Computations of Aerodynamic Performance Databases using Output-Based Refinement

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Oral Presentation Only
Motivation

- How well is the vehicle’s aerodynamic performance estimated?
- Is the mesh appropriate for every flow condition and vehicle configuration?

Langley Glide-Back Booster Database: ~2900 Cases
Objectives

Toward automation of CFD analysis

- Handle complex geometry problems
- Control discretization errors via solution-adaptive mesh refinement
- Focus on aerodynamic databases of parametric and optimization studies
  1. **Accuracy**: satisfy prescribed error bounds
  2. **Robustness and speed**: may require over $10^5$ mesh generations
  3. **Automation**: avoid user supervision
- Obtain “expert meshes” independent of user skill
- Run every case adaptively in production settings
Approach

1. Embedded-boundary Cartesian mesh method (1990’s)
   - Arbitrarily complex domains, efficient and accurate
   - Irregularity confined to body intersecting cells

2. Incremental strategy for h-refinement of nested Cartesian meshes (2002)
   - Fast local re-meshing of flagged cells
   - Guaranteed reliability
   - Early work used feature detection and $\tau$-extrapolation

3. Adjoint-weighted residual error estimates (2007)
   - Mesh enrichment targets output functionals
   - Functional error-bound estimates
   - Implementation exploits nesting of Cartesian meshes for fast interpolation
Numerical Error
Uniform Mesh Refinement

- Numerical solution on a mesh with cell-size $H$ gives approximate functional:
  \[ J(U_H) \]
- Goal is to estimate functional error:
  \[ \mathcal{J}(U) = J(U_H) + E \]
- Express the error as a function of the flow solution
  \[ E = f(U_H) \]
Consider a simpler problem of computing relative error:

\[ J(\mathbf{U}_h) = J(\mathbf{U}_H) + e \]

For second-order accurate spatial discretization and cell-size in the asymptotic range, the functional error is:

\[ E = e + \frac{1}{4}e + \frac{1}{4^2}e + \cdots \]

\[ = \frac{4}{3}e \]

We will use an adjoint solution on mesh $H$ to estimate

\[ e = f(\mathbf{U}_H, \psi_H) \]
Adjoint Error Estimates

• Consider a functional $J(U_H)$ computed from the solution of Euler equations discretized on an affordable mesh with cell-size $H$:

$$R(U_H) = 0$$

• In addition, consider an embedded mesh with cell-size $h$ obtained via uniform refinement of the baseline mesh

• We seek to compute the error relative to the embedded mesh without solving the problem on the fine mesh

$$e = |J(U_h) - J(U_H_h)|$$

Venditti & Darmofal, 2002
• Estimate of functional on embedded mesh is obtained from Taylor series expansions about the coarse mesh solution

\[ J(U_h) \approx J(U^H_h) + \frac{\partial J(U^H_h)}{\partial U_h}(U_h - U^H_h) \]

\[ R(U_h) = 0 \approx R(U^H_h) + \frac{\partial R(U^H_h)}{\partial U_h}(U_h - U^H_h) \]

• These equations are combined to give

\[ J(U_h) \approx J(U^H_h) - \psi^T_h R(U^H_h) \]

where \( \psi \) satisfies the adjoint equation

\[ \left[ \frac{\partial R(U^H_h)}{\partial U_h} \right]^T \psi_h = \frac{\partial J(U^H_h)}{\partial U_h}^T \]
Estimate of functional on embedded mesh is obtained from Taylor series expansions about the coarse mesh solution

\[
J(U_h) \approx J(U_h^H) + \frac{\partial J(U_h^H)}{\partial U_h}(U_h - U_h^H)
\]

\[
R(U_h) = 0 \approx R(U_h^H) + \frac{\partial R(U_h^H)}{\partial U_h}(U_h - U_h^H)
\]

These equations are combined to give

\[
J(U_h) \approx J(U_h^H) - \psi_h^T R(U_h^H)
\]

where \( \psi \) satisfies the adjoint equation

\[
\left[ \frac{\partial R(U_h^H)}{\partial U_h} \right]^T \psi_h = \frac{\partial J(U_h^H)}{\partial U_h}^T
\]

Adjoints provide a weighting on residual errors.
Adjoint Correction and Error Bound

• Since the adjoint solution is not known on the embedded mesh, we use an approximate solution from the coarse mesh to obtain

\[
J(U_h) \approx J(U^H_h) - (\psi^H_h)^T R(U^H_h) - (\psi_h - \psi^H_h)^T R(U^H_h)
\]

Adjoint Correction  Remaining Error

• \(U^H_h, \psi^H_h\) denote reconstructed solutions lifted from coarse mesh to embedded mesh. We use linear interpolation

• \(\psi_h\) is unknown. We approximate it with a quadratic interpolant

\[ U_H \rightarrow U_h \]
\[ J(U_h) \approx J(U^H_H) - (\psi^H_h)^T R(U^H_h) - (\psi_h - \psi^H_h)^T R(U^H_h) \]

- Predict functional on a fine mesh with cell-size \( h \) from a coarse mesh solution with cell size \( H \)
Adjoint Correction

\[
J(U_h) \approx J(U_H) - (\psi_H^T R(U_H)) - (\psi_h - \psi_H^T R(U_H))
\]

- Predict functional on a fine mesh with cell-size \( h \) from a coarse mesh solution with cell size \( H \)
Error Bound Estimate

\[ J(U_h) \approx J(U_h^H) - (\psi_h^H)^T R(U_h^H) - (\psi_h - \psi_h^H)^T R(U_h^H) \]

- Bound on remaining error in each coarse cell \( k \)
  \[ e_k = \sum \left| (\psi_Q - \psi_L)^T R(U_L) \right|_k \]

- Net functional error
  \[ E = \sum_{k=0}^{N} e_k \]

- Given a user specified tolerance TOL, termination criterion is satisfied when \( E < TOL \)
Refinement Parameter

• Define maximum allowable error level in each coarse cell via equidistribution: \( t = \text{TOL} / N \)

• Refinement parameter in each cell is given by
  \[
  r_k = \frac{e_k}{t}
  \]

• Refine cells for which \( r_k > \lambda \)
  where \( \lambda \geq 1 \) is a global threshold factor

Error Histograms
Results
Focus on Applications

Part A.  Accuracy
- Launch Abort Vehicle with jets - uniform mesh refinement study

Part B.  Efficiency
- Sonic-boom signature test case - computational cost summary

Part C.  Databases
- Nozzle-Guide-Vane Missile
- Launch Abort Vehicle with Jettison Motor plumes
Launch Abort Vehicle with ACM Jets

**Ignition**

**Mach ~0.75**
- 6 sec
- ~5300 ft altitude, ~3300 ft downrange

**ACM + Canards turn LAV to heat shield forward**

**Mach ~0.3**
- 15 sec

**LAS is jettisoned with ACM still burning. CM in free flight for ~3 seconds until drogue chute deployment.**

**Mach ~0.2**
- 20 sec

ACM initially pushes LAV to ~25 deg alpha during AM burn.

**Mach ~0.2**
- 21 sec

LAS is jettisoned with ACM still burning. CM in free flight for ~3 seconds until drogue chute deployment.

**Mach ~0.3**
- 1 sec

**Mach ~0.75**
- 6 sec

**Pad-abort mission profile**

8 Abort Control Motors (ACMs)
4 Abort Motors (AMs)

4 Separation Motors (SMs)

C.G.
Launch Abort Vehicle with ACM Jets

*Ignition*

Mach 0 sec

Mach 0.75

- Mach 0.75
- ACM Trim at 0 deg alpha during ACM coast phase. Slows down from Mach 0.8 to 0.2 in ~10 seconds and drops in qbar from 800 to 100 psf.
- ACM holds LAV at ~25 deg alpha during AM burn.
- ACM initially pushes LAV to ~25 deg alpha during AM burn.

Mach 0.3

- 8 Abort Control Motors (ACMs)
- 4 Abort Motors (AMs)
- 4 Separation Motors (SMs)
- C.G.

Mach 0.2

- Mach 0.2
- ACM + Canards turn LAV to heat shield forward
- LAS is jettisoned with ACM still burning. CM in free flight for ~3 seconds until drogue chute deployment.

Mach 0 sec

- Ignition

Pad-abort mission profile
Launch Abort Vehicle with ACM Jets

Problem Setup

- Examine aerodynamic performance with ACM jets (AIAA 2008-1281)
- Selected case: $M_\infty = 4$, $\alpha = 20^\circ$, due to significant plume penetration
- Power boundary conditions applied at plenum face (assumes perfect gas)
Launch Abort Vehicle with ACM Jets

Functional

- Functional: \( C_N + 0.4C_A \)
- Consider two cases:
  - **Case A**: Functional defined over nose-cone surface only, \( TOL=0.0005 \)
    - Accuracy verification: Uniform mesh refinement study
    - Take advantage of supersonic freestream conditions to limit refinement to nose-cone region
  - **Case B**: Functional defined over entire vehicle, \( TOL=0.006 \)
    - Typical engineering database case
Launch Abort Vehicle
Initial mesh and solution on symmetry plane

Mach contours, $M_\infty = 4, \alpha = 20^\circ$
Case A: Finest Mesh of Uniform Refinement Study (Side-view, 75M Cells)

Mach contours, \( M_\infty = 4, \alpha = 20^\circ \)
Case A: Finest Mesh of Uniform Refinement Study (Side-view, 75M Cells)
Case A: Finest Mesh of Uniform Refinement Study (Front-view, 75M Cells)
Case A: Adapted Mesh (Side-view)
14 Cycles; 310k Cells

Mach contours, $M_\infty = 4, \alpha = 20^\circ$
Case A: Functional and Error Convergence

• Difference in functional values is below 0.05% on finest mesh
• Two orders-of magnitude savings in total number of cells
• Adaptive computation required just 9 minutes of wall-clock time on an 8-core Intel Xeon desktop
Case B
Final mesh and solution on symmetry plane

10M cells

15 adaptations, Mach contours, $M_\infty = 4$, $\alpha = 20^\circ$
Case B
Type IV Shock-Shock Interference

Close-up view of lower surface ACM and plume, colored by Mach number
Case B
Final mesh at various x-stations

15 adaptations, $M_\infty = 4$, $\alpha = 20^\circ$
Case B
Front view of plumes on final mesh

$M_\infty = 4, \alpha = 20^\circ$
Launch Abort Vehicle
Plume Visualization on Final Mesh (~7.7M cells)

- Side-view: plumes shown as iso-surfaces of total temperature colored by Mach number. Also shown are Mach number on symmetry plane and $C_p$ shading on body.
- Main jet interaction occurs as lower-surface plume strikes sides of the boost protective cover.
- Largest errors in functional are near edges of main plume near the ACMs.

$M_\infty = 4$, $\alpha = 20^\circ$
Launch Abort Vehicle
Bottom view of plumes on final mesh

- Paths of three main plumes from the lower surface ACMs to the heat-shield. Main jet splits into two plumes that contact the aft region of the vehicle

$M_\infty = 4, \alpha = 20^\circ$
Determination of plume paths and appropriate refinement of plume edges is not possible \textit{a-priori}, yet these features determine the “aerodynamic shape” of the vehicle.

Adjoint error analysis identifies regions where jet interaction effects are important for the computation of aerodynamic coefficients and triggers mesh refinement.

Functional convergence settles down at \(~1\)M cells, however, additional research is required to improve estimates of the error-bound.
Results
Focus on Applications

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Part C.  Databases
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- Launch Abort Vehicle with Jettison Motor plumes
69° Swept Delta Wing-Body

- NASA TN D-7160
  - \( M_\infty = 1.68 \)
  - \( \alpha = 4.74^\circ \)
  - Sensor offset, \( h/L = 3.6 \) & \( \{0.2, 0.4, 0.8, 1.2, 2.0, 2.8\} \)

- Initial mesh \( \sim 22 \text{ k cells} \)

\[
J_s = \int_0^L \left( \frac{\Delta p}{p_\infty} \right)^2 \, ds
\]
69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74^\circ$

$L = 17.52$

Isobars

22 k cells
69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74^\circ$

$L = 17.52$

Isobars

2.26 M cells
69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74^\circ$

Initial mesh ~ 22k cells

Isobars

- $L = 17.52$
- $2.0L$
- $2.8L$
- $3.6L$

2.26 M cells
69° Swept Delta Wing-Body

- NASA TN D-7160
  - \( M_\infty = 1.68 \)
  - \( \alpha = 4.74° \)

\[ L = 17.52 \]

\[ \frac{h}{L} = 3.6 \]

\[ \{0.2, 0.4, 0.8, 1.2, 2.0, 2.8\} \]

Initial mesh ~ 22k cells

Isobars

Cart3D: 2.26 M cells

Experiment, \( \frac{h}{L} = 3.6 \)
69° Swept Delta Wing-Body

- NASA TN D-7160
  - $M_\infty = 1.68$
  - $\alpha = 4.74^\circ$
  - $h/L = \{0.2, 0.4, 0.8, 1.2, 2.0, 2.8, 3.6\}$

- Simulation performed on desktop workstation
  - Dual quad-core (8 cores)
  - Intel Xeon, 3.2Ghz
  - 16 Gb memory

- Total simulation time 53 mins. (all adaptations & mesh gen)

Total = 53 mins.
Results
Focus on Applications

Part A. Accuracy

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Part B. Efficiency

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Part C. Databases

- Nozzle-Guide-Vane Missile
- Launch Abort Vehicle with Jettison Motor plumes
Error Controlled Aero Database

- Realistically complex model with plenum, guide vanes, etc.

- Perform (data blind) aero analysis over range of operating conditions
  
  - $M_\infty = \{0.5, 0.7, 0.9, 1.1, 1.3, 1.6, 2.0\}$
  
  - $\alpha = \{0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ\} = 35$ cases total

  - Output functional: $J = C_N + 0.1C_A$, $\text{TOL} = 0.05$

- Starting mesh has $\sim 8000$ cells
Error Controlled Aero Database

- Realistically complex model with plenum, guide vanes, etc.
- Perform (data blind) aero analysis over range of operating conditions:
  - $M_\infty = \{0.5, 0.7, 0.9, 1.1, 1.3, 1.6, 2.0\}$
  - $\alpha = \{0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ\}$ = 35 cases total
- Output functional: $J = C_N + 0.1C_A$, $TOL = 0.05$
- Starting mesh has ~8000 cells
Example Case

\[ M_\infty = 0.9, \quad \alpha = 10^\circ \]
Example Case

\(M_\infty = 0.9, \alpha = 10^\circ\)
Error Controlled Aero Database

\(M_\infty = 0.5\)

\(\alpha = 0^\circ\) \hspace{1cm} \(\alpha = 10^\circ\) \hspace{1cm} \(\alpha = 20^\circ\)

\(630 \text{ k cells}\) \hspace{1cm} \(835 \text{ k cells}\)

Mach Contours
Error Controlled Aero Database

\[ M_\infty = 0.7 \]

\[ \alpha = 0^\circ \quad \alpha = 10^\circ \quad \alpha = 20^\circ \]

\( 565 \text{ k cells} \)

\( 1.1 \text{ M cells} \)

Mach Contours
Error Controlled Aero Database

\[ M_\infty = 0.9 \]

\[ \alpha = 0^\circ \]
\[ \alpha = 10^\circ \]
\[ \alpha = 20^\circ \]

Mach Contours

1.6 M cells

665 k cells
Error Controlled Aero Database

\( M_\infty = 1.1 \)

\( \alpha = 0^\circ \quad \alpha = 10^\circ \quad \alpha = 20^\circ \)

550 k cells

1.3 M cells

610 k cells

Mach Contours
Error Controlled Aero Database

$M_\infty = 1.3$

$\alpha = 0^\circ$  $\alpha = 10^\circ$  $\alpha = 20^\circ$

Mach Contours

660 k cells
Error Controlled Aero Database

\[ M_{\infty} = 1.6 \]

\[ \alpha = 0^\circ \]
\[ \alpha = 10^\circ \]
\[ \alpha = 20^\circ \]

Mach Contours

900 k cells

1.5 M cells
Error Controlled Aero Database

$M_\infty = 2.0$

$\alpha = 0°$

$\alpha = 10°$

$\alpha = 20°$

1.4 M cells

900 k cells

Mach Contours
Error Controlled Aero Database

Normal Force Coefficient

\[ C_N \] vs. \( \alpha \), deg for different Mach numbers (M).

- \( M = 0.5 \)
- \( M = 0.7 \)
- \( M = 0.9 \)
- \( M = 1.1 \)
- \( M = 1.3 \)
- \( M = 1.6 \)
- \( M = 2.0 \)
Error Controlled Aero Database

Axial Force Coefficient
Error Controlled Aero Database

Pitch moment about nose
Error Controlled Aero Database

Error bound on output functional
Error Controlled Aero Database

Error bound on output functional

Error Bound Estimate

- $M = 0.5$
- $M = 0.7$
- $M = 0.9$
- $M = 1.1$
- $M = 1.3$
- $M = 1.6$
- $M = 2.0$
$M_\infty = 1.6, \alpha = 5^\circ$
Error Controlled Aero Database

Error bound on output functional

![Graph showing error bound estimates for different Mach numbers (M)].

- M = 0.5
- M = 0.7
- M = 0.9
- M = 1.1
- M = 1.3
- M = 1.6
- M = 2.0

The graph displays the error bound estimate as a function of angle (Alpha, deg) for various Mach numbers, illustrating how the error bound changes with different Mach numbers.
Error Controlled Aero Database

Error bound on output functional

![Graph showing error bound estimate for different Mach numbers (M)].

Legend:
- M = 0.5
- M = 0.7
- M = 0.9
- M = 1.1
- M = 1.3
- M = 1.6
- M = 2.0
Error Controlled Aero Database

- Functional
- Corrected Functional
- Error Bound Estimate

*Number of Cells*

- $10^4$
- $10^5$
- $10^6$

*Functional Value*

- $10$
- $10^4$
- $10^5$

- $10$
- $10^4$
- $10^5$

*Alpha, deg*

- $0$
- $5$
- $10$
- $15$
- $20$
- $25$

- $M = 0.5$
- $M = 0.7$
- $M = 0.9$
- $M = 1.1$
- $M = 1.3$
- $M = 1.6$
- $M = 2.0$
**Error Controlled Aero Database**

- Error Bound Estimate
  - $M = 0.5$
  - $M = 0.7$
  - $M = 0.9$
  - $M = 1.1$
  - $M = 1.3$
  - $M = 1.6$
  - $M = 2.0$

- Number of Cells
  - 0
  - 0.5
  - 1
  - 1.5
  - 2
  - 2.5
  - 3
  - 3.5
  - 4

- Functional Value
  - Corrected Functional
  - Error Bound Estimate

- Force/Mom Coef.
  - $C_A$
  - $C_N$
  - $C_Y$

- $M_\infty = 0.7$, $\alpha = 10^\circ$
  - $C_A$
  - $C_N$
  - $C_Y$

- MG Cycles
  - 0
  - 250
  - 500
  - 750
  - 1000
  - 1250

- Alpha, deg
  - 10
  - 15
  - 20
  - 25
Launch Abort System
Tower Jettison Database

Pad-abort mission profile

1. Mach ~0.75
   - 6 sec
   - ~5300 ft altitude, ~3300 ft downrange
   - ACM trims LAV at ~0 deg alpha during ACM coast phase. Slows down from Mach 0.8 to 0.2 in ~10 seconds and drops in qbar from 800 to 100 psf

2. Mach ~0.3
   - 15 sec
   - ACM initially pushes LAV to ~25 deg alpha during AM burnout
   - ACM + Canards turn LAV to heat shield forward

3. Mach ~0.2
   - 20 sec
   - LAS is jettisoned with ACM still burning. CM in free flight for ~3 seconds until drogue chute deployment

4. Mach 0
   - 0 sec
   - Ignition

8 Abort Control Motors (ACMs)
4 Abort Motors (AMs)
4 Separation Motors (SMs)
C.G.
Launch Abort System Tower Jettison

- Objective: Analyze aerodynamic forces and moments during LAS tower jettison
- Include effects of jettison motor firing with translation and rotation of the Crew Module (CM) relative to the Launch Abort Module
Geometry Configuration Space

- Four configuration parameters for CM position and orientation: $\Delta x$, $\Delta y$, $\Delta z$, $\theta$
Database Cases

• Jettison Motor Plume Conditions:
  • JM on and JM off
  • Scale thrust for altitude
• Trajectory: maintain $q_\infty \approx \text{Const.}$

• Run Conditions:
  $M_\infty = \{0.5, 0.7, 0.9, 1.1, 1.3, 1.6\}$
  $\alpha = \{155^\circ, 160^\circ, 165^\circ, 170^\circ, 175^\circ, 180^\circ\}$
  $\beta = \{0^\circ, 5^\circ\}$
  $CM\Delta x, CM\Delta y, CM\Delta z, CM\Delta \theta$

\~1200 Cases
Functional and Adaptation Strategy

• Challenging simulations
  ‣ Complex, detailed geometry
  ‣ Bodies in close proximity
  ‣ Strong upstream-firing jets
  ‣ Shocks and wakes

• Output functional: \( J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM} \)

• Solution technique is a compromise since most of these cases are unsteady, and need high resolution
  ‣ Want the best answer as cheaply as possible

• Adaptation follows “worst-things-first” strategy (AIAA 2008-0725)
  ‣ Refine largest contributors to output error first
Initial Mesh

- Background mesh essentially symmetric and coarse to avoid biasing solution

~3000 Cells
Example Final Mesh (10 Adapt Cycles)

- Output functional: \( J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM} \)
- \( M_\infty = 1.1, \alpha = 160^\circ \) with the CM @ \((\Delta x, \Delta y, \Delta z, 10^\circ)\)
Example Final Solution (10 Adapt Cycles)

- Output functional: \( J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM} \)
- \( M_\infty = 1.1, \alpha = 160^\circ \) with the CM @ \((\Delta x, \Delta y, \Delta z, 10^\circ)\)
Convergence of Aerodynamic Coefficients

- Output functional: \( J = (0.8|C_N| + 0.2|C_A|)_{CM} + (|C_N| + 0.4|C_A|)_{LAM} \)
- \( M_\infty = 1.1, \alpha = 160^\circ \) with the CM @ \((\Delta x, \Delta y, \Delta z, 10^\circ)\)

- Convergence of forces and moms. on CM with mesh refinement
Comparison with Unsteady Simulation

- How do these iteration averages compare with unsteady simulation?
- Performed comparisons at Mach 0.7, & 1.1
- “Best unsteady mesh” generated by 1 additional refinement of steady mesh, using low threshold to “fill out” adaptation regions
- Example case: $M_\infty = 1.1$, $\alpha = 160^\circ$ with the CM @ ($\Delta x$, $\Delta y$, $\Delta z$, 10°)

Steady mesh & $C_p$, ~2.95 M Cells

Unsteady mesh & $C_p$, ~5.2 M Cells
Comparison with Unsteady Simulation

- How do these iteration averages compare with unsteady simulation?
- Performed comparisons at Mach 0.7, & 1.1
- “Best unsteady mesh” generated by 1 additional refinement of steady mesh, using low threshold to “fill out” adaptation regions
- Example case: \( M_\infty = 1.1, \alpha = 160^\circ \) with the CM @ \((\Delta x, \Delta y, \Delta z, 10^\circ)\)

Steady mesh iso-Mach, \(~2.95\) M Cells

Unsteady mesh iso-Mach, \(~5.2\) M Cells
Comparison with Unsteady Simulation

$M_\infty = 1.1, \ \alpha = 160^\circ$ with the CM @ ($\Delta x, \Delta y, \Delta z, \ 10^\circ$)

- Agreement to third significant digit
- Differences in averages are same size as differences due to averaging window
- Similar results for other components at both Mach 0.7 & Mach 1.1
Plume Shape

$T_o$ iso-surface showing approximate plume shape

Adaptation chases only those regions of plumes that effect loads

$M_\infty = 1.3, \alpha = 160^\circ$
Comparison of JM On and Off Flowfields

$M_\infty = 1.1, \alpha = 155^\circ$, 1.36 M cells
Surface $C_p$

$M_\infty = 1.1, \alpha = 155^\circ$, 2.85 M cells
Surface $C_p$

JM plumes move bow shock $\sim18$ ft upstream
Database Samples

Loads on CM and LAM in proximity
($\Delta x$, 0.0, 0.0, 0°)

Loads on CM

Loads on LAM
Database Samples

Loads on CM and LAM in proximity
($\Delta x$, 0.0, 0.0, 0°)

Loads on CM

Loads on LAM

LAT Jettison Configuration

P Robinson

Delta X = 19.8

Delta Z = 0

NASA
Database Samples

Loads on CM and LAM in proximity

($\Delta x, 0.0, 0.0, 0^\circ$)
Database Samples

Loads on CM and LAM in proximity 
($\Delta x$, 0.0, 0.0, 0°)

Loads on CM

Loads on LAM
Database Samples

 Loads on CM and LAM in proximity
($\Delta x, 0.0, -\Delta z, 0^\circ$)
Database Samples

Loads on CM and LAM in proximity
\((\Delta x, 0.0, \Delta z, 0^\circ)\)
Summary

Presented a reliable and efficient approach for error estimates and mesh refinement of complex geometry problems

1. Handles complex geometry problems in an automatic fashion
2. Tolerant of coarse initial meshes
3. Behavior of functional, correction, and error estimate provide an indication of errors due to lack-of-convergence in steady simulations

- It is our best mesh generator ... refinement complements and surpasses expert knowledge
- Allows users to focus on data validation and analysis instead of mesh generation
Present and Future Work

- Sonic-boom applications (Mathias Winzter, AIAA 2008-6593)
- Address unsteadiness issues in difficult cases
  - Affordable mesh refinement and error bound for “mildly” unsteady flow
  - Formal unsteady adjoint development
- Control accuracy of objective functions in optimization studies

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