Aerodynamics and Debris Transport for the Space Shuttle Launch Vehicle

Stuart Rogers
Applied Modeling and Simulation Branch
NASA Advanced Supercomputing Division
NASA Ames Research Center

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**NAS Supercomputing Facility**
- Ames wind-tunnels and ballistic range
NASA Advanced Supercomputer Facility

- Provides massive computing power to all of NASA

Pleiades: 112,896 cores
  - 7th biggest computer in the world (Nov 2011)

Columbia: 4608 cores
  - Formerly 2nd biggest computer in the world

Over 1.3 Tflops total compute capability
Timeline of NAS, Ames CFD, and Space Shuttle Applications

- **1980**: NAS Begins
- **1985**: Cray X-MP 0.2 Gflops
- **1990**: Cray C90 15 Gflops
- **1995**: SGI Origin 2000 128 Gflops
- **2000**: SGI Origin 3800 1.2 Tflops
- **2005**: Pleiades 608 Tflops
- **2010**: CFD Applications

**Software Releases**
- ARC3D
- INS3D
- F3D
- TLNS3D
- Cart3D
- Overflow 1.6
- Overflow 1.8
- Overflow 2.0
- Chimera Grid Tools
- Pegasus5
- Overflow 2.1
- Overflow 2.2
- Cart3D 1.4

**Grid Points**
- **1985**: $10^5$ grid points
- **1990**: $10^6$ grid points
- **1995**: $10^7$ grid points
- **2000**: $10^8$ grid points

**Space Shuttles**
- STS-107

**Supercomputers**
- Cray X-MP
- Cray Y-HP
- Cray C90
- SGI Origin 2000
- SGI Origin 3800
- Pleiades

**Other Technologies**
- NAS Begins
- SGI Origin 3800 1.2 Tflops
- Columbia 67 Tflops
Columbia and crew were lost on Feb 1\textsuperscript{st}, 2003

CAIB testing showed how a 1.7 lbm piece of foam traveling over 770 ft/sec could damage RCC wing leading edge

Simulations performed at Ames were integral to the accident investigation and subsequent return-to-flight efforts
Support for STS-107 Accident Investigation

- Significant improvements to fidelity of Overflow CFD model of SSLV
- Steady-state simulations of many points along trajectory of STS-107
  
  “The aerodynamic loads on the bipod ramps as calculated by the CFD results were well within the design certification limits, and were a small fraction of the design limits at the debris-release conditions at MET=81.7 seconds”

- Time-accurate 6-DOF simulations of SSLV and bipod-ramp foam debris using Cart3D
Geometry Details

New Grids with Bipod Ramp

New Grids without Bipod Ramp

Old Grid System

Control Surface and nozzle deflections
Cart3D 6-DOF Simulations, Mach=2.46

Cart3D
Trajectory Results

Outline of RCC panels
Overflow solutions of ascent

- Analyze aero loads on External Tank design changes
- Provide CFD flow-fields for debris analysis
- Correlation of 3% Wind-Tunnel tests

Debris Transport Analysis

- Develop next generation of debris analysis software
- Develop aerodynamic models for debris
CFD Analysis of SSLV Ascent

- 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
IA-700 Wind Tunnel Tests
ARC 9x7 Unitary, AEDC 16T
Bi-pod Ramp Removal
RTF Solutions
Addition of Ice/Frost Ramps

Mach = 1.55
Alpha = -3.5 deg
Beta = -0.4 deg
MET = 61 sec
Alt = 39,600 ft
Stagnation pressure is artificially high in the PSP data because of poor camera angles.
External Tank Redesign Assessments

- Multiple ice/frost ramp redesigns
- Ascent & entry windows airloads
- Discrete airloads data book updates
- Venting database updates
- Aerothermal support

- RCS Tyvek® covers
- Bipod Ramp Removal
- +Z Aerovent Modification
- PAL Ramp Removal
- Modified Aft Longeron
- LO₂ feedline bracket redesigns
Space Shuttle Ascent Debris Analysis
Debris Transport Process Overview

Debris Sources
- 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

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 6DOF unsteady simulations
  - Significant improvements to debris-trajectory computations
  - Wrote software for debris collision and proximity detection
  - Wrote general purpose sorting and filtering of impact data

- Millions of debris trajectories have been computed and analyzed
Debris Aerodynamics Modeling

Debris Transport currently requires
- **Drag model**: determines impact velocity
- **Cross-range model**: determines impact locations

Use Cart3D CFD methods to simulate debris released in a supersonic freestream

Compute hundreds of 6-DOF trajectories using a Monte-Carlo approach, varying:
- Shape
- Material properties
- Initial orientation
- Initial rotation rates

Have developed drag and cross range models for:
- Foam divots
- Ablator material
- Hemisphere ice balls
- Bellows ice
- Umbilical ice
- Gap fillers
Foam Drag Modeling

Drag

Kinetic Energy

[Graphs showing drag coefficient and non-dimensional kinetic energy as functions of Mach number and non-dimensional axial distance.]
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.

Crossrange Model Provides all possible impact locations

Drag Model Leads to “Zero-Lift Line”
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
6-DOF Method Validation
Ames GDF ballistic data Distance vs Time

- Mach 2.51, 6000 g’s deceleration
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
Cross-Range Model Validation

- Cart3D 6-dof predictions bound ballistic data
  - CFD (all) represents several hundred CFD trajectories generated from offset C.G. and asymmetric models
- Even mild asymmetry generates strong crossrange
Additional Foam Testing

- CUBRC supersonic wind-tunnel foam ejection tests

- DFRC F15 flight ejection tests: 38 divots
  - 31 supersonic divots trimmed in high-drag orientation
  - 5 subsonic divots oscillated or tumbled
  - 2 divots re-contacted and broke apart
  - Deceleration matches nominal foam drag model
Updated Launch Commit Criteria

Determine allowable ice-ball size on the External Tank
Debris-Transport Analysis Procedure

- Compute all possible ice-debris trajectories
  - Release from 7600 locations (blue dots)
  - 35 different masses

- Compute impact conditions
  - RCC impact kinetic energy
  - Tile damage depths

- Map all impact data back to 1562 different source zones (red-grid cells)

- In each source zone, determine largest mass which does not exceed component capability
DTA By the Numbers

- 33 million ice-ball trajectories computed
  - 7600 release locations
  - 35 masses
  - 31 flight conditions
  - 2 ice-ball densities
  - 2 release velocities

- 10 million executions of the dprox code
  - 1562 subset zones
  - 35 masses
  - 31 flight conditions
  - 2 ice-ball densities
  - 3 impactor targets (tile, wing LE RCC, nosecap)

- 5 billion impacts evaluated

- 12,000 CPU hours used
Maximum Allowable Ice-Ball Diameters
List of Debris Assessments

T0 umbilical ice
Orbiter/ET umbilical ice
RCS Tyvek covers
Tile gap-fillers
Orbiter blankets
Ceramic inserts
SSME Ice
Flow-control valves

ET PAL ramp foam
ET Flange foam
ET iceballs
ET ice/froat ramps
ET intertank foam
ET feedline bellows ice
ET feedline bracket ice

SRB Weather-seal
SRB phenolic glass
SRB Ablator material
SRB viton-coated nylon
SRB BSM RTV
Example: Flow-Control Valve Debris
High Pressure GH2 Flow Regulator

Impact Velocity, ft/sec

Impact Angle, deg
Example: SRB Booster Separation Motor RTV
Day of Launch Support

Mission Control Center, Johnson Space Center, Houston

Debris analysis team spends the hours before the launch making sure the vehicle is ready to fly

- Final Inspection Team
- Dozens of video cameras
- Looking for ice, cracks in foam, and anything unusual

My job includes being able to simulate potential debris and provide potential impact conditions

- Execute debris analysis on NAS computers and produce data in less than an hour
Bat Debris
Space Bat
Concluding Remarks

- CFD simulations of SSLV ascent have become a valuable tool for the program.

- Debris transport simulation has been used to quantify the debris environment during ascent:
  - Helped the program focus on mitigation of the most dangerous debris sources.
  - Make certain that the vehicle will only launch in a safe configuration.
The End