Relating a Jet-Surface Interaction Experiment to a Commercial Supersonic Transport Aircraft Using Numerical Simulations

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Outline

- Introduction

- Goals

- LM1044-3 Concept Aircraft

- Jet-Surface Interaction Experimental Models

- LM1044-3 Aircraft Simulations

- Jet-Surface Interaction Model Simulations

- Conclusions

Introduction

- NASA and industry partners desire to reintroduce commercial supersonic airliners.

- Technical challenges:
  - Reduce sonic boom noise.
  - Maximize range.
  - Reduce airport community noise.

Lockheed Martin LM1044
Commercial Supersonic Transport Concept

- Departure from isolated engines; engines located in close proximity to wing and tail surfaces.

- But, the effects of jet noise shielding and radiation from surfaces is not fully understood.

- The jet-surface interaction acoustic experiment was conducted in the NASA Glenn Research Center Nozzle Acoustic Test Rig (NATR) using models representative of the LM1044-3 aircraft jet-surface interactions. (Bridges, AIAA Paper 2016-3042)

Goals

Use Reynolds-Average Navier-Stokes simulations to:

- Relate nozzle flow of supersonic commercial airliner concept (LM1044-3) to jet-surface interaction experiment models.

- Perform screening simulations of jet-surface interaction experiment models.

- Compute aerodynamic loads on jet-surface interaction experiment models.

- Compute inlet performance of LM1044-3 at take-off and climb angles of attack.

LM1044-3 Concept Aircraft

- Low-boom, supersonic passenger aircraft.
  - 80 passengers.
  - >5000 nmi range.
  - Mach 1.7 cruise.
- Three engines:
  - 1 center, over aft deck, 2° AOA wrt aircraft.
  - 2 outboard, under wing, 0° AOA wrt aircraft.
- External compression, axisymmetric spike inlets.
  - Auxiliary doors open for low-speed via translating cowl.
  - Simplified inlet used for simulations: no internal support struts.
- Three-stream, inverted velocity profile nozzles.

RANS simulation of isolated IVP nozzle

Isometric View

Top View

Side View

Bottom View
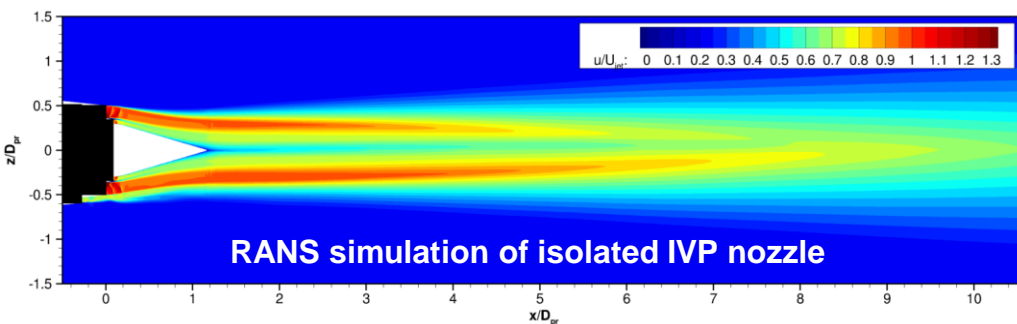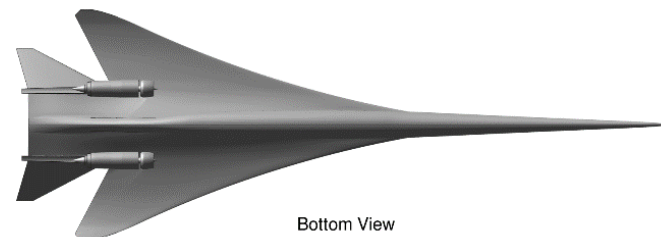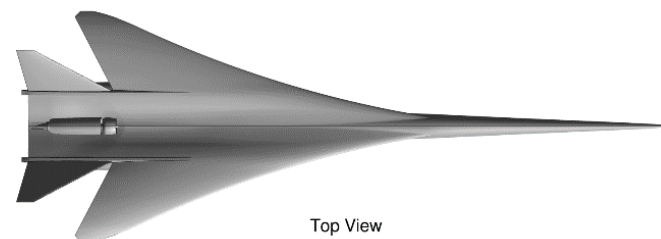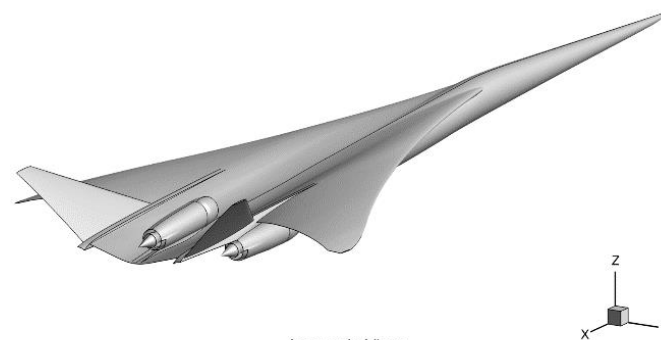
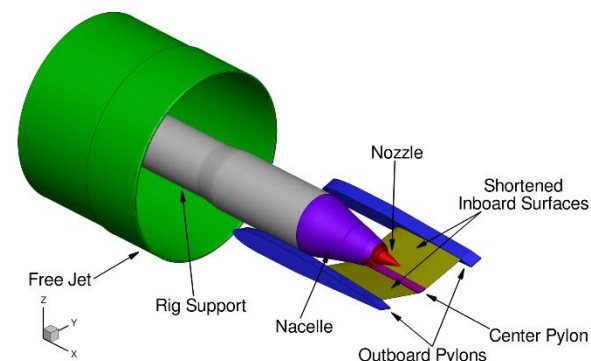# Jet-Surface Interaction Experimental Models

- Models designed for Nozzle Acoustic Test Rig at the NASA GRC.
  - NATR can simulate forward flight to Mach 0.35 with 53 inch diameter freejet.
  - 30 lbm/s combined nozzle flow – limits maximum diameter of nozzle.

- Experimental models represent the LM1044-3:
  - Outboard engine: pylon with inboard and tail surfaces.
  - Center engine: pylons with inboard and tail surfaces.
  - Modified center engine: truncated inboard surface by ~53%; removed tail surfaces (unnecessary acoustically).
  - Model scale of 1:8.2.
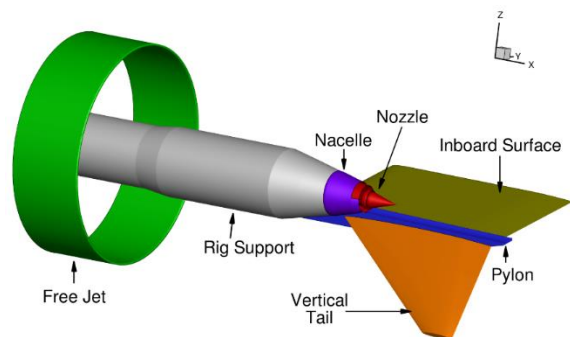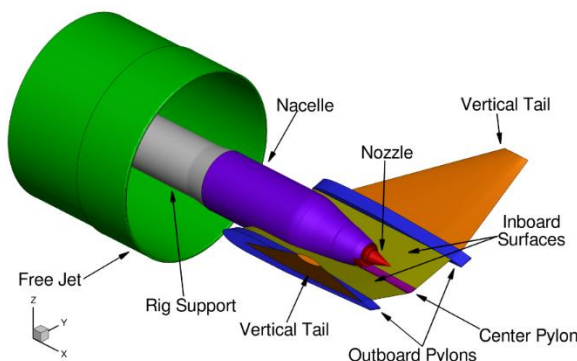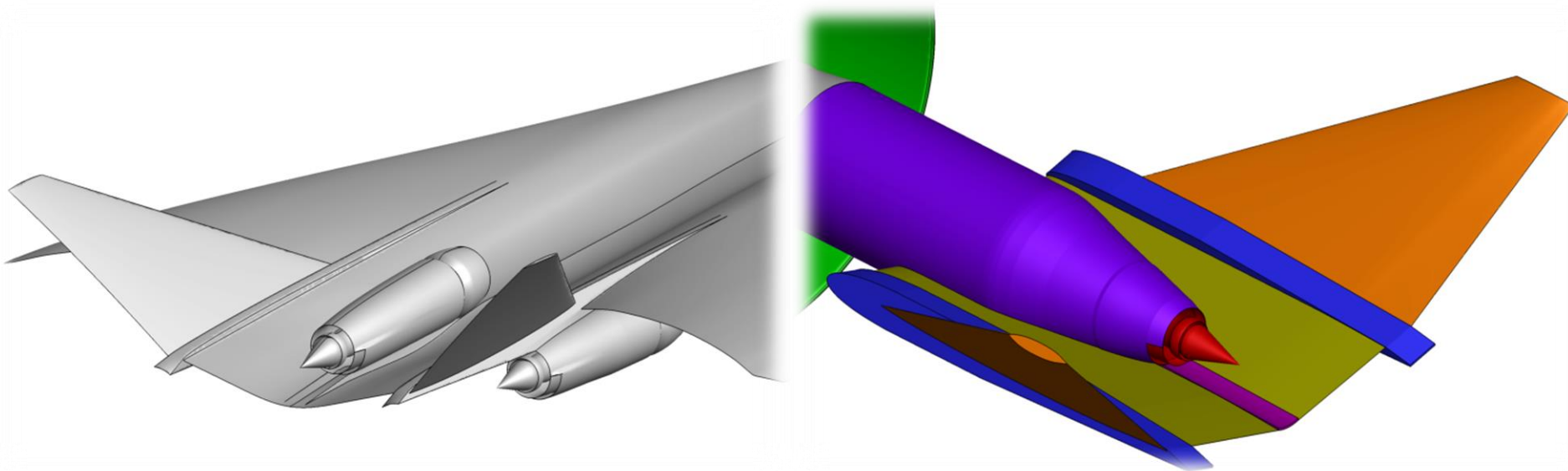
Outboard Engine   **Center Engine (Original)**   **Modified Center Engine**

Jet-Surface Interaction Experiment: Differences in Engine Junction Regions

LM1044-3 Aircraft   **NATR Center Engine Model (Original)**

- LM1044-3 nacelle diameter to nozzle diameter: 1.33:1.

- NATR model jet rig diameter to nozzle diameter: 2.53:1.
  - Maximum diameter of the NATR model nozzle is massflow-limited (30 lbm/s).

- LM1044-3 nacelle is installed on pylon; NATR jet rig is submerged in aft deck.

- Junction region of NATR could be problematic -- a focus of screening simulations.

- Goal: NATR models that are representative of LM1044-3. → Modify models if necessary.

Numerical Modeling:
RANS Solver and Resources

- ## FUN3D v12.7
  - Node-based, finite-volume Navier-Stokes solver for unstructured grids.
  - Developed at the NASA Langley Research Center.
  - https://fun3d.larc.nasa.gov/
  - Used Menter SST turbulence model.
  - Steady-state (local time-step) <u>and</u> time accurate (global time-step) simulations performed.

- ## All simulations performed on the NASA Advanced Supercomputing System.

Numerical Modeling: LM1044-3 Simulations

<u>Flow conditions:</u>

- M_∞=0.3
- AOA=0°, 6°, 9°
- Inlet massflow: 860 lbm/s
- Nozzle flow:
  - Inner: NPR=1.78, NTR=1.245
  - Primary: NPR=2.00, NTR=1.887
  - Buffer: NPR=1.78, NTR=1.245

<u>Unstructured grids:</u>

- Generated using Pointwise (surface and volume).
- Original grid:
  - Viscous wall spacing of 0.0001 inch for nominal y^+<1.0.
  - 27.9 million nodes.
- Coarsened grid:
  - Viscous wall spacing of 0.0002 inch.
  - 27.2 million nodes.
- Refined plume grid:
  - Original grid, with plume refinement region 12.5×D_{pr} downstream.
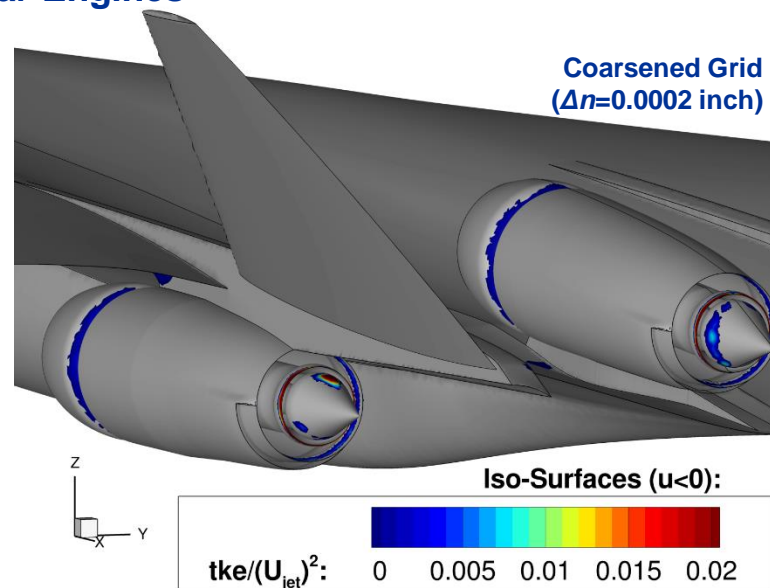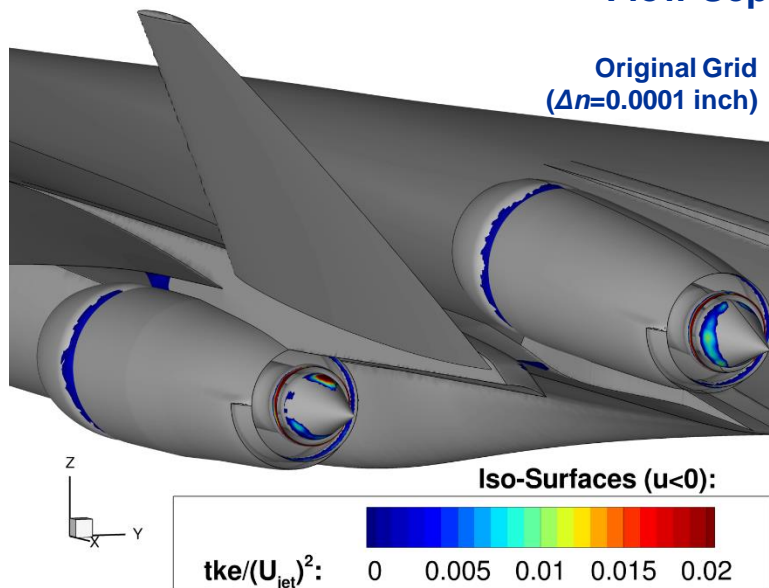 - 39.3 million nodes.

Original Grid

Refined Plume Grid
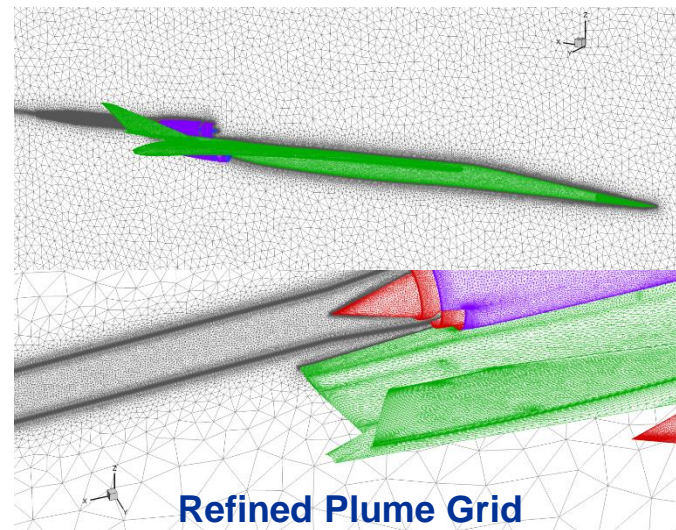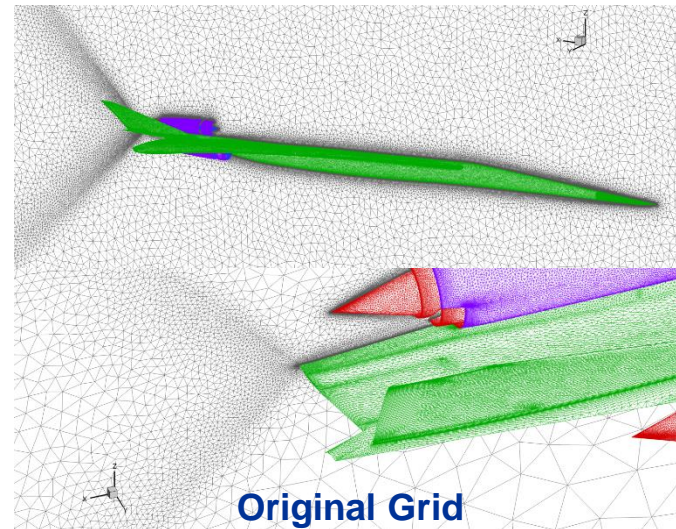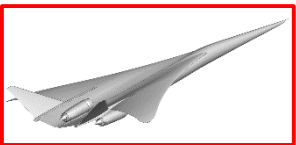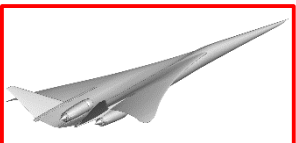
Simulations of LM1044-3: Effects of Near-Surface Grid

Lift and Drag on Airframe Surfaces at AOA=0°

	Original Grid (Δn=0.0001 inch)	Coarsened Grid (Δn=0.0002 inch)	Difference
C_L	0.0175	0.0172	1.51%
C_D	0.0060	0.0061	−0.18%
L/D	2.89	2.89	1.69%

Flow Separation Near Engines

Original Grid (Δn=0.0001 inch)

Iso-Surfaces (u<0):

$tke/(U_{jet})^2$: 0 0.005 0.01 0.015 0.02

Coarsened Grid (Δn=0.0002 inch)

Iso-Surfaces (u<0):

$tke/(U_{jet})^2$: 0 0.005 0.01 0.015 0.02

Simulations showed good agreement; used wall grid spacing of 0.0001 inch.

Simulations of LM1044-3:
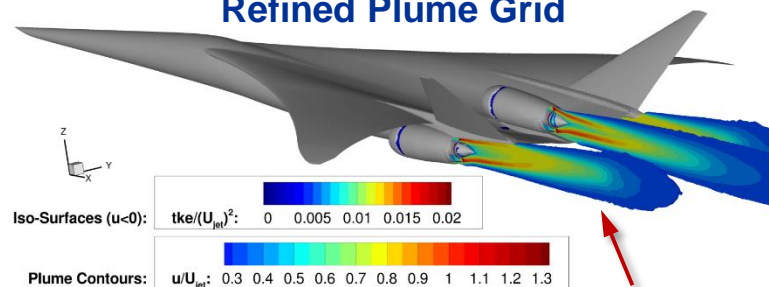# Effects of Jet Plume Grid

Original Grid
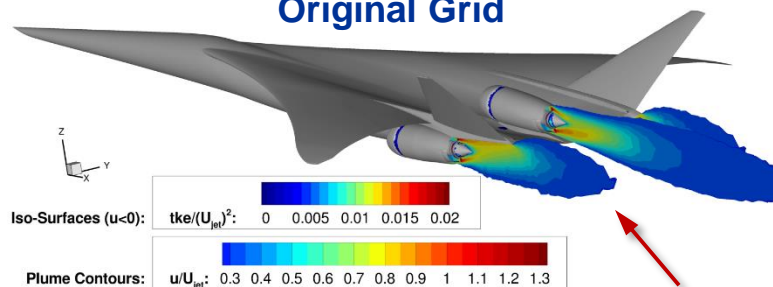
Refined Plume Grid

**Short jet plumes.
No TKE in shear layers.**

**Longer jet plumes.
Realistic-looking TKE field.**

LM1044-3 simulations used the grid
with the refined plume region.
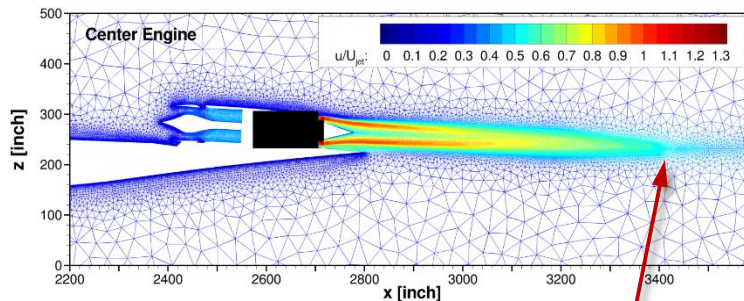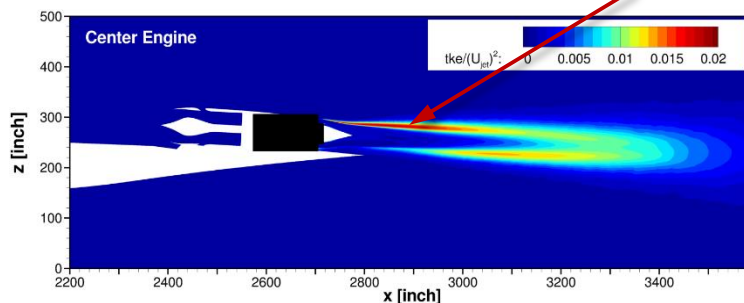
**Jet Plume ends at end of
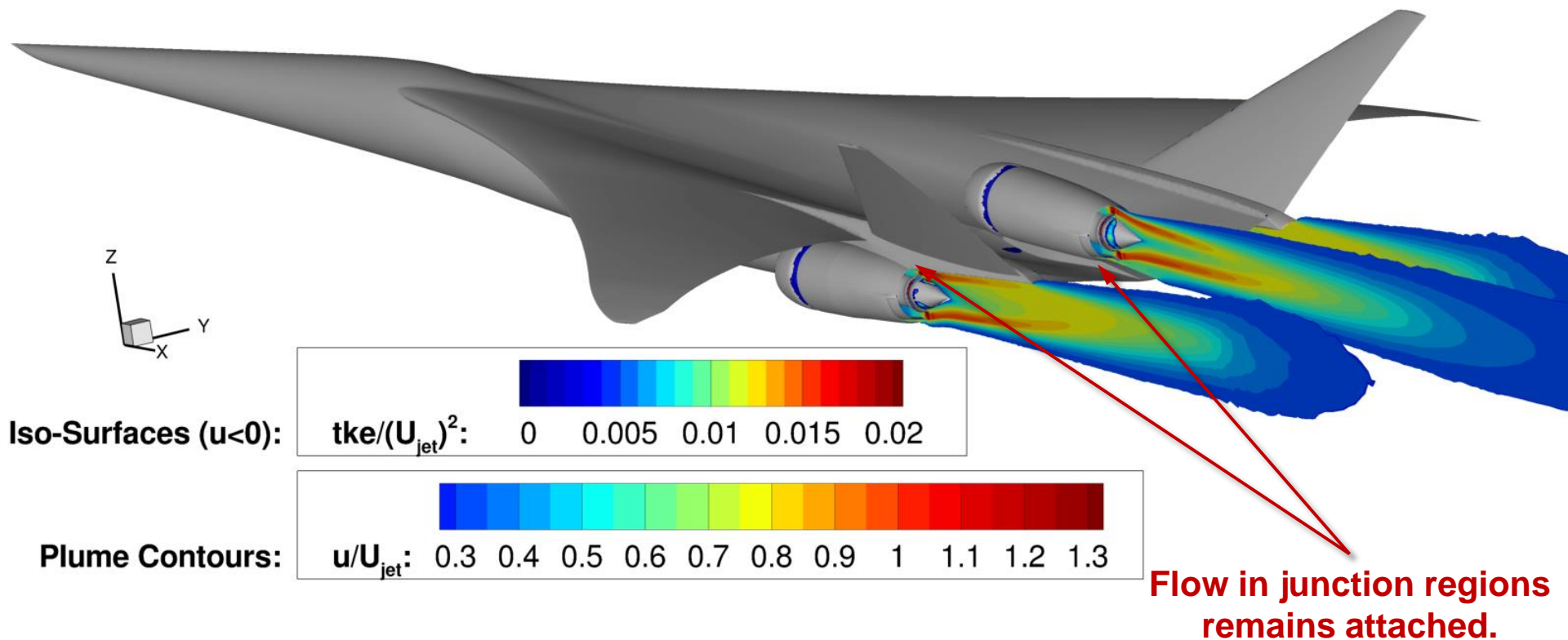refined plume region.**
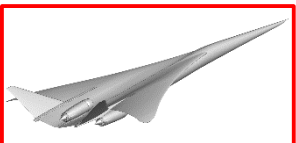
Simulations of LM1044-3: General Observations

Iso-Surfaces (u<0): $tke/(U_{jet})^2$: 0   0.005   0.01   0.015   0.02

Plume Contours: u/U_{jet}: 0.3   0.4   0.5   0.6   0.7   0.8   0.9   1   1.1   1.2   1.3

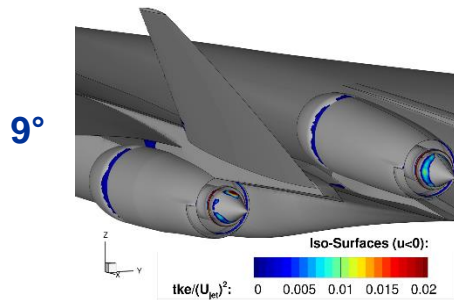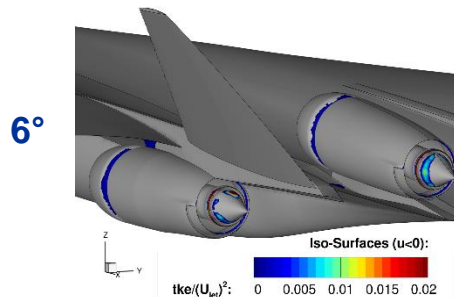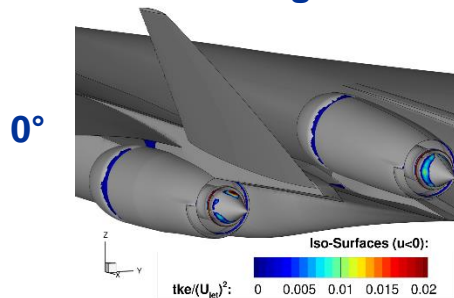**Flow in junction regions remains attached.**

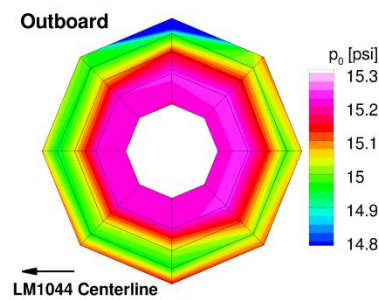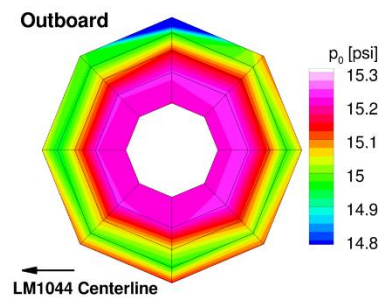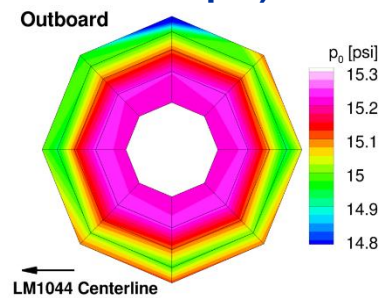The NATR models require a similar flowfield in the junction regions to be representative of LM1044-3.
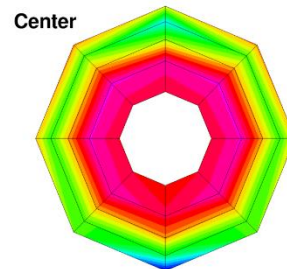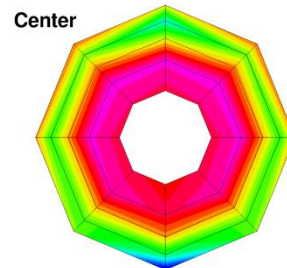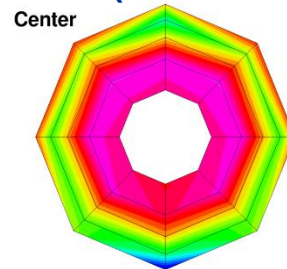
Simulations of LM1044-3:
Effects of Angle of Attack: 6°, 9°.

**Flow Separation
Near Engines**

**Inlet AIP Total Pressure
(Contour Levels: 14.8-15.3 psi)**

As AOA increases, no significant differences in:
1) flow around aircraft engines; or 2) inlet AIP total pressure.

Simulations of LM1044-3:
Inlet Performance vs. Angle of Attack

- Used standard 40 equal area-weighted probe points downstream of the diffuser to measure inlet performance.

- Circumferential (IDC) and radial (IDR) inlet distortion computed using General Electric "Method D" Distortion Methodology from Moore (AFAPL-TR-72-111).

- Inlet total pressure recovery agrees well with Morgenstern, et al. (NASA/CR—2015-218719).

- Only small changes in inlet distortion and total pressure recovery as AOA increases; NATR model is relevant despite limitation of AOA=0°.

- Distortion was believed to be small enough not to produce noise source at fan face.

| Angle of Attack	0°	6°	9°
Center Engine			
Circumferential Inlet Distortion (IDC)	0.01184	0.01137	0.01101
Radial Inlet Distortion (IDR)	0.00376	0.00398	0.00410
Total Pressure Recovery ($p_2/p_{0,\infty}$)	0.99189	0.99111	0.99063
Outboard Engine			
Circumferential Inlet Distortion (IDC)	0.01216	0.01654	0.01915
Radial Inlet Distortion (IDR)	0.00610	0.00605	0.00612
Total Pressure Recovery ($p_2/p_{0,\infty}$)	0.99264	0.99239	0.99206

Numerical Modeling:
Jet-Surface Interaction Experiment Simulations

Flow Conditions:

- M_∞=0.01

- $M_{freejet}$=0.3

- Nozzle flow:
  - Inner: NPR=1.78, NTR=1.245
  - Primary: NPR=2.00, NTR=1.887
  - Buffer: NPR=1.78, NTR=1.245

Unstructured Grids:

- Center engine grids generated using Pointwise (surface and volume).
  - Viscous wall spacing of 0.0002 inch.
  - Refined plume region, 12.5×D_{pr}.
  - 51.1 million nodes (original geometry).
  - 27.7 million nodes (modified geometry).

- Outboard engine grid generated using Pointwise (surface) and AFLR3 (volume).
  - Viscous wall spacing of 0.0001 inch.
  - No refined plume region.
  - 18.9 million nodes.

Center Engine (Original)

Modified Center Engine

Outboard Engine
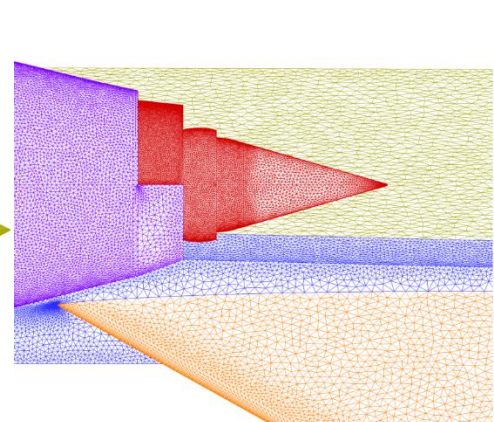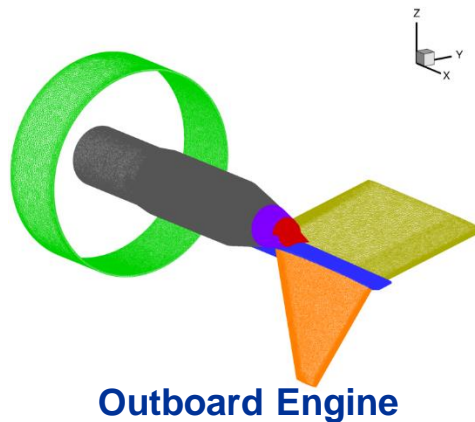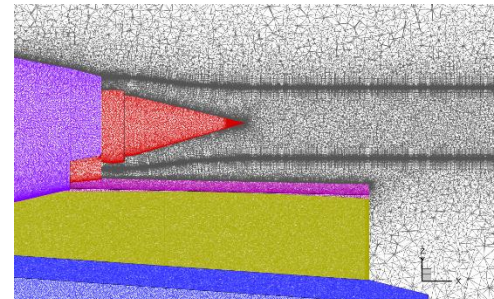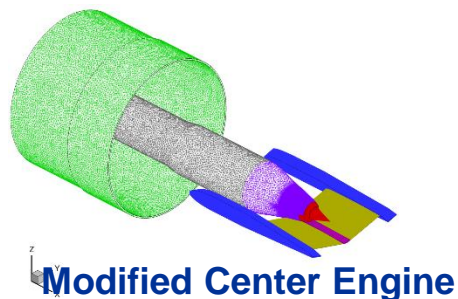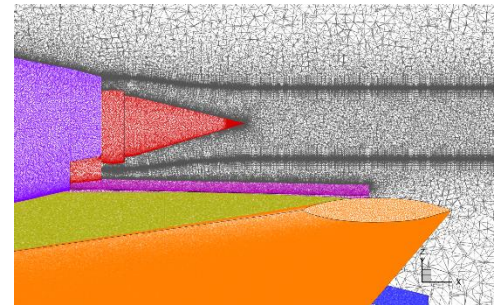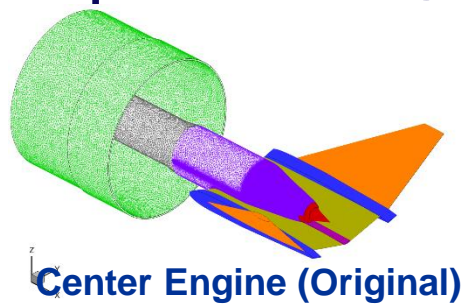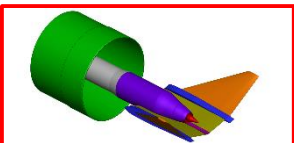
Simulation of NATR Center Engine: Convergence of Aerodynamic Loads
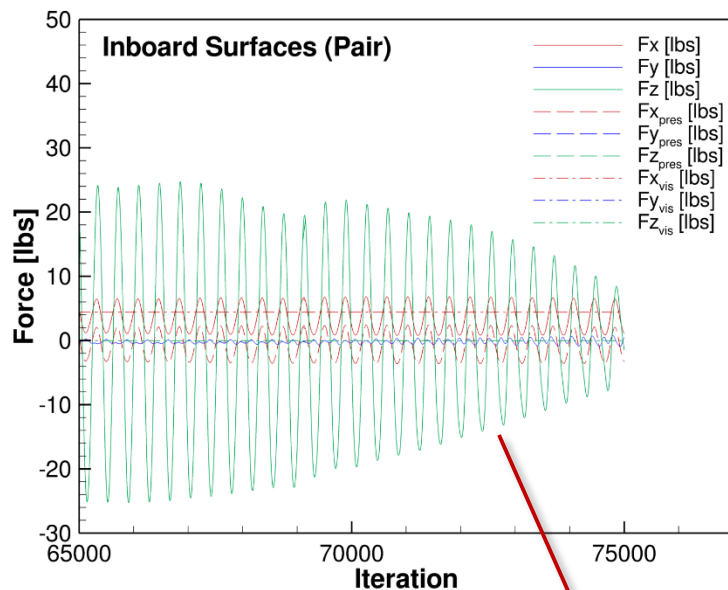
Global CFL number/local time step

Ensemble-Averaged Forces

Global time step
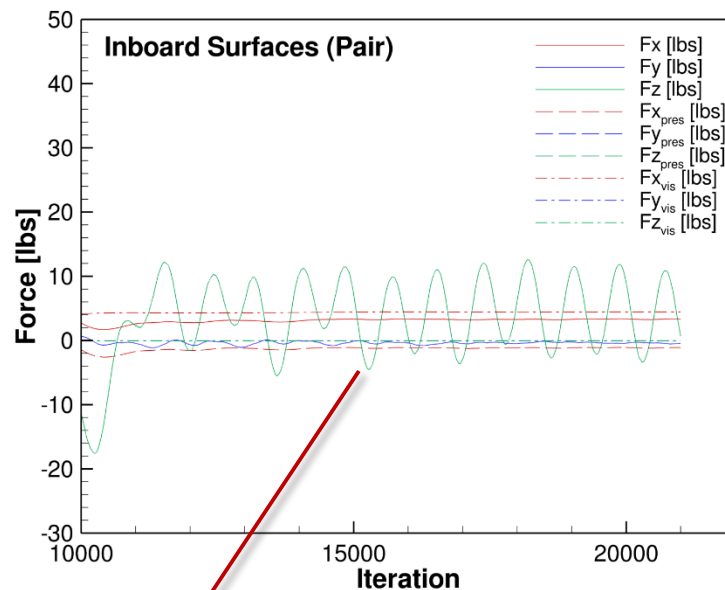
Time-Averaged Forces

- Time-averaged and ensemble-averaged loads were comparable.
  - But, time-accurate simulation twice as expensive (computational time).
  - Decided to use ensemble-averaged loads for future simulations.
- Aero loads were relatively small compared to expected model weight.

Simulation of NATR Center Engine:
Nozzle Flowfield

Center Engine Symmetry Plane

Iso-Surface: u<0.
Contours: TKE.
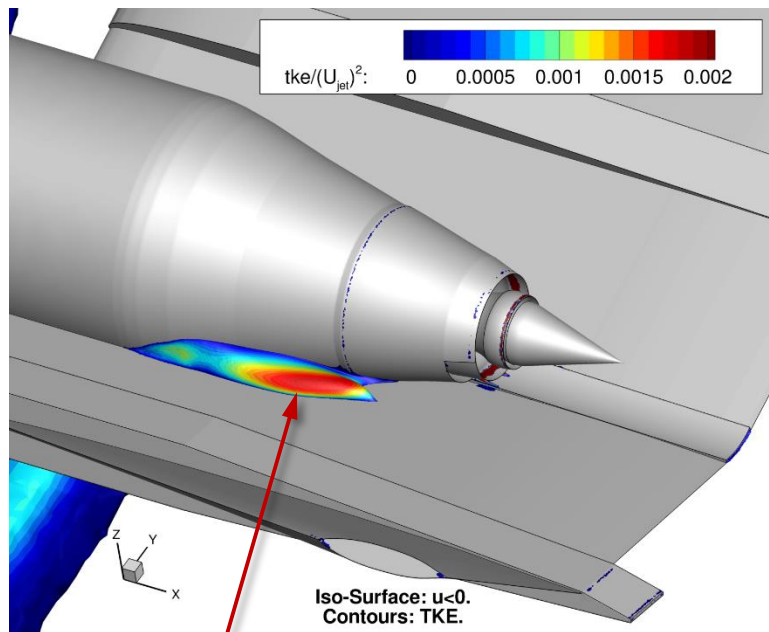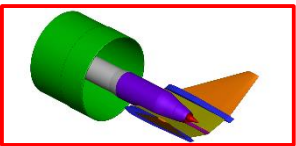
Flow separation likely caused by corner flow in presence of adverse pressure gradient due to nozzle boattail.
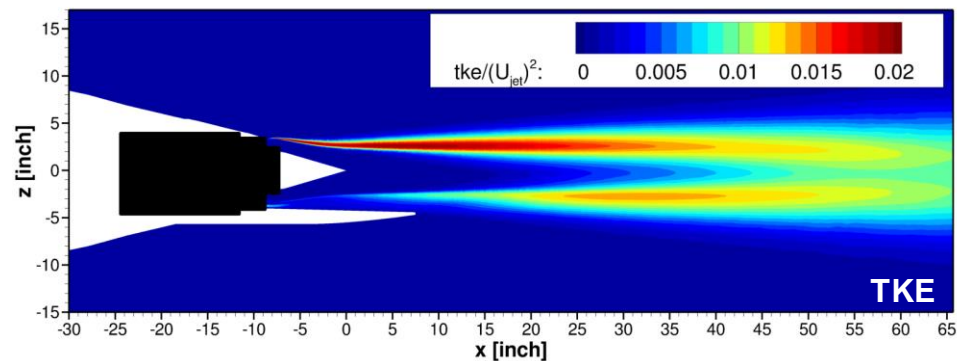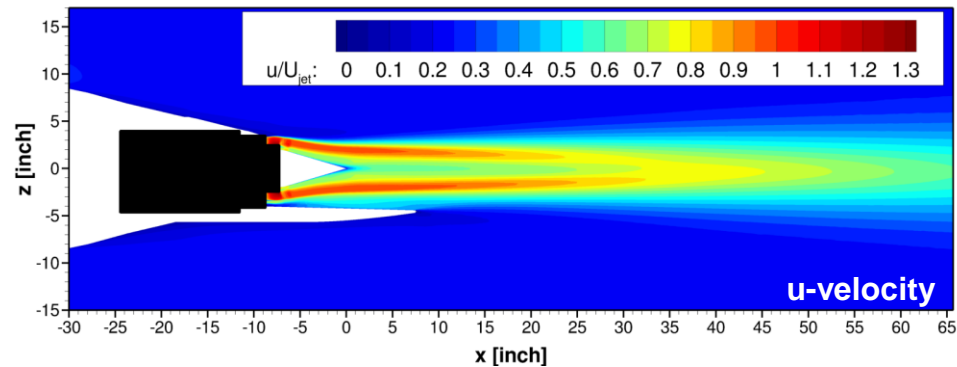
Along symmetry plane, jet flow looks similar to that of LM1044-3.
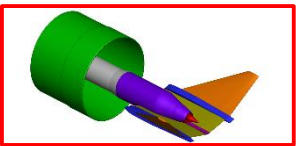
Simulation of NATR Center Engine: Junction Flow
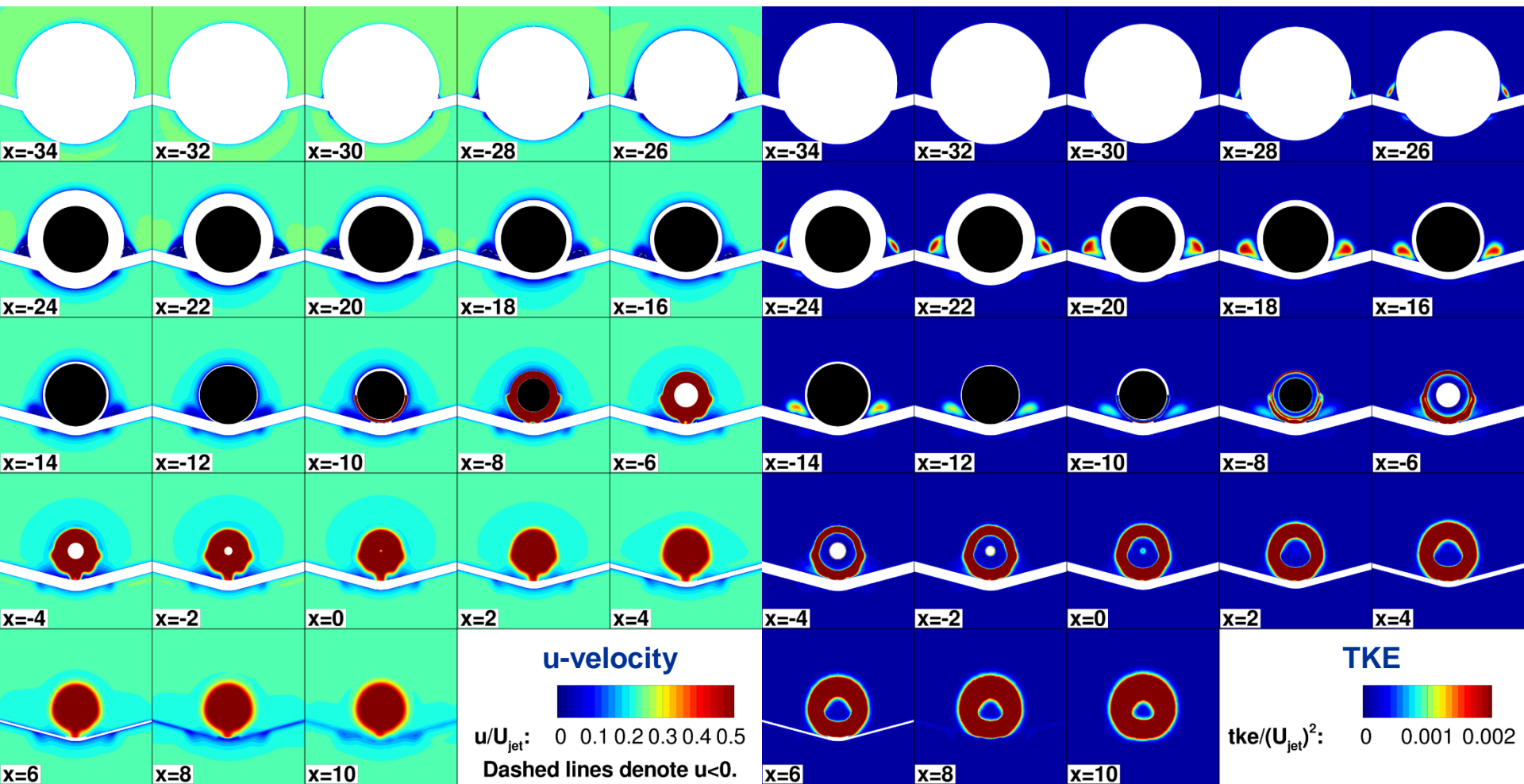
- Flow separation region from 25 inches to 15 inches upstream of primary nozzle exit.

Modifications to NATR Center Engine Model
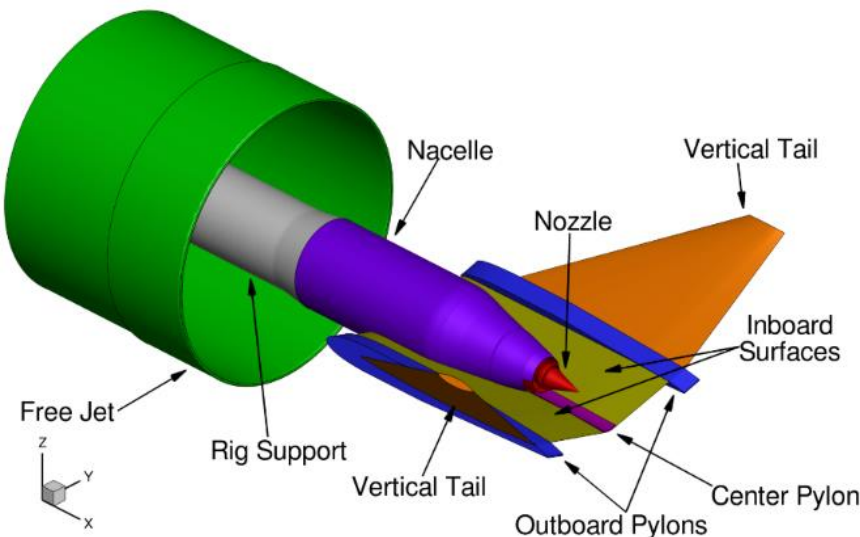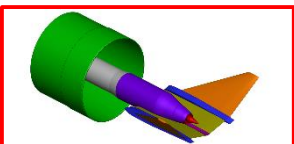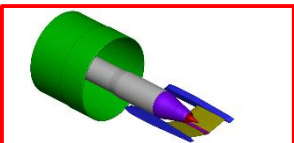
Original NATR Center Engine Model
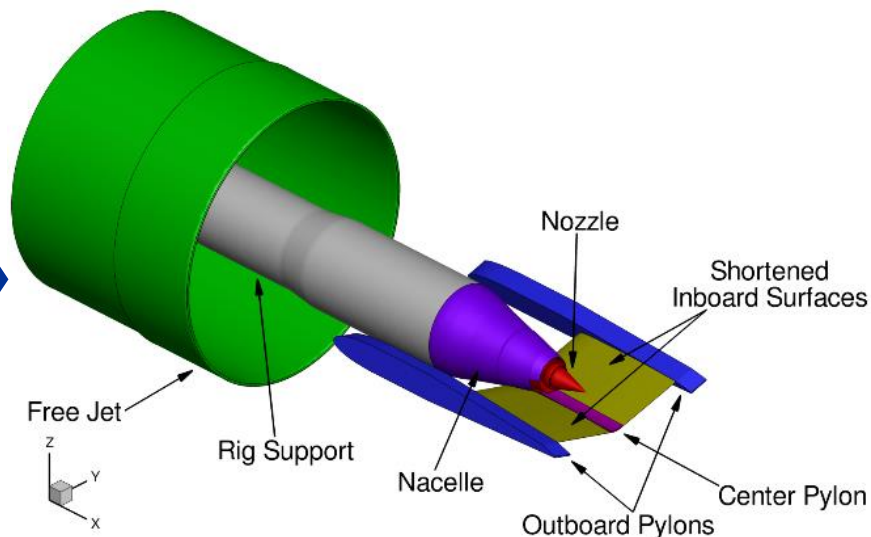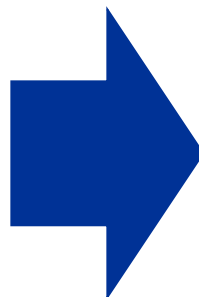
Modified NATR Center Engine Model

- To reduce separated junction flow, truncated inboard surfaces by moving leading edge 28 inches downstream.
  - Reduced chord length by 53%.
- Removed tail surfaces.
- Preliminary acoustic tests (no freejet flow) showed that removing surfaces did <u>not</u> affect jet noise radiation (Bridges, AIAA Paper 2016-3042).

NATR Center Engine Models: Comparison of Junction Flows

Original NATR Center Engine Model

Modified NATR Center Engine Model

$tke/(U_{jet})^2$:   0   0.0005   0.001   0.0015   0.002

Iso-Surface: u<0.
Contours: TKE.

Iso-Surface: u<0.
Contours: TKE.
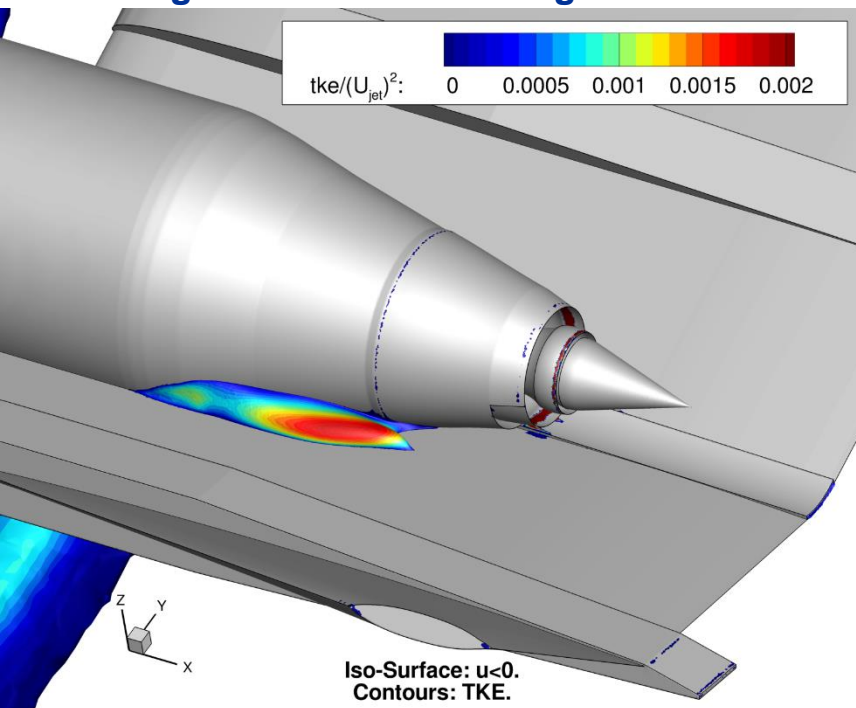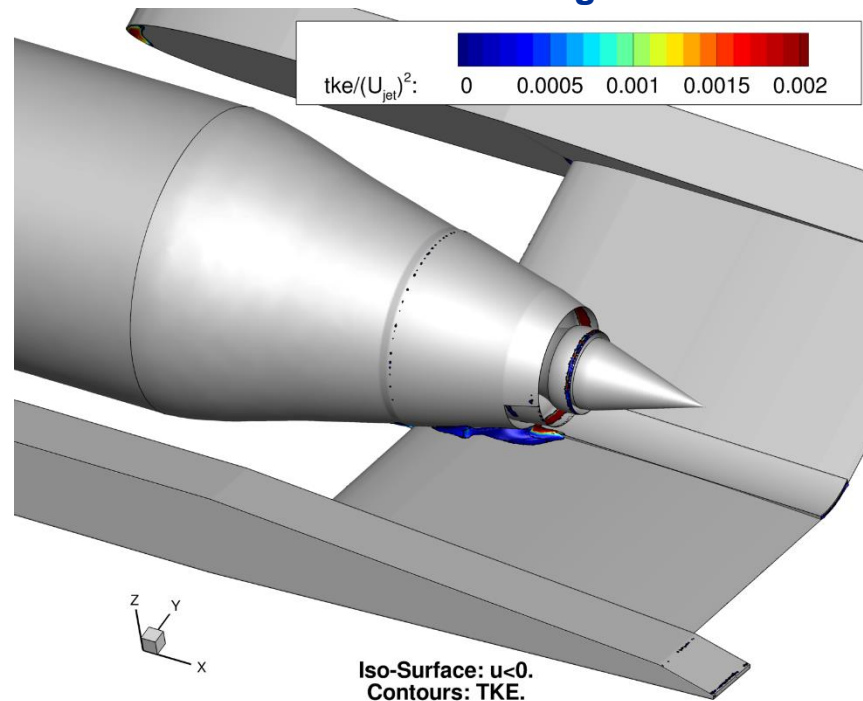
- Truncating the inboard surface greatly reduced the separated flow in junction region.
  - Length of flow separation was reduced by 60%.
  - Peak *TKE* was reduced by 62%.
- Modified NATR center engine model more closely mimics LM1044-3 center engine.
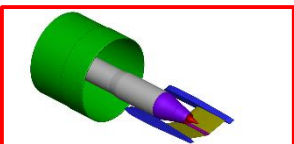
Simulation of
Modified NATR Center Engine
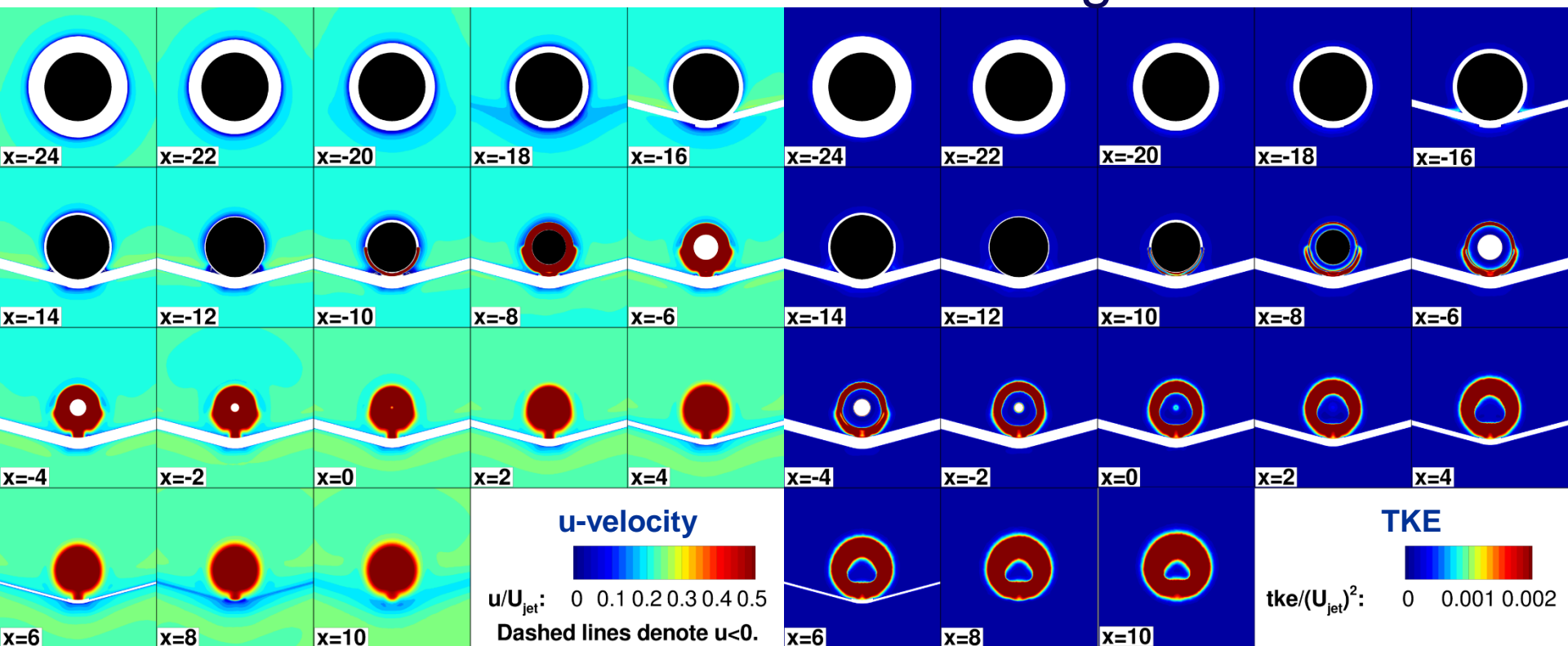
- Truncating the inboard surfaces reduced the amount of separated junction flow.
  - Reducing length of corner flow reduces boundary layer growth in junction region.
  - Reduces the affects of the adverse pressure gradient from nozzle boattail.

- Ensemble-averaged aero forces were found not to present any challenges for mechanical design.
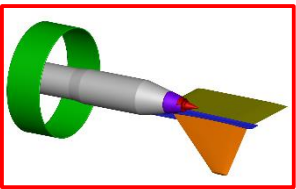
Simulation of NATR Outboard Engine

- No separated flow observed in junction regions of NATR outboard engine model.
  - Greater separation between jet rig and inboard and tail surfaces.

- Ensemble-averaged aero forces were found not to present any challenges for mechanical design.

u-velocity

u/u_{jet}: 0 0.1 0.2 0.3 0.4 0.5
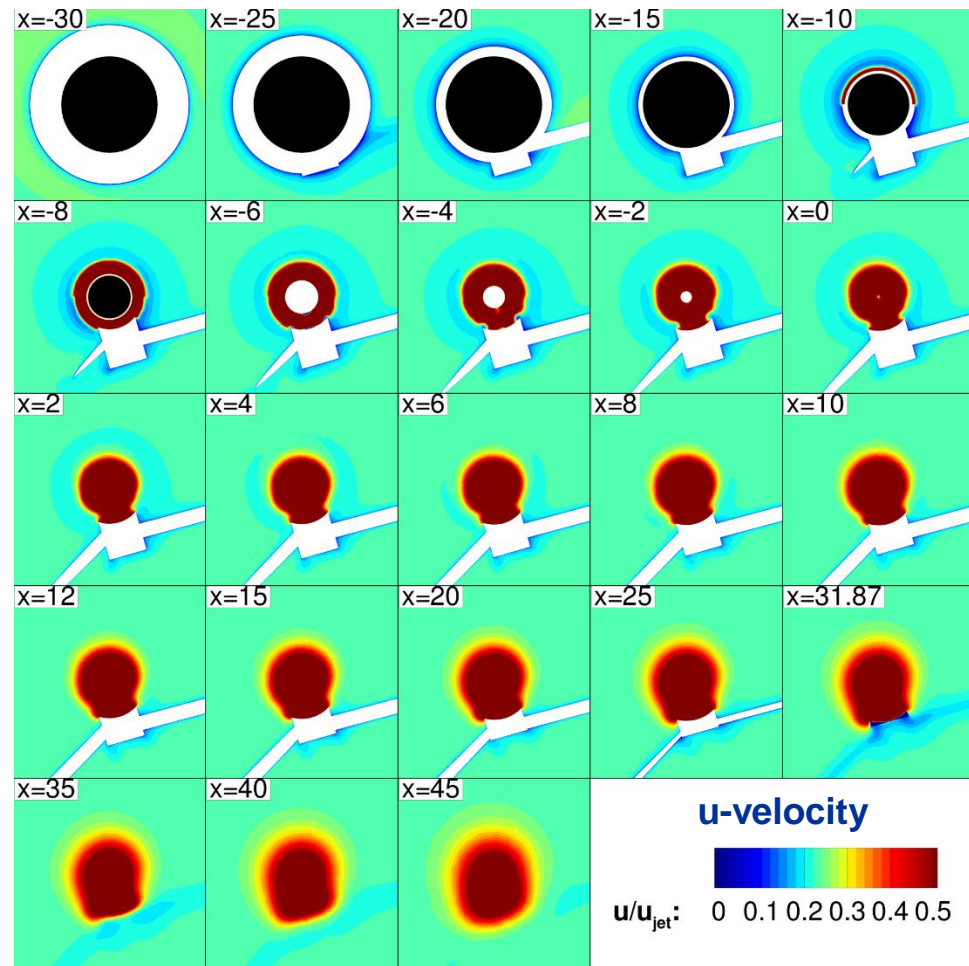
Conclusions

- The NATR experimental hardware relates well to the LM1044-3 aircraft.
  - Whereas the LM1044-3 engine nacelles were free of significant flow separations, the NATR outboard engine model was free of separated flow while the modified NATR center engine model had some separated flow in the junction region near the nozzle exit.
  - Whereas the NATR is limited to AOA=0°, the LM1044-3 flowfield did not significantly change as AOA increased from 0° to 9°.

- Screen simulations of experimental hardware reduced the risk of potential sources of rig noise.
  - NATR outboard engine model was free of potential noise sources.
  - Modified the NATR center engine model to reduce size and intensity of separated junction flow.

- Computed the aerodynamic forces on experimental hardware for structural design.
  - Forces were unsteady, but ensemble-averaged.
  - Average aerodynamic forces were found to be relatively small and did not present challenges to structural design.

Conclusions

- Computed inlet flowfield for inlet performance and fan noise analysis.
  - Simulations showed good agreement with previously reported total pressure recovery.
  - Showed that inlet total pressure recovery does not decrease as AOA increases.
  - Showed that the inlet has low circumferential and radial distortion at take-off conditions; does not increase substantially at AOA increases.
  - Quick assessment of distortion determined it would not produce noise source at the fan face.

- Showed the importance of grid refinement and placement for unstructured grid simulations of jet flows.
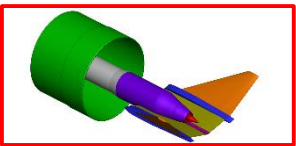 - Refining the jet plume is paramount for predicting length and TKE field of the jet plume.

Acknowledgements

- This work was supported by the NASA Commercial Supersonics Technologies Project under the NASA Advanced Air Vehicles Program.

- The authors also wish to thank:
  - James Bridges
  - Christopher Heath
  - Mark Sanetrik

Back-Up Slides

Aerodynamic Loads:
NATR Center Engine (Original)

Component	F_x [lb]				F_y [lb]				F_z [lb]			
	Unsteady			Steady	Unsteady			Steady	Unsteady			Steady
	Avg	Min	Max	Avg	Avg	Min	Max	Avg	Avg	Min	Max	Avg
Center Pylon	0.26	−0.28	0.78	0.48	−0.05	−0.13	0.01	−0.05	−2.04	−16.12	12.90	−2.63
Inboard Surfaces (pair)	2.09	−0.46	4.95	3.51	−0.21	−2.62	4.04	−0.19	−1.91	−43.57	43.43	−3.89
Nacelle	14.82	−1.65	23.09	12.61	0.46	−9.43	7.33	−0.51	24.23	11.11	40.84	25.10
Outboard Pylons (pair)	5.77	3.76	8.69	5.57	−0.72	−5.08	4.04	−0.02	6.13	−9.01	17.18	10.15
Tails (pair)	−0.90	−9.27	15.28	3.11	−1.63	−29.07	36.08	−0.58	−8.42	−73.76	91.33	10.27

Aerodynamic Loads:
Modified NATR Center Engine

Component	F_x [lb]			F_y [lb]			F_z [lb]		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Center Pylon	0.77	0.51	1.03	−0.05	−0.07	−0.03	−1.14	−2.99	1.03
Inboard Surfaces (pair)	3.39	0.63	6.32	−0.27	−0.82	0.60	8.93	−4.39	24.47
Nacelle	11.58	5.13	16.23	0.08	−1.44	1.64	2.72	−0.77	5.92
Outboard Pylons (pair)	7.06	5.39	8.49	−0.17	1.43	1.14	8.94	5.17	12.97
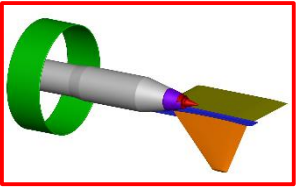
Aerodynamic Loads:
NATR Outboard Engine

Component	F_x [lb]			F_y [lb]			F_z [lb]		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Vertical Tail	4.59	4.59	4.59	−1.01	−0.99	−1.02	2.25	2.23	2.26
Pylon	6.77	6.77	6.77	−2.02	−2.02	−2.03	2.40	2.39	2.40
Inboard Surface	6.98	6.98	6.98	4.94	4.93	4.95	−17.27	−17.24	−17.29
Nacelle	−0.41	−0.40	−0.41	1.86	1.86	1.87	−0.42	−0.42	−0.43