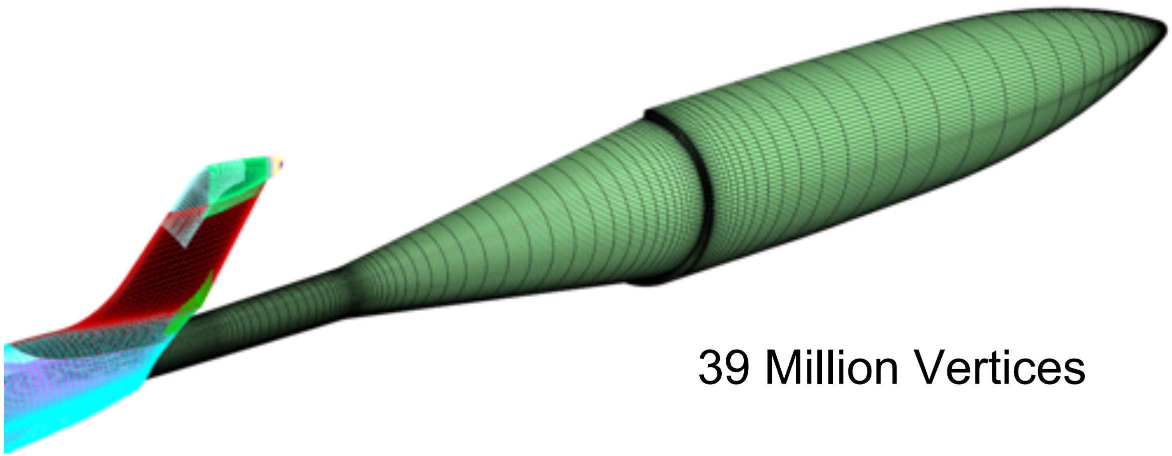
USM3D

- Grid convergence studies
- Free-air simulations
  - WBSV
  - WBSNPV
- SA vs SA-QCR2000

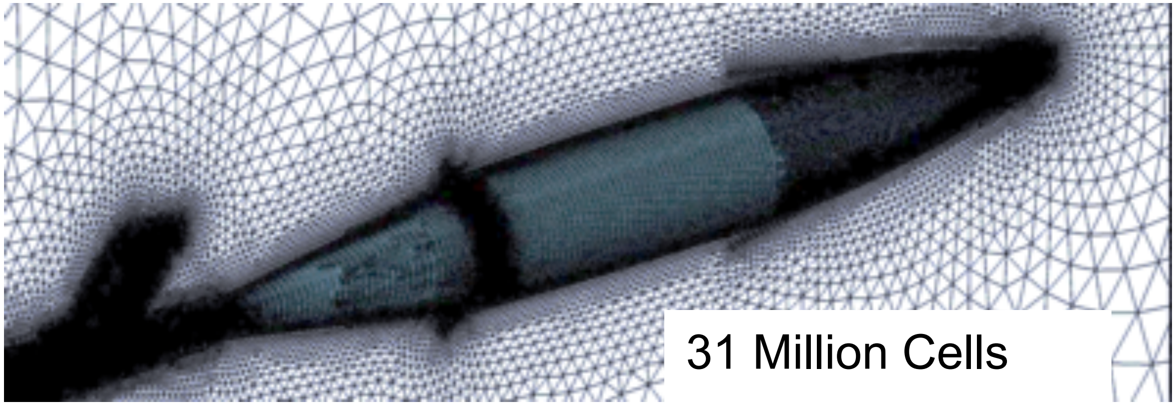
- **Wind Tunnel Conditions**:
  - $T_{Freestream} \approx 493\ ^\circ R$
  - $T_{Stagnation} \approx 550\ ^\circ R$
  - Mach 0.745
  - $Re_c = 3.31 \times 10^6$
  - $-2^\circ < \alpha \lesssim 4^\circ$

Mesh for Wind Tunnel Validation

- Grid refinement was run for both codes



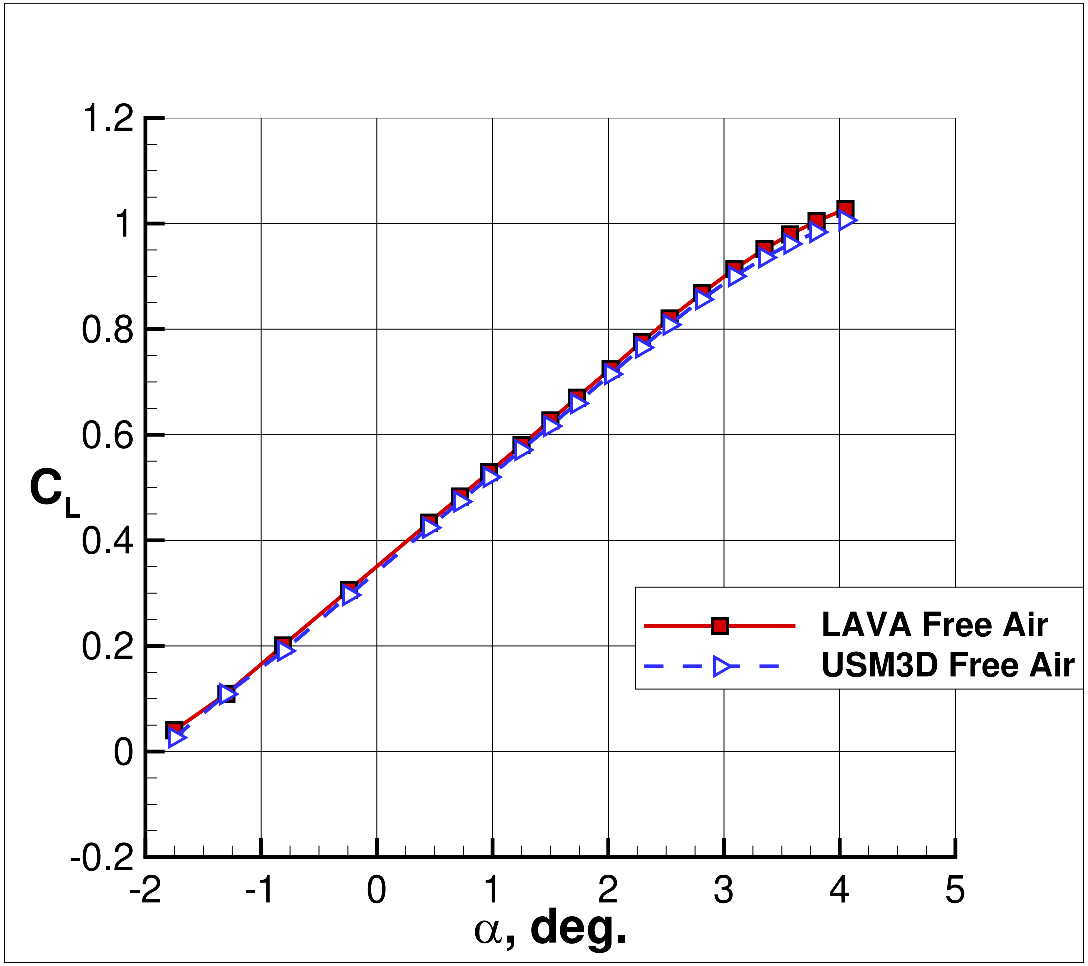
- LAVA simulations were run with a medium grid resolution rather than the fine grid to reduce computational cost



- USM3D found their medium grid to be sufficiently fine

Validation with Wind Tunnel Data

Free Air – WBSNPV Config 23



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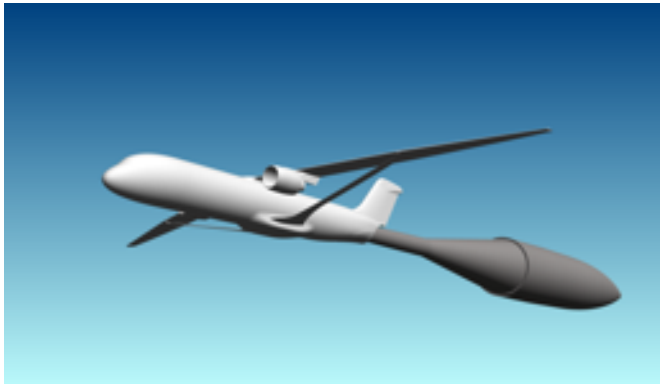

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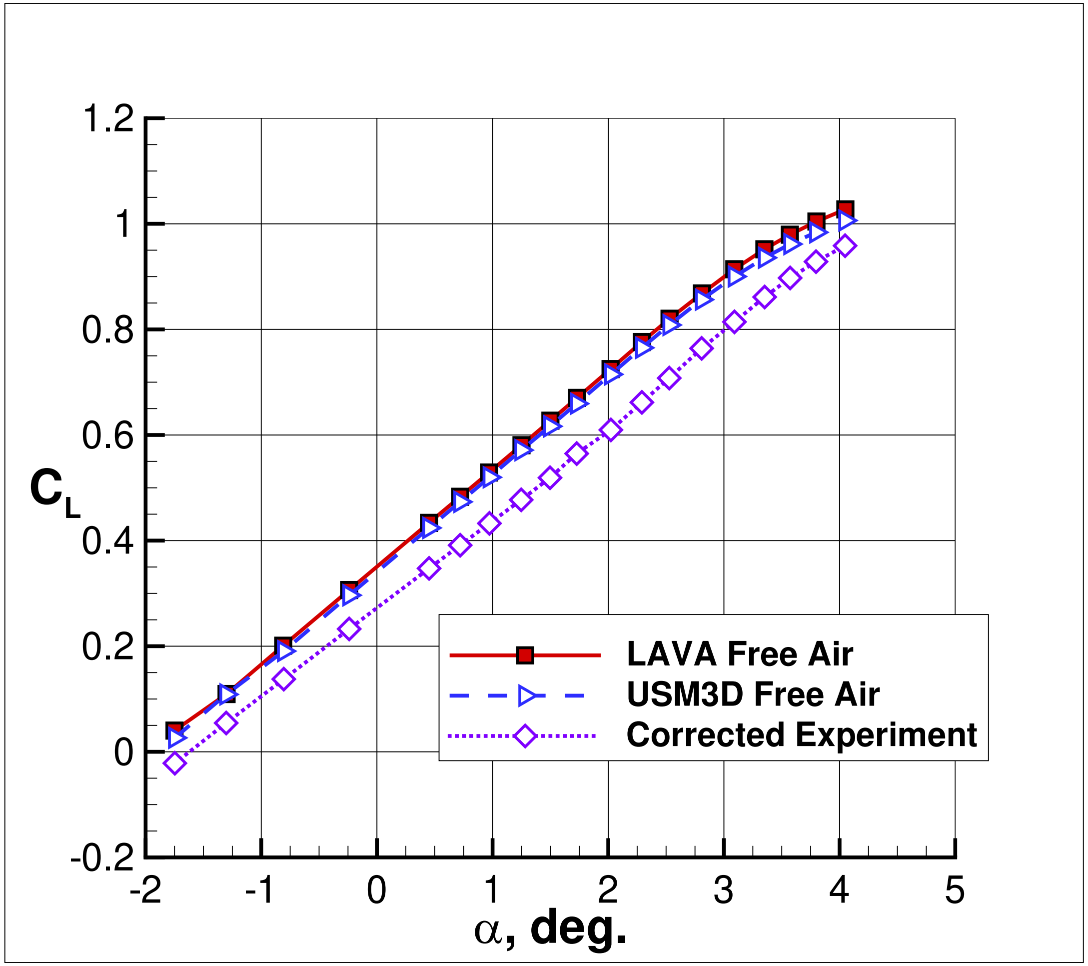

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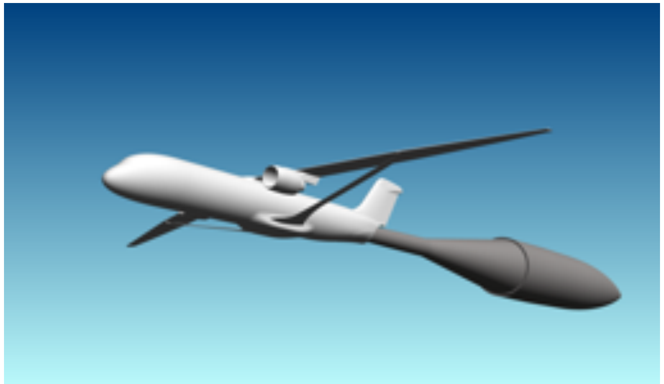

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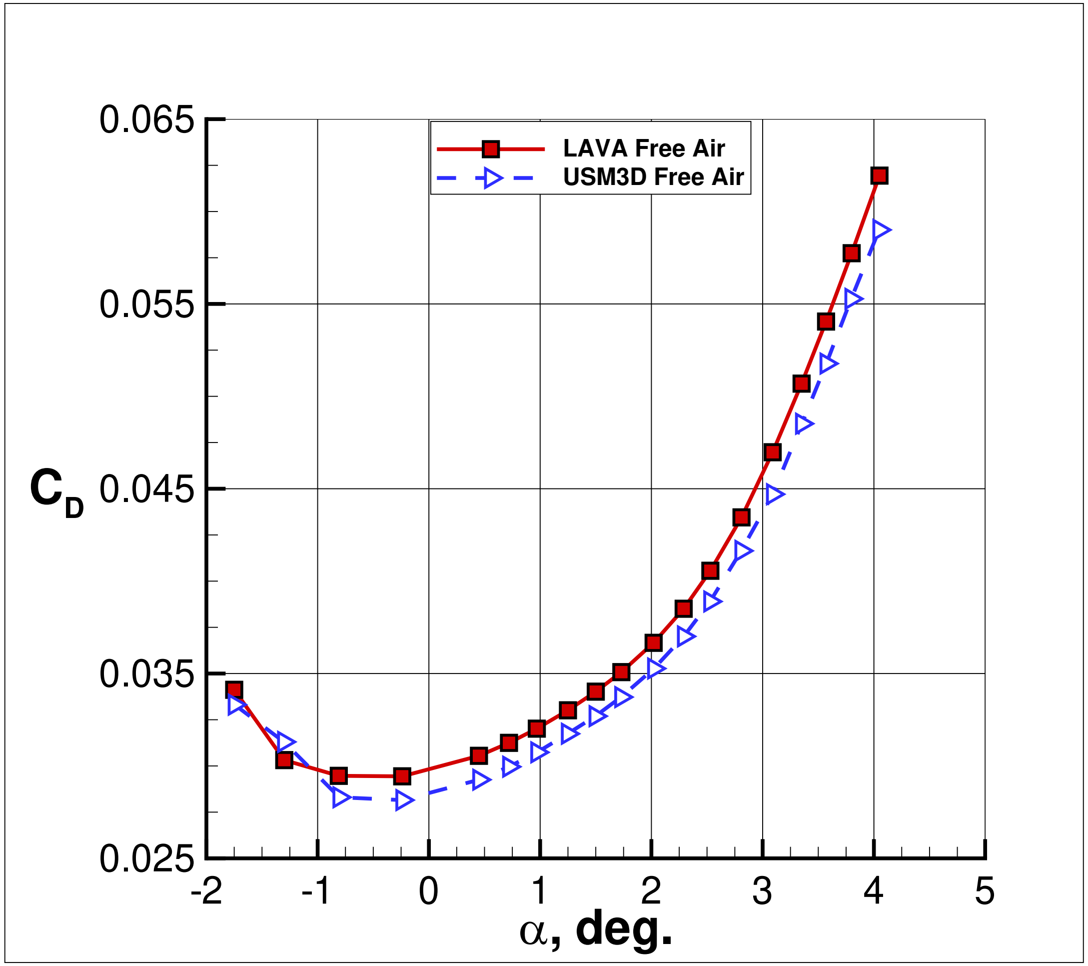

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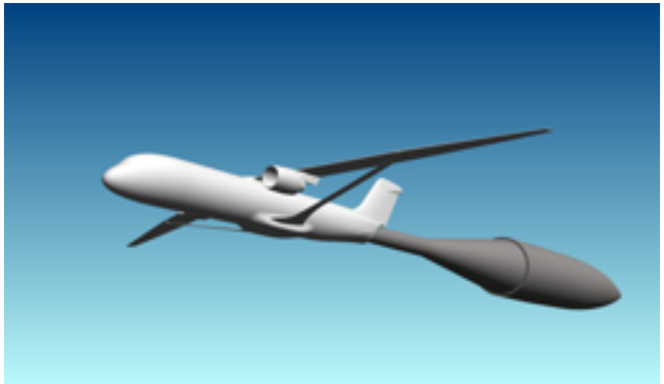

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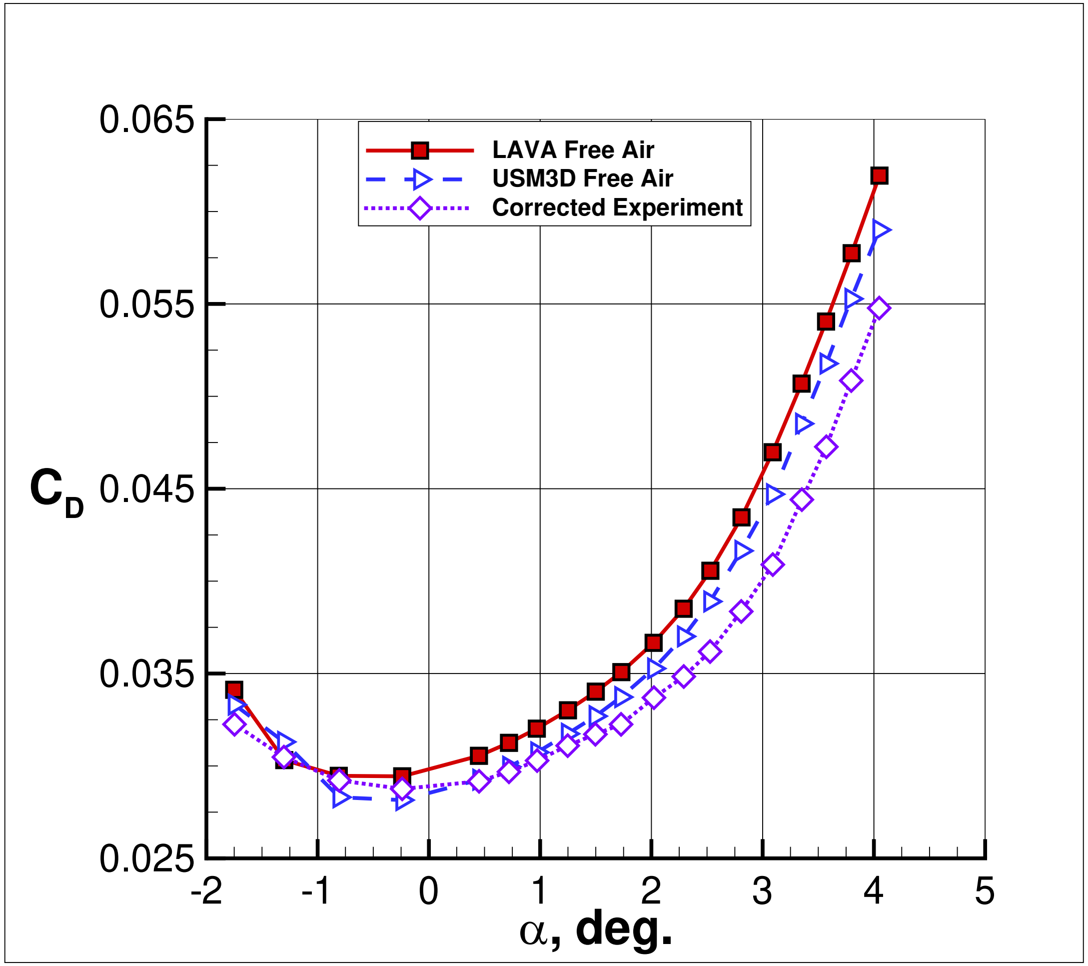

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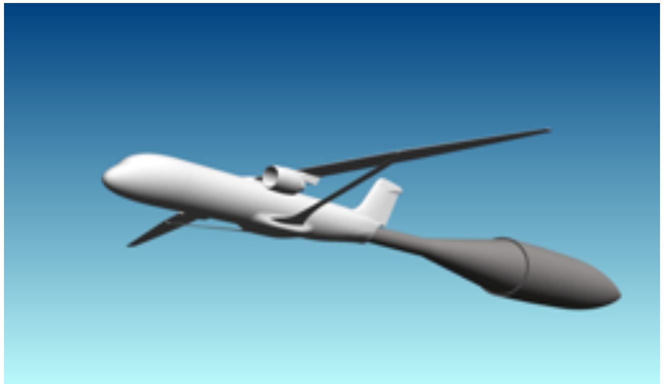

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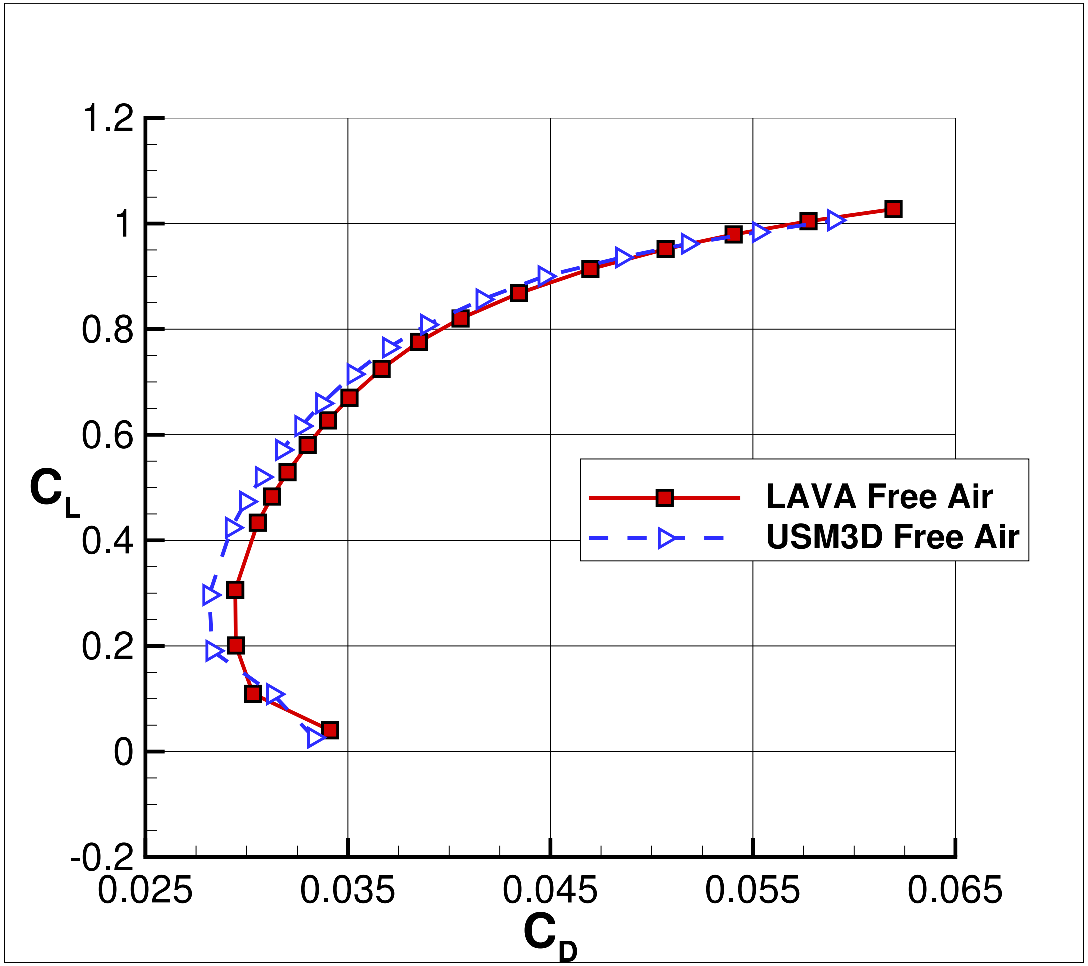

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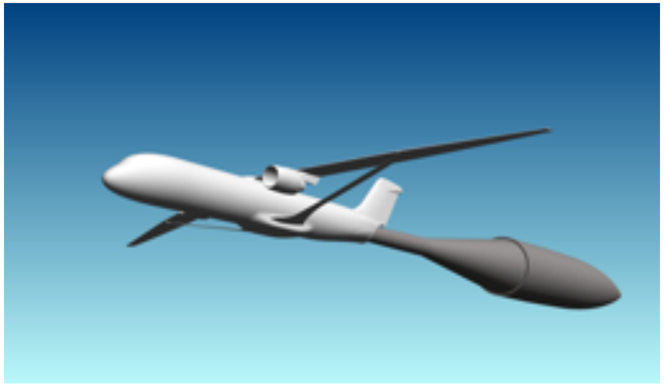

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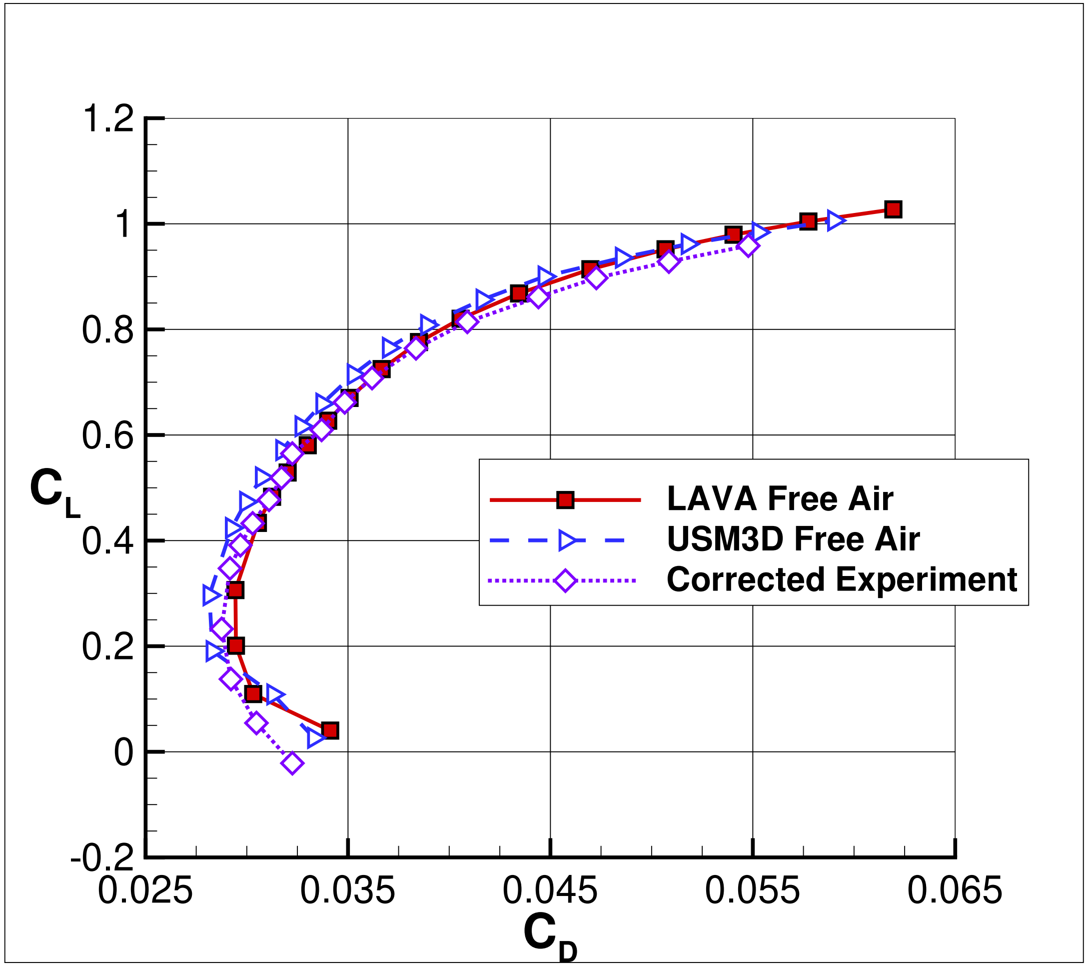

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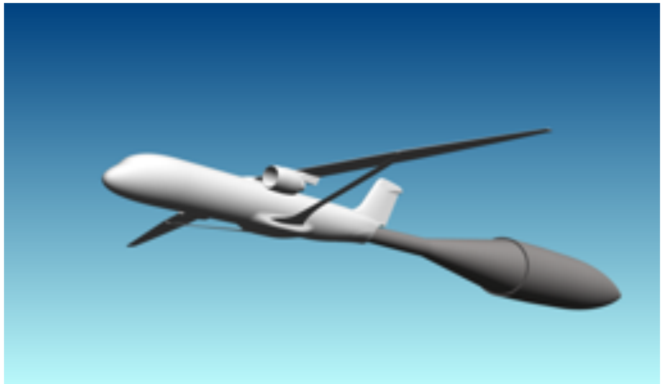
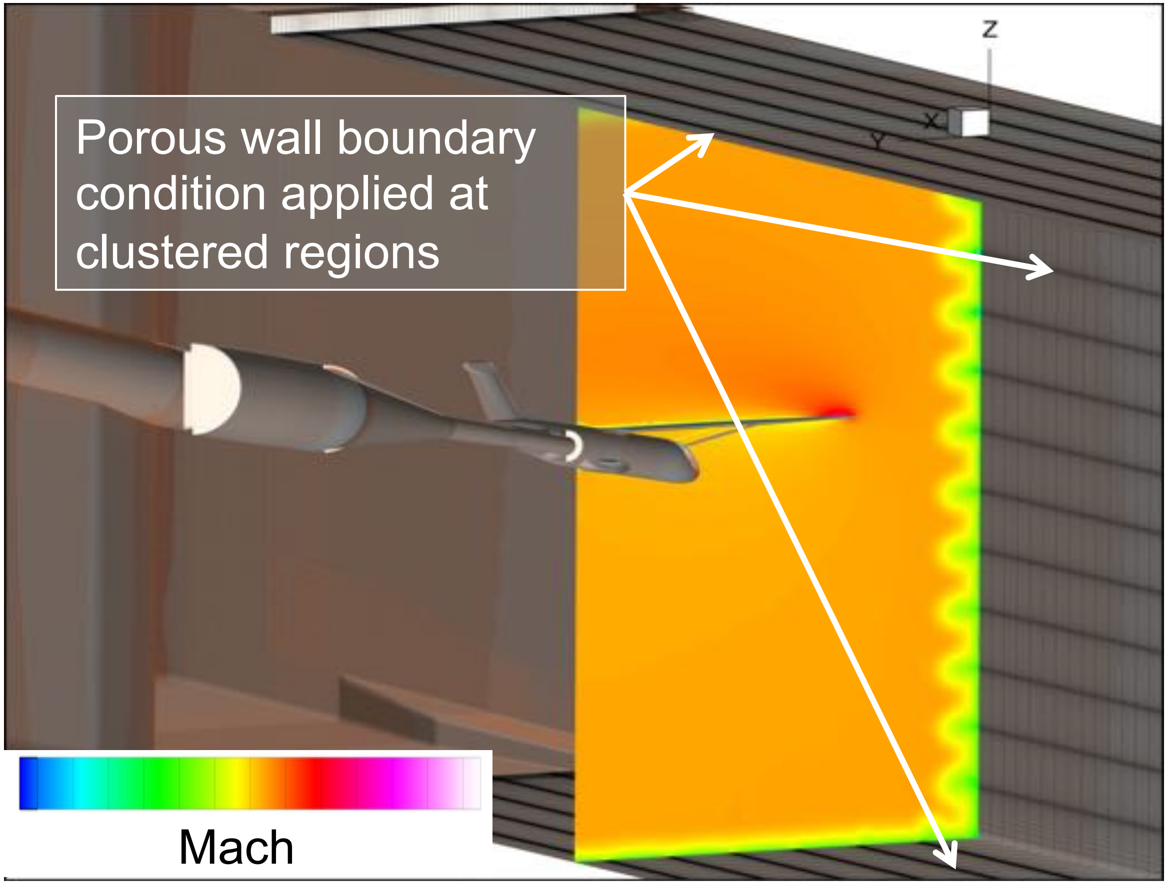


Porous Wall Boundary Condition

- Porous-wall boundary condition models the baffled slots from the real wind tunnel
- Boundary condition is initialized with a constant plenum pressure
- Boundary condition targets a net mass flow of zero by adjusting plenum pressure
- Baffled geometry is approximated using a porosity factor

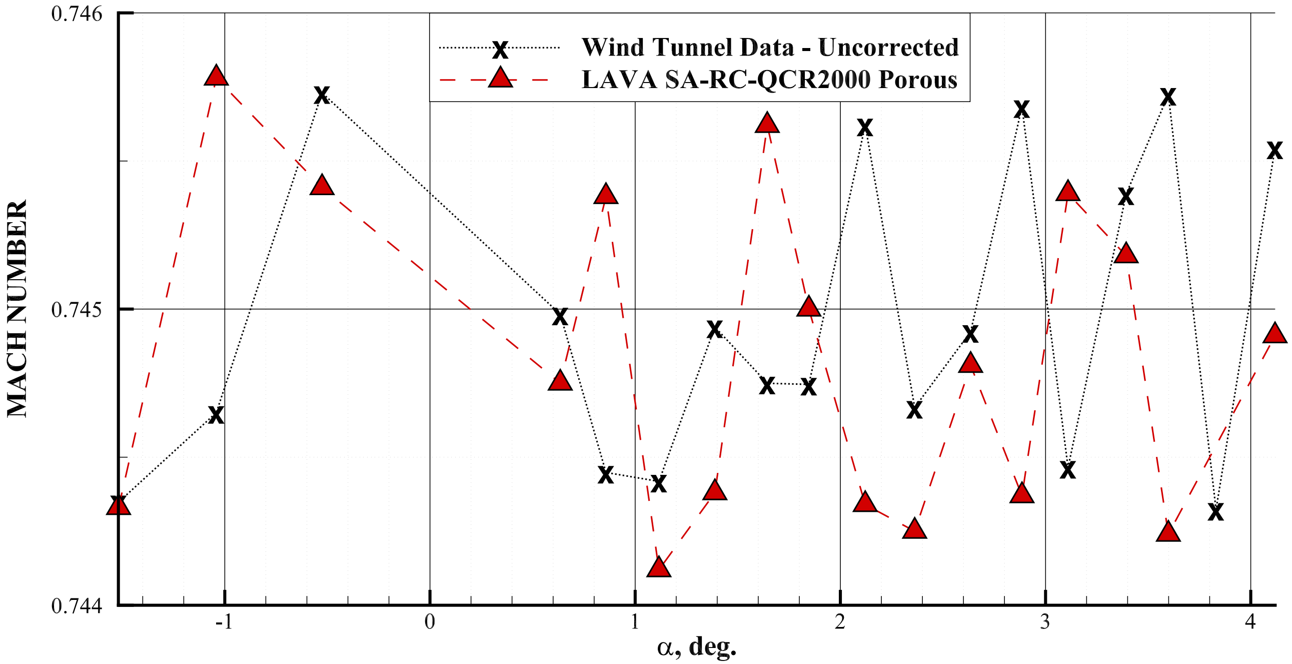


Half Body Porous Wall Simulation

Mach contours on cut plane showing the effects of the porous boundary conditions near the wall

Mach Number for Porous Wall Solutions

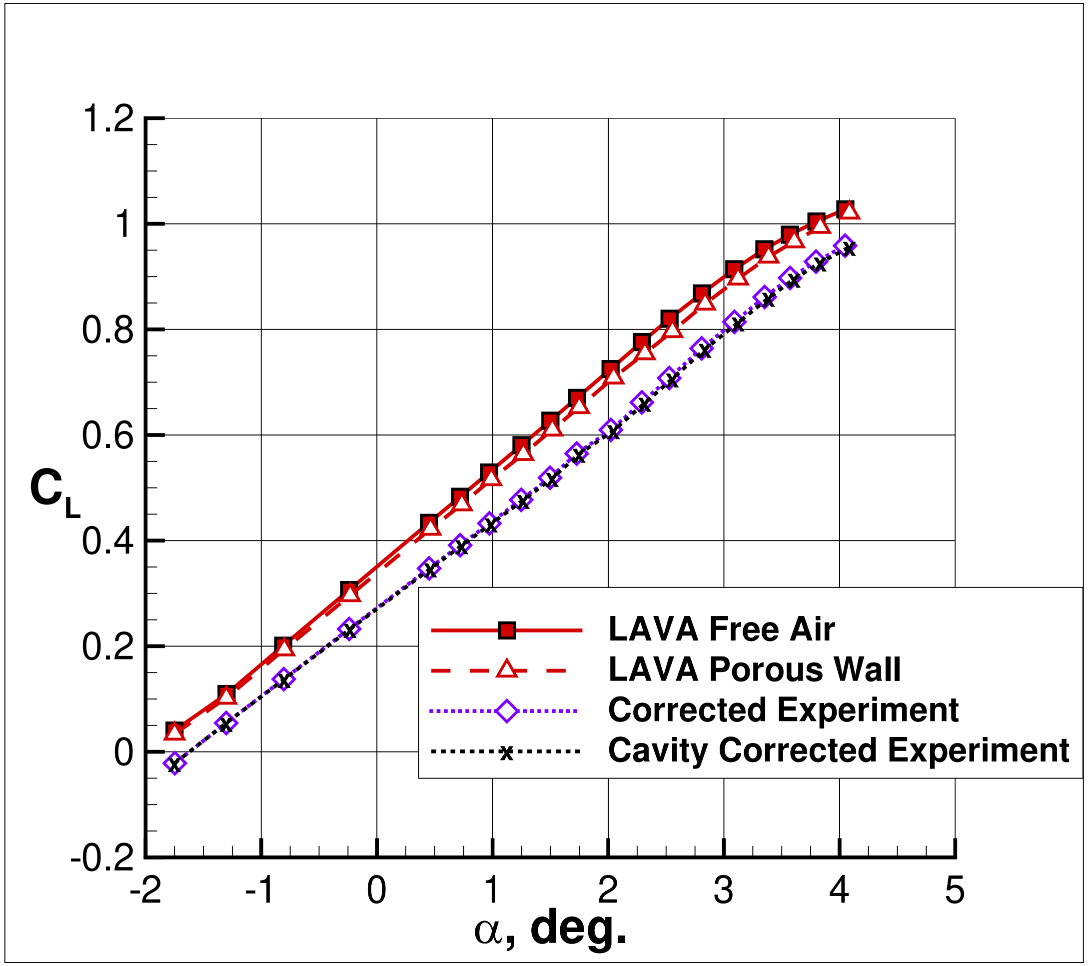
- Porous wall was run with stagnation inflow / subsonic outflow which required specifying a back pressure at the diffuser exit
- Back pressure was used to drive the Mach number in the test section
- Iterative process of adjust back pressure was used to converge to appropriate Mach number



All points within 0.001 from target Mach number

Validation with Wind Tunnel Data

Porous Wall – WBSNPV Config 23



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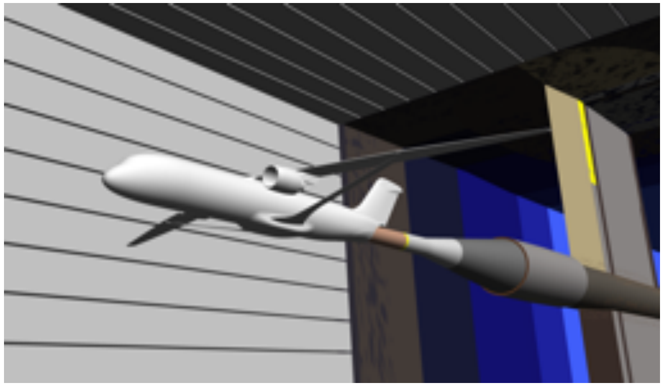

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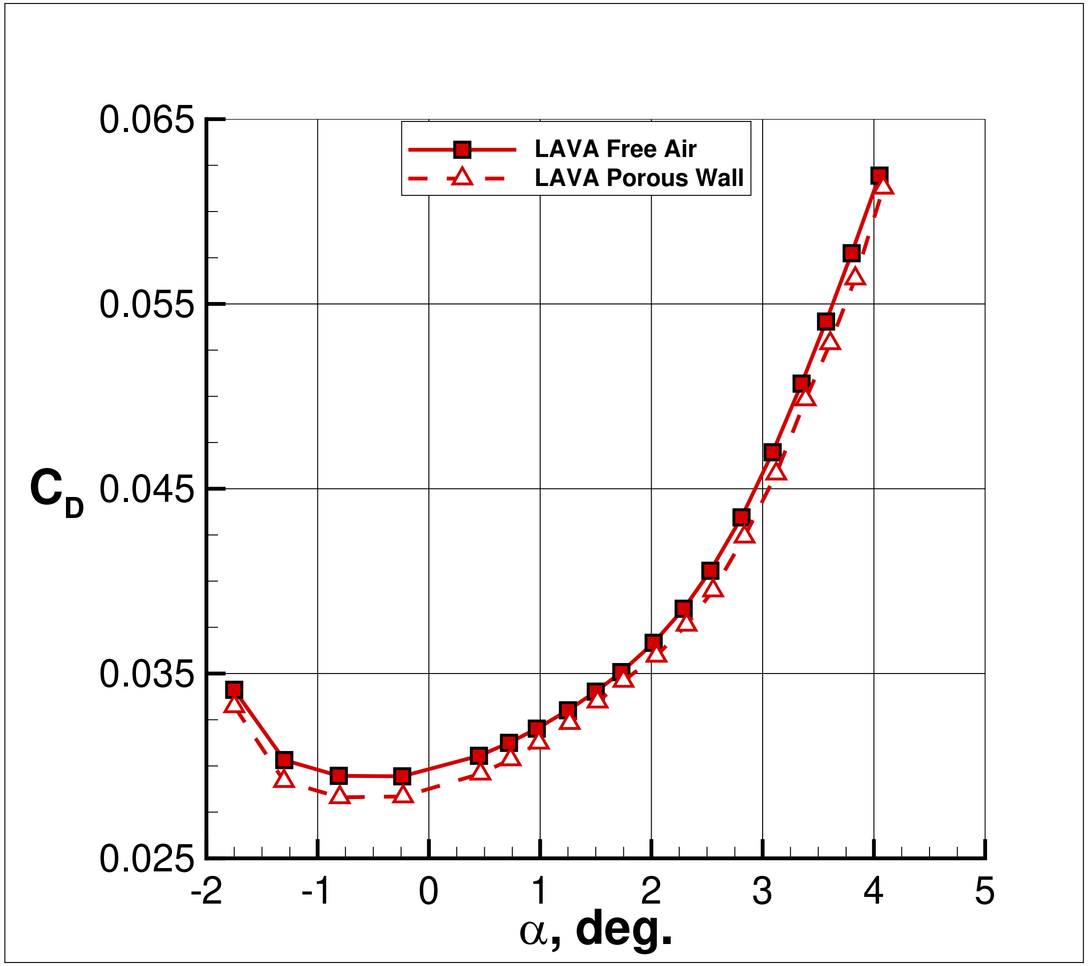

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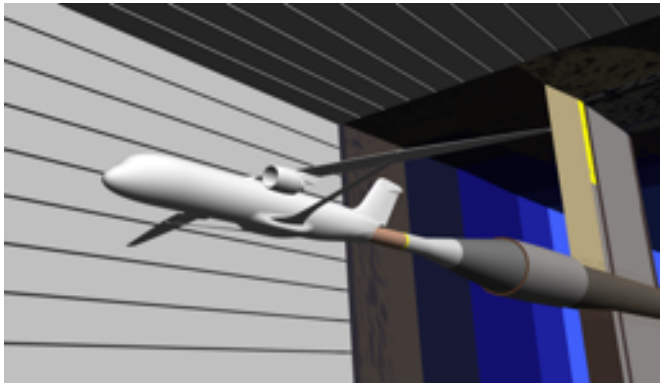

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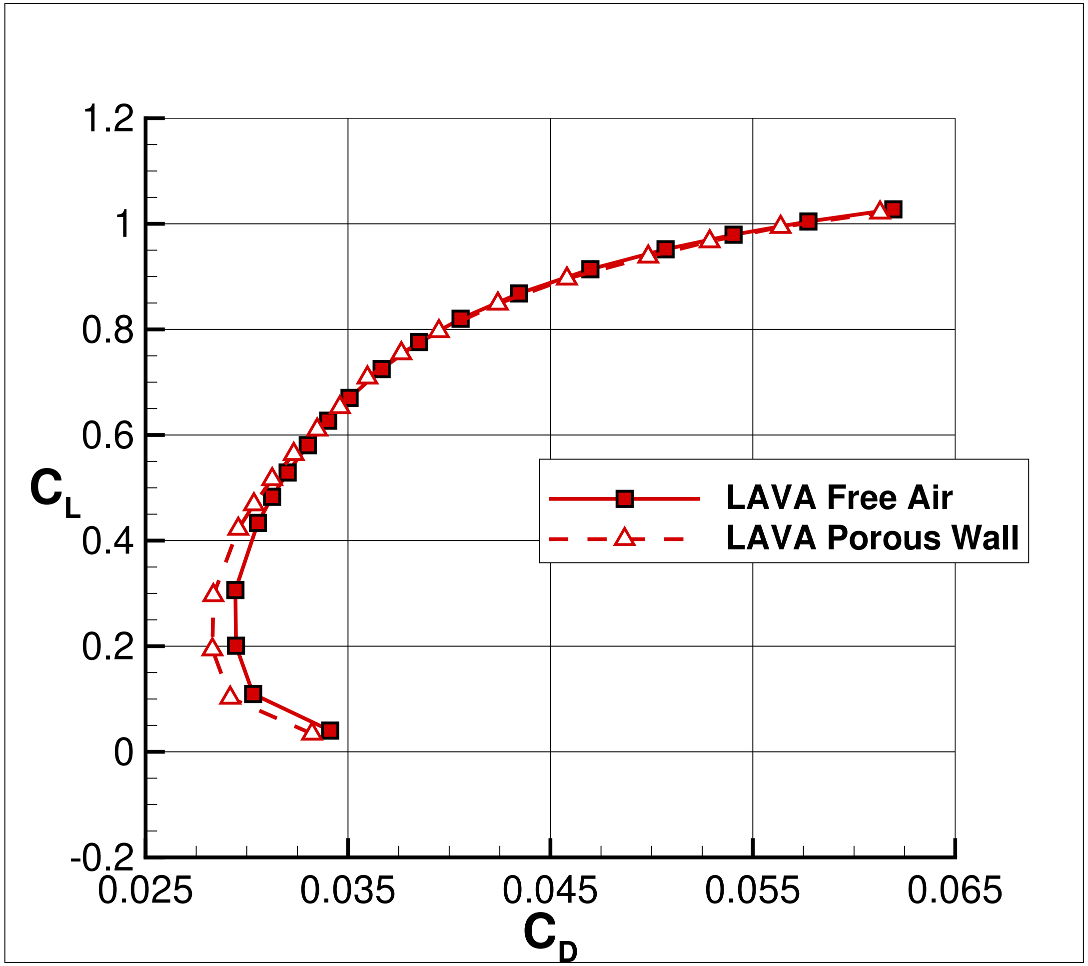

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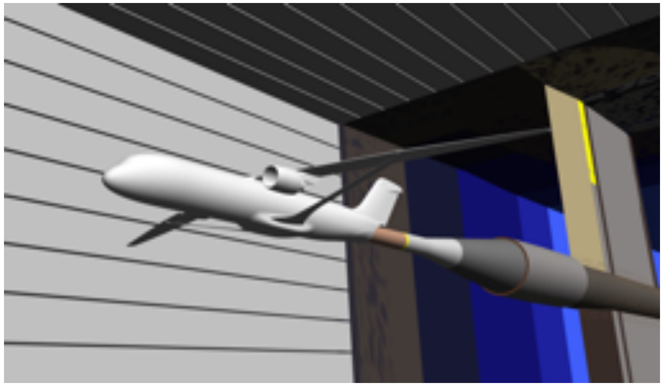
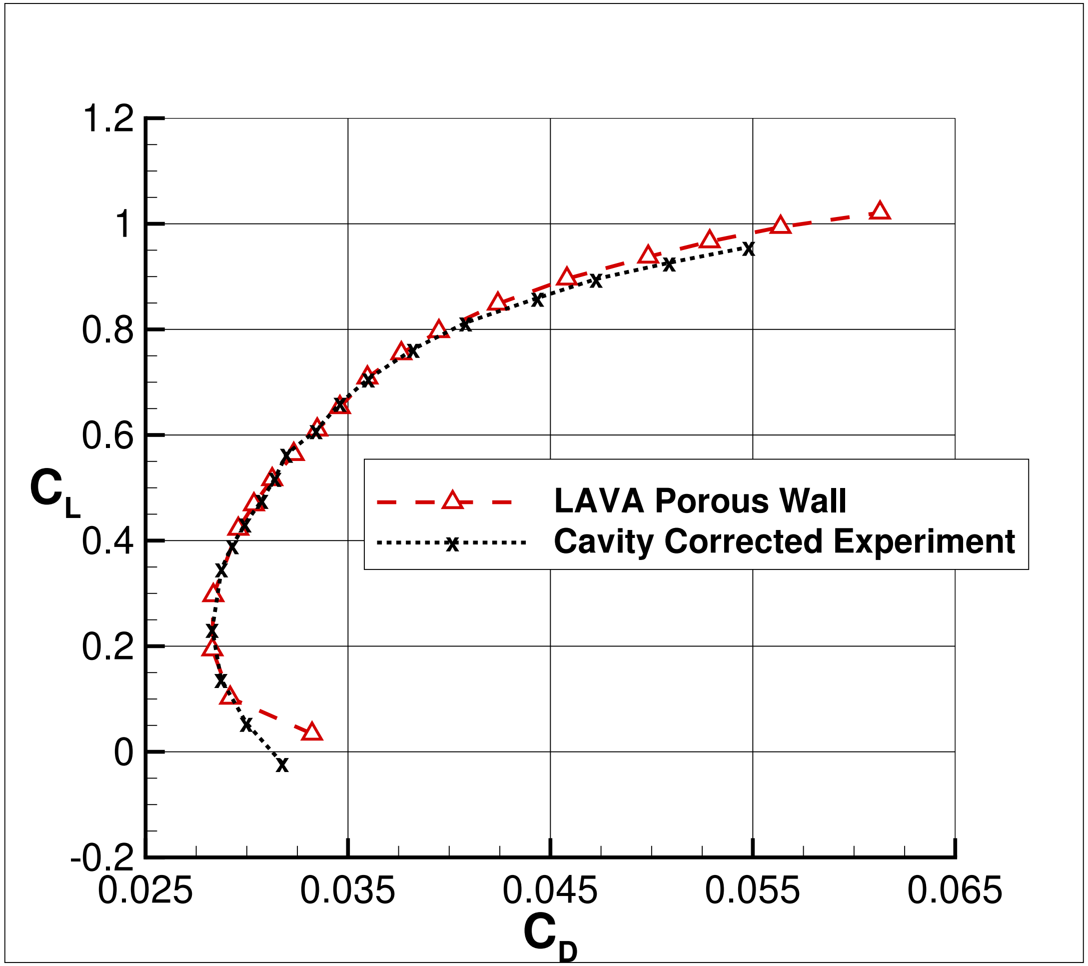
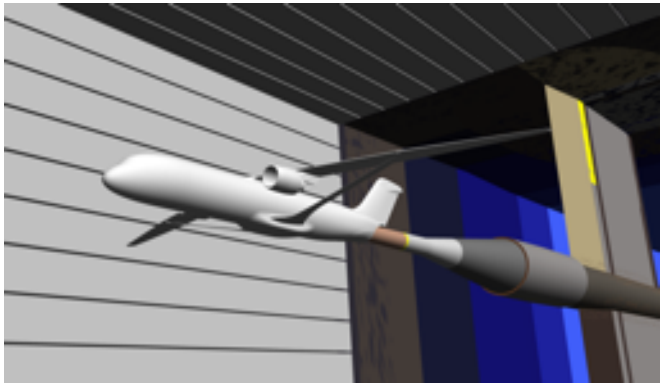


Validation with Wind Tunnel Data

Porous Wall – WBSNPV Config 23

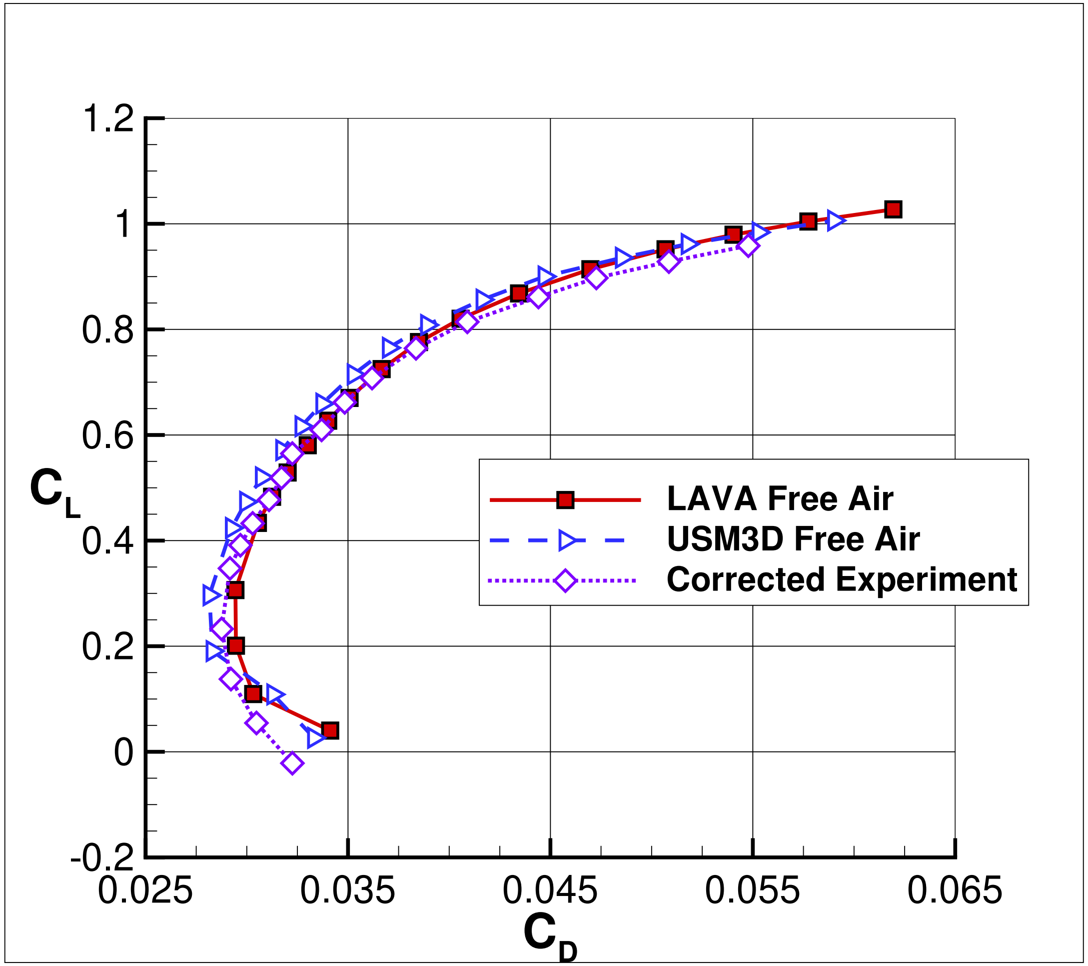


- **Conditions**:
  - $T_{Freestream} \approx 493\ ^{\circ}R$
  - $T_{Stagnation} \approx 550\ ^{\circ}R$
  - Mach 0.745
  - $Re_c = 3.31 \times 10^6$
  - $-2^{\circ} < \boldsymbol{\alpha} \lesssim 4^{\circ}$

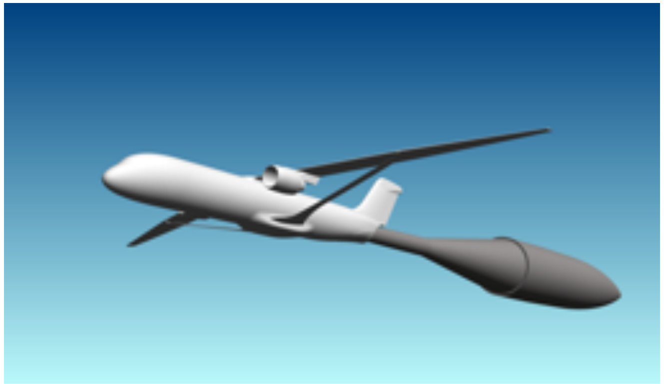


Validation with Wind Tunnel Data

Free Air – WBSNPV Config 23

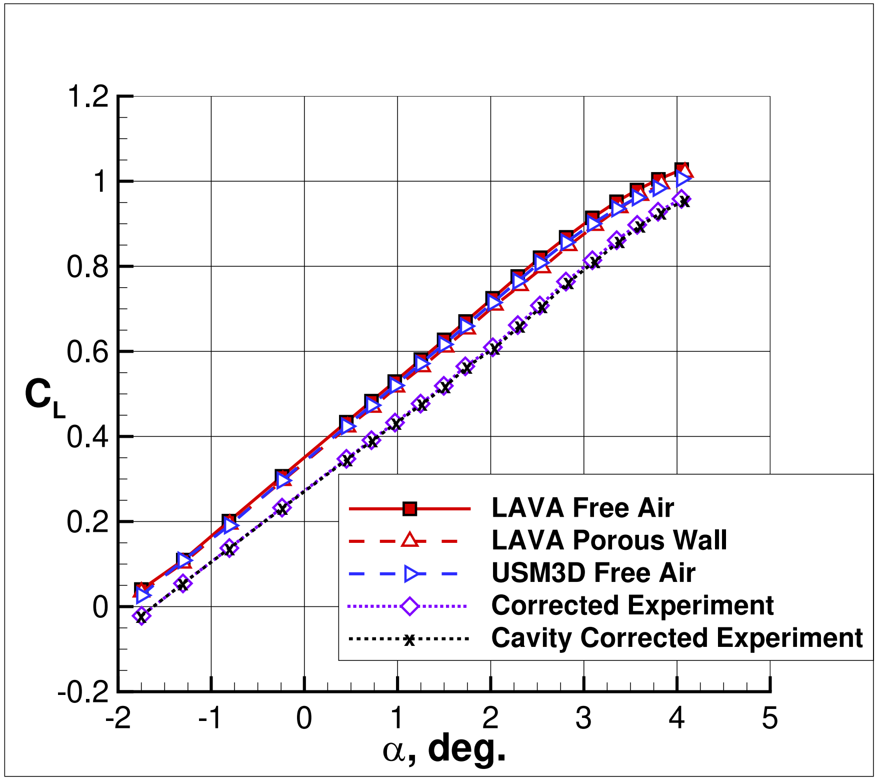


- **Conditions**:
  - $T_{Freestream} \approx 493\ ^\circ R$
  - $T_{Stagnation} \approx 550\ ^\circ R$
  - Mach 0.745
  - $Re_c = 3.31 \times 10^6$
  - $-2^\circ < \boldsymbol{\alpha} \lesssim 4^\circ$

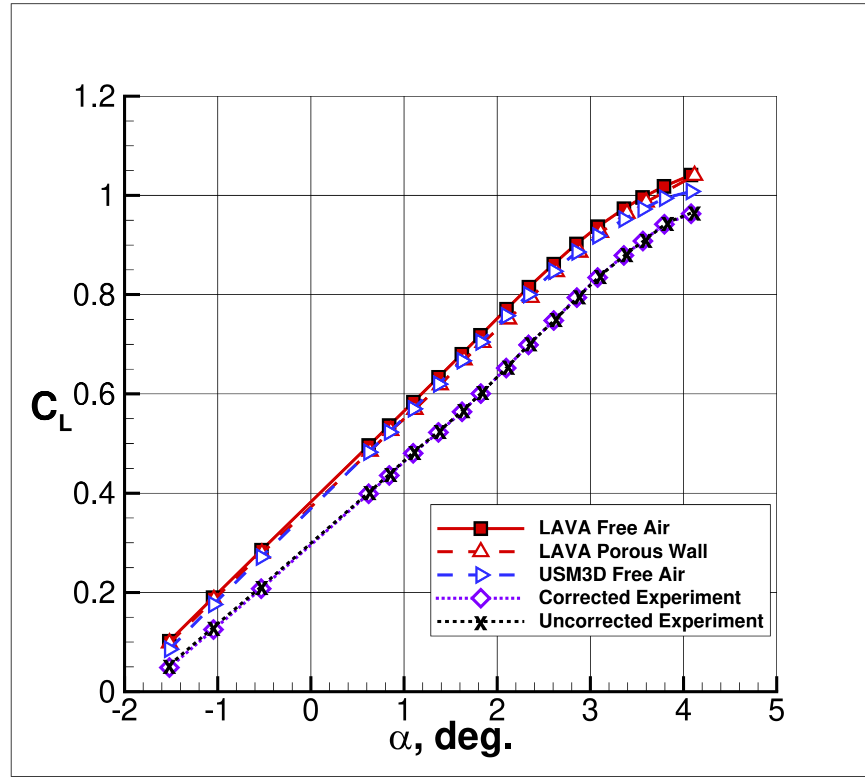


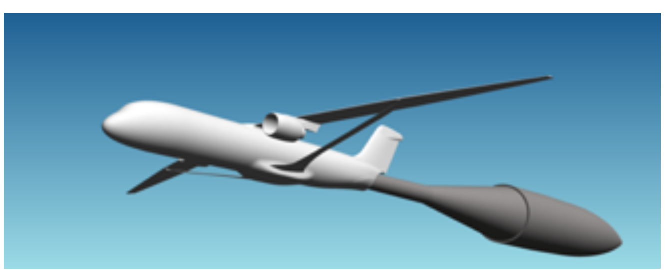
Consistency Across Configurations

WBSNPV – Config 23



WBSV – Config 21





Conditions:

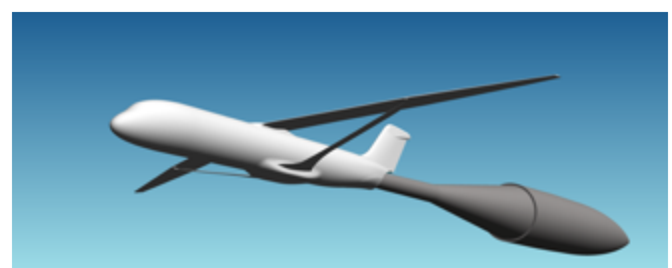
$T_{Freestream} \approx 493$ °R

$T_{Stagnation} \approx 550$ °R

Mach 0.745

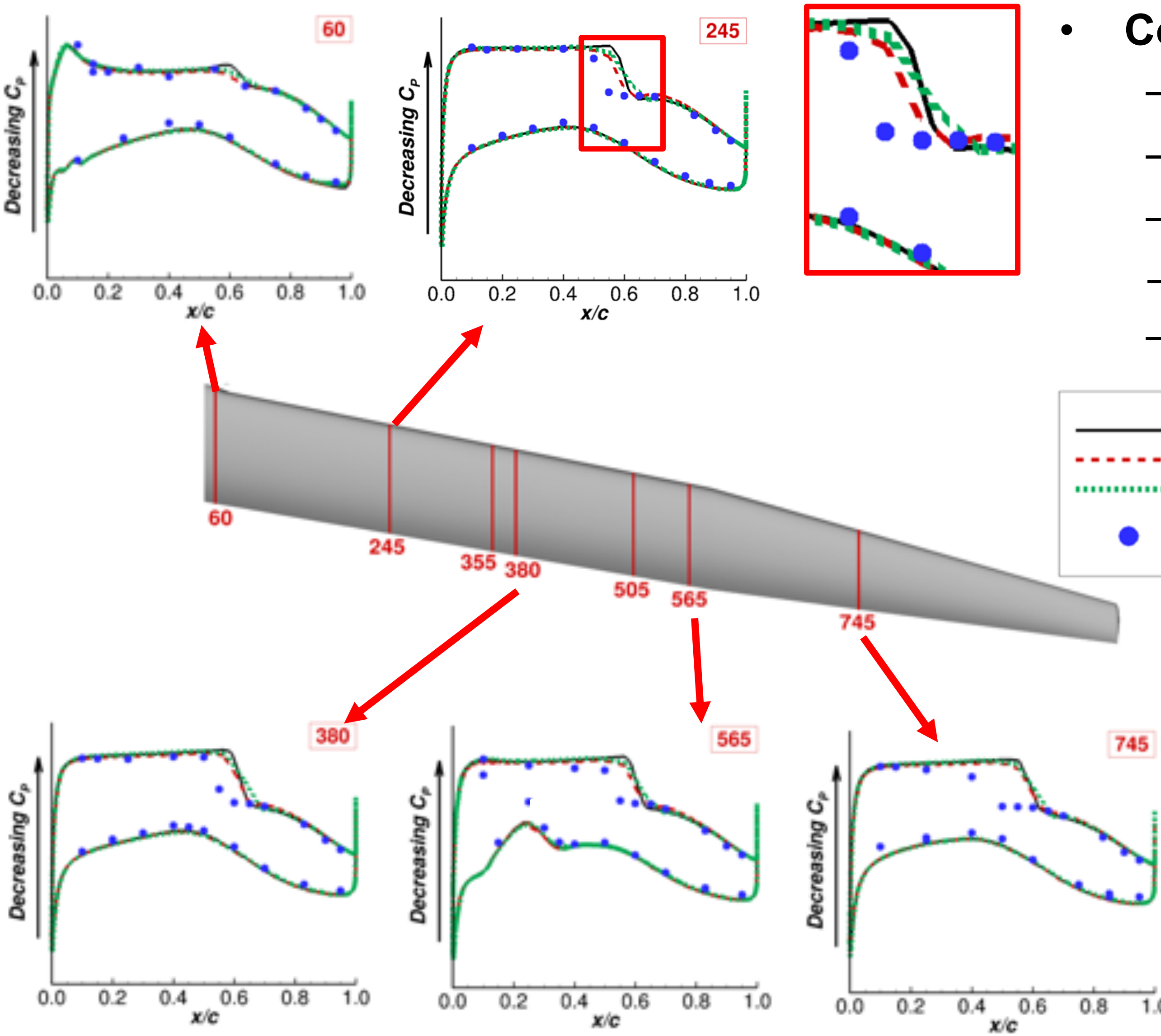
$Re_c = 3.31 \times 10^6$

-2° < **α** ≲ 4°



Validation with Wind Tunnel Data

Porous Wall – WBSV Config 21



- **Conditions**:
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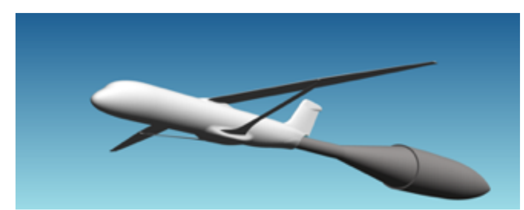
  - $T_{Stagnation} \approx 550\ ^{\circ}R$
  - Mach 0.745
  - $Re_c = 3.31 \times 10^6$
  - $-2^{\circ} < \boldsymbol{\alpha} \lesssim 4^{\circ}$

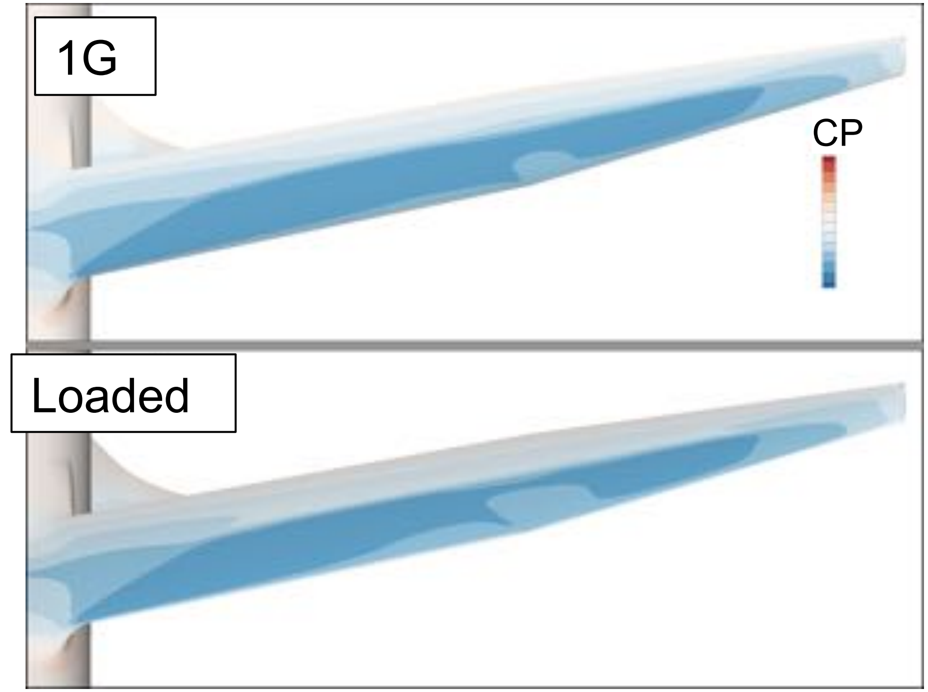
USM3D, Free Air, $\alpha = 2.6066^{\circ}$
Porous Wall, $\alpha = 2.6350^{\circ}$
LAVA, Free Air, $\alpha = 2.6066^{\circ}$
Test 343 - Run 290, $\alpha_{ALPWICS} = 2.6066^{\circ}$ $\alpha_{ALPHU} = 2.6350^{\circ}$



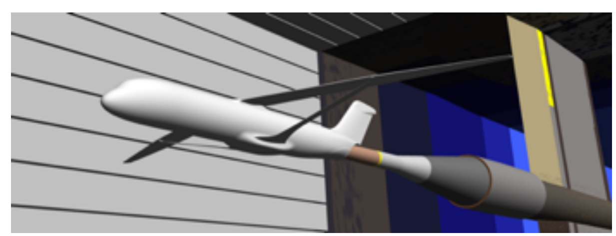
Approximation of Loaded Deformation

- Initial **1G** geometry
  - Designed for 1G loads experienced during cruise
- Wind tunnel **loaded** geometry
  - Twist data from Model Deformation Measurement (MDM) system

Geometry	C_L	C_D
1G	0.8480	0.03663
Loaded	0.8446	0.03676
Experiment (Uncorrected)	0.7522	0.03305
Change	0.5%	1.3 Counts



LAVA Porous Wall Simulation
Using Fine Grid Resolution

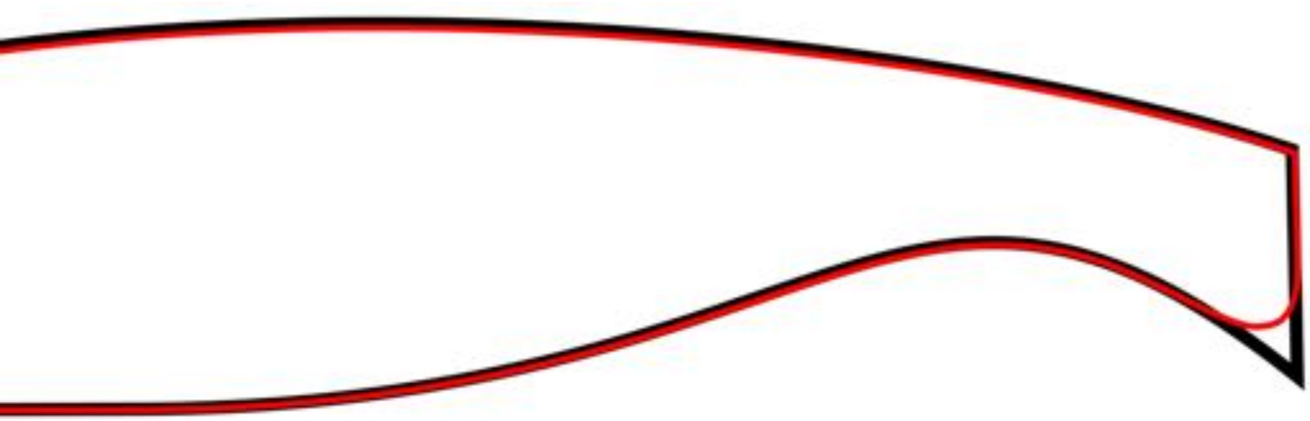


Rounding the Trailing Edge

- Sharp trailing edge design could not be achieved to due manufacturing tolerances
- Resulted in a model with a rounded bottom portion of trailing edge

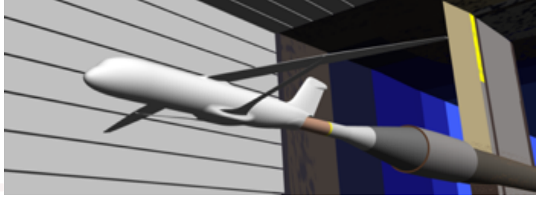
- Modified our geometry based on Boeing study showing a shift in CL when simulating an approximation of rounded trailing edge

- Used tolerance to guide modification of existing wing mesh.
- Used CGT to modified the grid to replicate rounding affect



Spanwise cut Illustrated
(Not to scale)

Rounding the Trailing Edge



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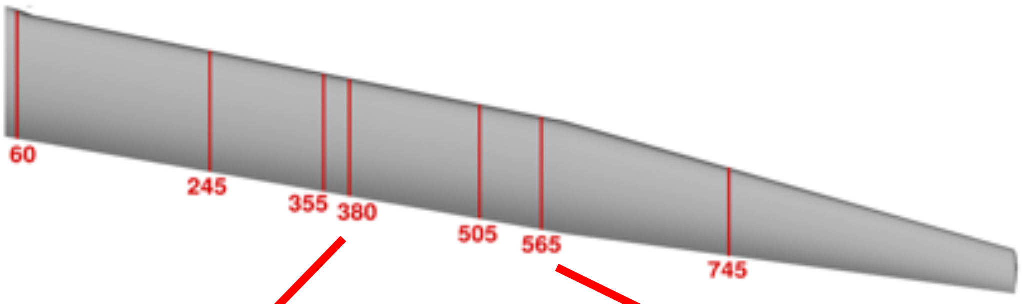
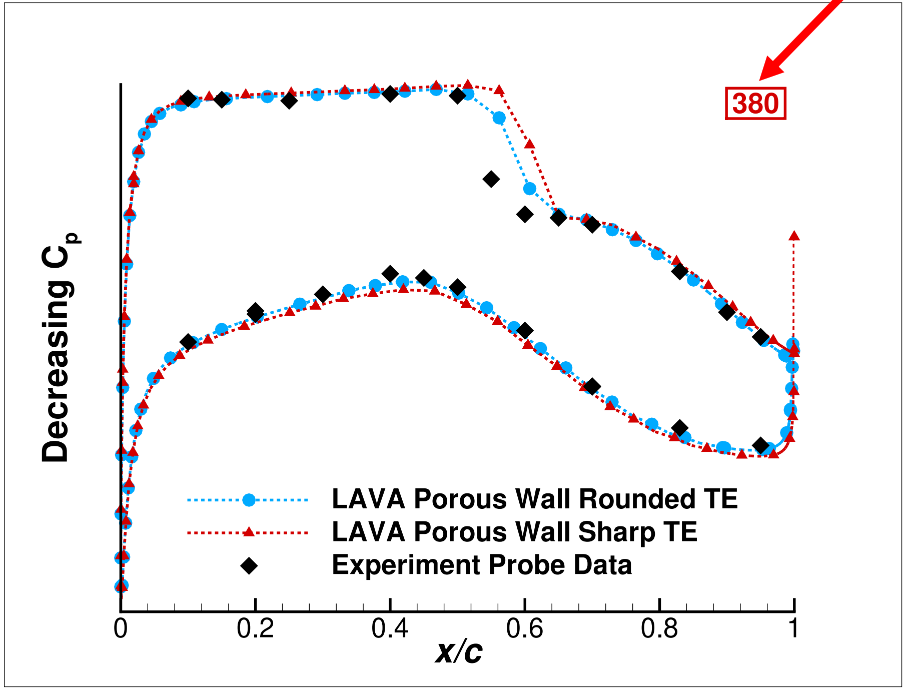
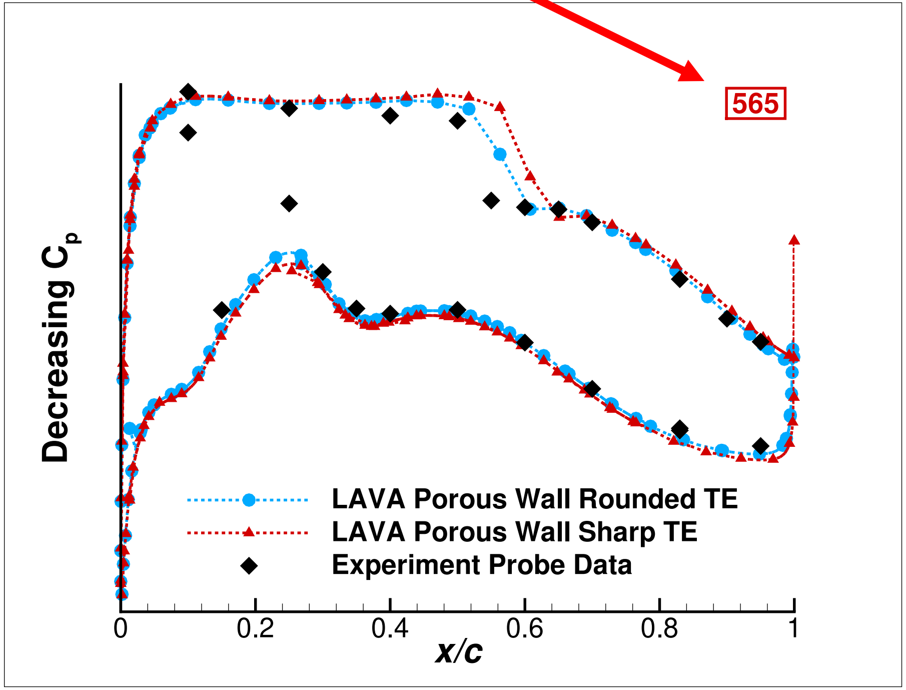
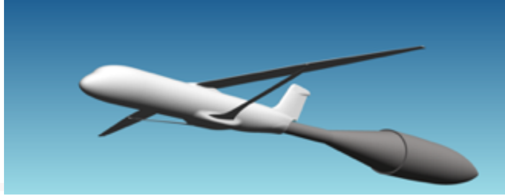
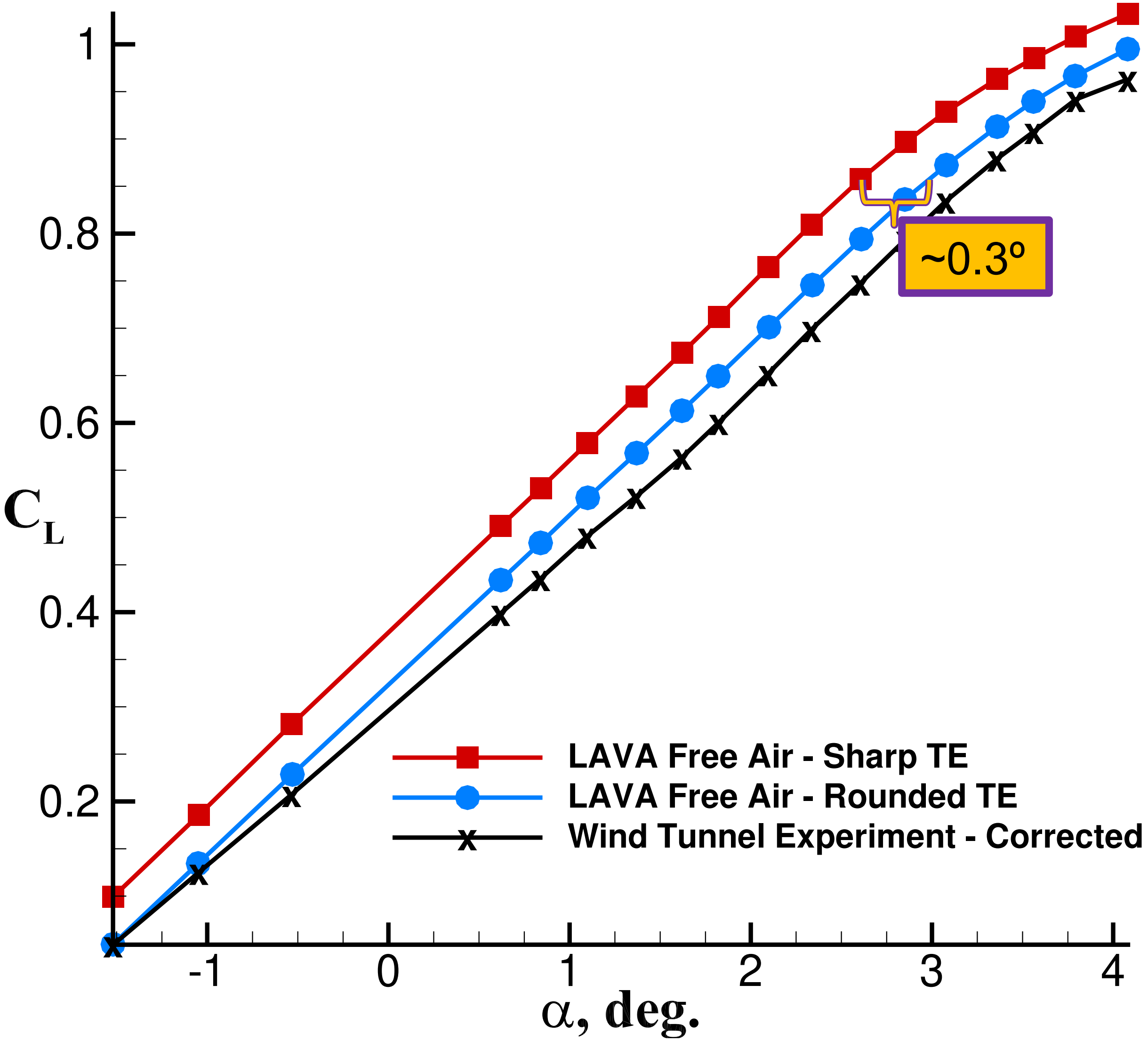






Rounding the Trailing Edge





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  - $Re_c = 3.31 \times 10^6$
  - $-2^{\circ} < \boldsymbol{\alpha} \lesssim 4^{\circ}$

- Reduced difference with experimental C_L data by 60%

Summary

Findings

- Code to code comparison essential for determining that the CFD was being solved properly, driving investigations into geometry

- Porous wall shows some improvement over free air:
  - In capturing the slope of the C_L-α sweep
  - Matching L/D performance

- Free-air simulations provide significant reduction in resource cost and effort.
  - 8 hours vs 3 day run time
  - No iterative process to determine Mach number

- Rounded trailing edge showed significant reduction of differences between CFD and experimental lift
  - In order to improve comparison with wind tunnel data accurate “as-tested” geometry of the test article is required

Future Work

- Apply best practices learned from this study to Mach 0.8 of TTBW

Acknowledgements

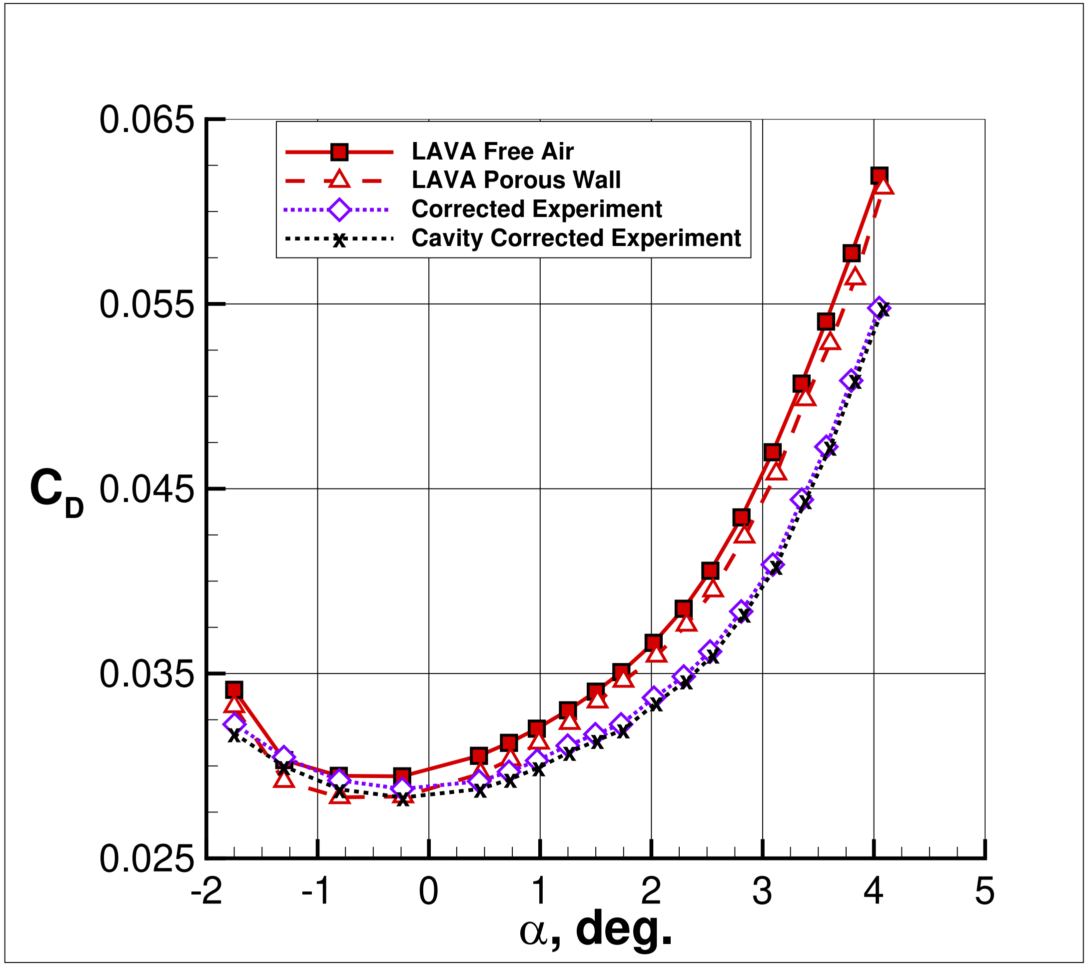
- This project was funded by Advanced Air Transport Technology (AATT) project and its sub-project High Aspect-Ratio Wing (HARW).
- Computer resources were provided by NASA Advanced Supercomputing (NAS) facility.
- The authors would like to acknowledge Michael G. Piotrowski for his contributions to the interpretation and implementation of the porous wall boundary condition into the LAVA solver.
- The authors would like to thank and acknowledge the Boeing team, especially Christopher Droney, Neal Harrison, Michael Beyar, Eric Dickey, and Anthony Sclafani, along with the NASA technical POC for the BAART contracts, Gregory Gatlin. This paper was made possible by them providing data on their model, their simulations, and the wind tunnel test.

Questions?

Questions?

Validation with Wind Tunnel Data

Porous Wall – WBSNPV Config 23



- **Conditions**:
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  - -2° < **α** ≲ 4°