Simulations of SSLV Ascent and Debris Transport
Space Shuttle Return-To-Flight

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Outline

- CFD simulations of the Space Shuttle Launch Vehicle ascent
- Debris transport analysis
- Debris aerodynamic modeling
CFD Analysis of SSLV Ascent

Motivation
- Predict air-loads on the redesigned External Tank
- Roll maneuver air-loads
- Debris analysis flow-fields
- 3% Shuttle wind-tunnel test loads prediction

Approach
- Overflow RANS flow solver
  - Central-differencing + scalar dissipation, 2nd order
  - Diagonalized approximate factorization implicit scheme
  - Spalart-Allmaras turbulence model
  - Multi-level parallelism, scalable to hundreds of CPUs
  - Use full-multi-grid sequencing to get started
- Overset (Chimera) gridding approach
  - Developed an automated grid-generation capability
  - Gimble angles for SSME and SRB nozzles
  - Control surface deflections
  - Plume boundary-condition generation for SSMEs and SRBs
- Validation with 3% WT model: Cp, PSP, PIV
CFD Analysis of SSLV Ascent

Results

- Over 400 Overflow solutions run for Return-to-Flight
- New grids generated for each ascent condition
  - 2 hours on 32 Itanium-2 CPUs
  - 30 to 50 million grid points each
- Average of ~1000 Itanium-2 CPU hrs / solution
  - ~20 hours of wallclock time running on 64 Itanium-2 CPUs
  - Never converges to a steady-state: aft end of ET, attachment hardware, plumes, etc
  - Typically run for ~10,000 iterations
Geometry Details

- New Grids with Bipod Ramp
- New Grids without Bipod Ramp
- Old Grid System

Control Surface and nozzle deflections
“Columbia”: World Class Supercomputing

- The NAS houses the world’s fastest operational supercomputer providing 61 teraflops of compute capability to the NASA user community
- Columbia is a 20-node supercomputer built on 512-processor nodes
- Columbia is the largest SGI system in the world with over 10,000 Intel Itanium2 processors
IA-700 Wind Tunnel Tests
ARC 9x7 Unitary, AEDC 16T
Wind Tunnel Test Comparisons - Orbiter Wing, Y = -380 inches

CFD - SA conditions: $M_a = 1.550$, $\alpha = 0.00^\circ$, $\beta = 0.00^\circ$, Reynolds $\# = 2.50 \times 10^5$, IX elevon = 10.00\(^\circ\), OB elevon = -2.00\(^\circ\)

IA700A PSP conditions: $M_a = 1.550$, $\alpha = 0.00^\circ$, $\beta = 0.00^\circ$, Reynolds $\# = 2.50 \times 10^5$, IX elevon = 10.00\(^\circ\), OB elevon = -2.00\(^\circ\)

IA700B PSP conditions: $M_a = 1.550$, $\alpha = 0.00^\circ$, $\beta = 0.00^\circ$, Reynolds $\# = 2.50 \times 10^5$, IX elevon = 10.00\(^\circ\), OB elevon = -2.00\(^\circ\)

IA700A conditions: $M_a = 1.550$, $\alpha = 0.00^\circ$, $\beta = 0.00^\circ$, Reynolds $\# = 2.50 \times 10^5$, IX elevon = 10.00\(^\circ\), OB elevon = -2.00\(^\circ\), Run = 890, Point = 6, LOX Roll = 15\(^\circ\)

IA700B conditions: $M_a = 1.550$, $\alpha = -0.30^\circ$, $\beta = -0.27^\circ$, Reynolds $\# = 2.50 \times 10^5$, IX elevon = 10.00\(^\circ\), OB elevon = -2.00\(^\circ\), Run = 212, Point = 4, LOX Roll = 0\(^\circ\)
Wind Tunnel Test Comparisons - External Tank - Phi = 203.75°

CFD - SA conditions: $M_m = 1.550, \alpha = 0.00°, \beta = 0.00°, \text{Reynolds } \# = 2.50 \times 10^6 \text{ft}^2$, IB elevon = 10.00°, OB elevon = -2.00°

IA700A PSP conditions: $M_m = 1.550, \alpha = 0.00°, \beta = 0.00°, \text{Reynolds } \# = 2.50 \times 10^6 \text{ft}^2$, IB elevon = 10.00°, OB elevon = -2.00°

IA700B PSP conditions: $M_m = 1.550, \alpha = 0.00°, \beta = 0.00°, \text{Reynolds } \# = 2.50 \times 10^6 \text{ft}^2$, IB elevon = 10.00°, OB elevon = -2.00°

IA700A conditions: $M_m = 1.550, \alpha = 0.03°, \beta = 0.00°, \text{Reynolds } \# = 2.50 \times 10^6 \text{ft}^2$, IB elevon = 10.00°, OB elevon = -2.00°, Run = 990, Point = 6, LOX Roll = 15°

IA700B conditions: $M_m = 1.550, \alpha = -0.33°, \beta = -0.27°, \text{Reynolds } \# = 2.50 \times 10^6 \text{ft}^2$, IB elevon = 10.00°, OB elevon = -2.00°, Run = 212, Point = 4, LOX Roll = 0°

Stagnation pressure is artificially high in the PSP data because of poor camera angles.
STS-50 Orbiter wing running loads
Mach 1.25, Alpha -3.3, Beta 0.0, $\delta_{ci/o} = 10.5/6.25$, $Q_{bar} = 640.7$ psf

Shear Force (KIPS)

Bending Moment
Million in-lb

Torsion
Million in-lb

Flight Data
1994 CFD
2004 CFD

J. Greathouse/JSC
IA-700 Transonic PSP vs. CFD

- Mach = 1.55, $\alpha = 0^\circ$, $\beta = 0^\circ$
  
  - Lighting & camera angles reduced measurement quality in ET nose and Orbiter lower surface regions
ARC 9 × 7 Mach 2.5 PIV Comparison

Optical distortion from ET bow shock caused PIV inaccuracies

Window glare results in artificial low velocity regions
Post STS-114 Solutions
Addition of Ice/Frost Ramps

Mach = 1.55
Alpha = -3.5 deg
Beta = -0.4 deg
MET = 61 sec
Alt = 39,600 ft
Debris Impact Assessment Process

Debris Source

Debris Transport Analysis

+Y ET/SRB Fitting

Damage Assessment
Debris Transport Process Overview

- **Debris Source/Outputs**
  - Material properties
  - Installed geometry
  - Likely debris shapes
  - Failure mechanism, initial conditions

- **DTA Inputs**
  - Freestream conditions
  - CFD-based flowfield
  - Debris aerodynamic models
  - Vehicle Geometry

- **DTA Environment**
  - Impact location, mass, velocity, incidence angle
  - Rotation rate

- **Element Impact Capability**
  - Material properties
  - Installed geometry
  - Impact tolerance
  - Damage tolerance
Debris Transport

- Ballistic debris integration:
  - Steady-state CFD flowfield
  - Integrate motion of point-mass subject to drag force due to relative local wind vector at current location in the flowfield
  - Neglects effect of cross-range dispersions due to lift

- Debris Transport software development:
  - Developed debris-drag models using Cart3D 6-DOF unsteady simulations
  - Significant improvements to debris-trajectory computations
  - Wrote software for debris collision and proximity detection
  - Wrote general purpose sorting and filtering of collision output

- Millions of debris trajectories have been computed and analyzed
Debris Code Analysis Options

**Deterministic**
Zero Lift Trajectory + Range of Initial Velocities

**Probabilistic**
Zero Lift Trajectory + Crossrange Cone

LH$_2$ Flange Foam
- Mass = 0.023 lb$_m$
- $\rho_{\text{foam}}$ = 2.34 lb/ft$^3$
- $V_{\text{pop-off}}$ = 113 ft/sec

Cross range = f(shape, mass, rotation rate/orientation)
Time History

Freestream velocity (ft/sec)

- 0.002 lbm frustum @ 50 ft
- 0.002 lbm frustum @ 75 ft
- 0.002 lbm frustum @ 100 ft
- 0.002 lbm frustum @ 125 ft
- 0.002 lbm frustum @ 150 ft

qbar (psf)

Debris velocity (ft/sec)

Mach no.

- 0.0
- 0.12
- 0.32
- 0.5
- 1.0
- 1.5
- 2.0
- 2.5
- 3.0
- 3.5
- 4.0
- 5.0

Roll Start
Roll Ends
SSME Ignition
Throttle Down
Throttle Up
STS-107
SRB Separation (BSM ejecta)
Debris Aerodynamics Modeling

- Debris Transport currently requires two aerodynamic models for each type of debris to be analyzed:
  - **Drag model**: determines impact velocity
  - **Cross-range model**: determines impact locations
- Impractical to determine model parameters using experimental techniques (too costly, time consuming, restricted to simple shapes).
- Use validated CFD methods (cheap, rapid turnaround, not restricted by geometry shapes).
- Compute hundreds of 6-DOF trajectories using a Monte-Carlo approach (vary shape, orientation, rotation rate) and model the resulting behavior.
- Have developed drag and cross range models for:
  - Tumbling cube
  - Foam divots (based on a conical frustum model)
  - Ablator material
  - Hemisphere, to model ice balls
Cart3D

- Automated mesh generation from CAD
- Partitioned on the fly for any number of CPUs
- Solves Euler equations:
  - Unstructured Cartesian cells
  - Finite-volume formulation
  - Multi-grid acceleration
  - Shared-memory parallelization w/ OpenMP
  - 4.5 million cells, 15 levels of refinement
Drag modeling uses 6-DOF data

• Kinetic energy (damage potential) used as “fitness function”

• Drag model validated against Ames GDF range data
  • Drag models created Feb. ’04
  • These models were used in the design of all the validation experiments
Foam Cross-Range Model

- Debris can generate aerodynamic “lift” in arbitrary direction during trajectory (referred to as crossrange).
- This effect is modeled in a post-processing step.
- Crossrange cone applied to zero-lift debris trajectories from ballistic code to determine possible impact points.
Foam Cross-Range Data

- Data from Monte-Carlo CFD 6-DOF trajectories used to develop crossrange cone.
- Several shapes used to develop crossrange behavior.
- Results can be scaled to arbitrary-sized debris.
- A probability can be assigned to any location within crossrange cone.
Validation With Gun Development Facility (GDF) Data

- There are two aspects to the validation effort:
  - Validate the ability of the Cart3D code to simulate a 6-DOF foam trajectory by direct comparison against range data. (validation of CFD method)
  - Validate the foam drag and cross-range models using the range data. (validation of models)
Ames Gun Development Facility

1.75" Powder Gun and Dump Tank

Sabot and Projectile

Side-View Cameras and Controllers

Test Section - Diaphragm, Lights, Light Screens, and Calibration Grids

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6-DOF Method Validation
Ames GDF ballistic data Distance vs Time

- Mach 2.51, 6000 g’s deceleration

**Axial Distance (Drag)**

![Graph showing Axial Distance vs Time with data points and a line for 6-DOF CFD.](image-url)
6-DOF Method Validation
Ames GDF ballistic data Pitch/Yaw vs Time

- Shot 3, Untripped
- Shot 5, Tripped
Drag Model Validation

- Low oscillation trajectory - shot 2, Mach = 3.00
Drag Model Validation

- Medium oscillation trajectory - shot 7, Mach = 2.81
Drag Model Validation

- High oscillation trajectory - shot 6, Mach = 2.46
Crossrange Validation

- Cart3D 6-dof predictions bound ballistic data
  - CFD (all) represents several hundred CFD trajectories generated from offset C.G. and asymmetric models
    - CFD data is used in dprox code to determine potential impact cone
- Even mild asymmetry generates strong crossrange
CUBRC Setup

View looking back upstream
What the two pieces looked like several feet down stream
Run 12
7.4 inch divot
AR 7.8
Mach 3.5
Q 729 psf
DFRC F-15B

BX-265 foam sheets

Flight Test Fixture
Results from F-15B Testing

- Conducted 9 flights using BX-265 foam sheets
  - Total of 38 divots liberated
- All 31 of the supersonic divots ‘trimmed’
  - Of these, 30 of 31 rotated leading edge away from the sheet trimming with the small diameter facing forward
    - Divot C at Mach 1.6 and 850 psf passed through this first trim point and trimmed with the large diameter forward (only divot to behave in this fashion)
  - 2 of the 5 subsonic divots tumbled after one oscillation
- 36 divots survived the aerodynamic deceleration associated with being ejected into the flow field
  - Two of the three divots generated using the lowest successful ejection pressure rotated back into the sheet
    - As a result of re-contact with the sheet, the divots fractured into several pieces
  - Ejection pressure did not appear to affect divot geometry
    - All divots tended to be slightly smaller than predicted (using 30° angle assumption)
1-dof Comparison to F-15B Data

The graph shows the comparison of downrange distance (ft) over time (s) for different conditions:

- **X nominal 1-dof (ft)**
- **X static 1-dof (ft)**
- **X tumble 1-dof (ft)**
- **X F-15B (ft)**

The data points and lines represent the performance of each condition over time.
STS-114 Ice/Frost Ramp Debris Event
Computed and Enhanced Video Trajectories

Mass = 0.03 lbm, 30 ft/sec pop-off velocity
Trajectory, 0.03 lbm
30 ft/sec pop-off velocity
Mass=0.03 lbm Trajectories

0 – 10 ft/sec pop-off velocity
LH2 PAL Ramp Foam Debris

- LH2 PAL ramp release conditions at SRB Sep +5 sec
  - Mach=4.19, Qbar=19.5, $\alpha = 1.23$ deg, $\beta = -0.87$ deg
- Mass estimated $\approx 0.98$ lbm
- BX-265 Foam density = 2.34 pcf
Qbar adjusted to 20 psf
Mass=1.0 lbm Trajectories

Only outer edge of cone intersects wing: low probability of hitting wing
Concluding Remarks

- CFD simulations of SSLV ascent have become a value data tool for the program
  - Significant computational and experimental validation efforts
- Deterministic debris transport simulation has been used to quantify the debris environment during ascent
  - Being extended to reentry cases
- Probabilistic debris simulation capability under development, significantly aided by CFD simulations