20+ Years of Computational Fluid Dynamics for the Space Shuttle

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Aerodynamic Tools

Modeling & Simulation  Ground Test  Flight Test
Space Shuttle Program Aerodynamics & Fluid Dynamics

**Design**
- ARC wind tunnel tests
  - 44 A/B

**Development**
- 176 C/D

**Operations**
- Test + CFD
  - 1982-present

**Retirement**
- FY 2011

**Key Events**
- OA-12 / IA9 1973 Unitary Tests
- STS-70 & subs
- 1984 Bancroft & Merritt graphic
- Cray X-MP solution
- Flight engines
Wind tunnel costs and times dominated aerodynamic database development before 1980.

Data from NASA SP-440 & online sources
But trends can change ...

Current wind tunnel costs $3,000 - $10,000/hour.
Length 56.14 meters/184.2 feet
Mass 2,041,166 kilograms/4.5 million pounds
Shuttle External Environments

Ground winds

Ignition Over Pressure
- 7.8 million lbs thrust

Ascent airloads
- Design $\bar{q} = 819$ psf

Separation Dynamics

Orbital debris

Hypersonic Entry
- 1650 °C/3000 °F

Ground Effects
“Engineering is the art of compromise,” Henry Petroski

**Design goal**
Lightest structure that can survive a harsh environment and maximize payload to orbit.

\[ \text{LH}_2 @ -423 \, ^\circ\text{F}/20.4 \, \text{K} \]

**External Tank**
- 154 ft/47 m long
- 60,000 lbs empty/1,600,000 lbs filled
- 27,215 kg empty/725,748 kg filled
- Empty/filled = 1/27
- Typical soda can, 1/28, 14 gm/394 gm

\[ \text{LO}_2 @ -297 \, ^\circ\text{F}/90.4 \, \text{K} \]
Post Challenger Shuttle Problems

• January 1986 No analytical capability to predict aerodynamics

• 1987 Joseph Steger & Pieter Buning/NASA ARC proposed development of an overset capability to simulate the Shuttle ascent configuration

• Initially focused on fast-separation abort and STS-1 trajectory lofting base pressure issues.

• Payload bay door loads and many more..

Historical Perspective

- Discrepancies exist between aerodynamic predictions and flight experience.

- Force and moment data was easily corrected with flight derived aerodynamic increments.

- Aerodynamic loads (pressure distribution) cannot be readily corrected because of limited flight pressure measurements.
Initial Grid System: 3 grids, 250K points (AIAA-88-4359)
STS ASCENT CONFIGURATION
COMPARISON OF PRESSURE COEFFICIENT
IA105A Wind Tunnel Test with F3D/Chimera Navier–Stokes Solver

Mach 1.05
Alpha -3 deg
Re 2.5x10^6/ft
(3% model)

Wind Tunnel

Computation

NASA Ames Space Shuttle Flow Simulation Group
PRELIMINARY 2/12/88
Space Shuttle Launch Vehicle (SSLV) Grid System Evolution

Early 80's grid system
3 Grids
10k surface points
0.3 million volume points

Late 80's grid system
14 Grids
35k surface points
1.6 million volume points

Early 90's grid system
113 Grids
268k surface points
16.4 million volume points

2004 grid system
267 Grids
636k surface points
34.8 million volume points
Bipod Ramp Redesign

Early 90’s grid system

Original design

Current configuration
Mach 1.25, STS-50 flight conditions
Surface: pressure coefficient
Flow-field: Mach number
NASA JSC Aeroscience Branch
Image Credit: Reynaldo Gomez
Solid Rocket Booster Surface Pressures

$\Phi = 0^\circ$, Mach 1.25, WT $Re$ (Gomez & Ma, AIAA-94-1859)
Flight Orbiter Wing Loads (Left Wing)
Mach 1.25, Flight Re
(Slotnick, Kandula, Buning, AIAA-94-1860)

Shear (KIPS)

Bending (Million in-lbs)

Torsion (Million in-lbs)

-50
-5
-5

200
25
15

100 200 300 400 500
Wingspan Location (inches)

100 200 300 400 500
Wingspan Location (inches)

100 200 300 400 500
Wingspan Location (inches)

CFD solution
STS-50 Flight Strain Gage Data
The loss of STS-107 initiated an unprecedented detailed review of all external environments.

Ascent **airloads**, acoustics, **heating**

Debris liberation, **transport** and capability assessments.

**Bipod redesign assessments.**

Greatly increased emphasis on verification & validation.

**STS-114 and subsequent missions**

- PAL ramp foam loss, additional redesign work.
- Prelaunch, inflight and postflight debris transport assessments.
Debris transport aerodynamic models & prediction tools developed
NSTS 08303 day of launch ice ball launch commit tool developed by Stuart Rogers/ARC NAS-07-004
Current SSLV grid system

600+ Grids
1.8M surface points
95+ million volume points
Wind tunnel validation and CFD extrapolation
Previous wind tunnel comparisons focused on wing loads.

CFD conditions: $M_{\infty} = 2.50$, $\alpha = 2.03^\circ$, $\beta = 0.00^\circ$, Reynolds # = $2.50 \times 10^6$/ft, IB elevon = $4.07^\circ$, OB elevon = $-4.39^\circ$

WTT conditions: $M_{\infty} = 2.50$, $\alpha = 2.03^\circ$, $\beta = 0.00^\circ$, Reynolds # = $2.50 \times 10^6$/ft, IB elevon = $4.07^\circ$, OB elevon = $-4.39^\circ$
Wind tunnel test pressure comparisons show good agreement with predictions.

![Graph showing wind tunnel test pressure comparisons](image-url)

JSC 2005-62925
Detailed comparisons along the LO$_2$ feedline were key to understanding protuberance airloads.
Proposed ice/frost ramp configuration, tested but not flown.
Inflight entry analyses

STS-118
Tile Damage

$M_\infty = 18$
$\alpha = 35^\circ$

Insight into local flow properties

Post flight Image
Parallel computing from prelaunch to landing

On-orbit Assessments

Hypervelocity Orbital Debris

Transonic airloads
Roll maneuver

Contingency Abort

Lift off

Entry Airloads

West/MSFC

Cetin Kiris/ARC
Timeline of Computing & Overset Space Shuttle Applications

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Machine</th>
<th>Flops</th>
<th>Code</th>
<th>Flops</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>NAS Begins</td>
<td>Cray X-MP</td>
<td>0.2 Gflops</td>
<td>ARC3D</td>
<td>10^5 grid points</td>
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<td>1985</td>
<td>Cray 2</td>
<td>Cray Y-MP</td>
<td>2.5 Gflops</td>
<td>F3D</td>
<td>10^6 grid points</td>
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<tr>
<td>1990</td>
<td>Cray C90</td>
<td>Cray C90</td>
<td>15 Gflops</td>
<td>OVERFLOW 1.6</td>
<td>10^7 grid points</td>
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<td>1995</td>
<td>SGI Origin 2000</td>
<td>SGI Origin 3800</td>
<td>1.2 Tflops</td>
<td>PEGASUS5</td>
<td>OVERFLOW 1.8</td>
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<tr>
<td>2000</td>
<td>SGI Altix</td>
<td>Columbia</td>
<td>2.3 Tflops</td>
<td>OVERFLOW 2.0</td>
<td>OVERFLOW 2.1</td>
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<tr>
<td>2005</td>
<td>Pleiades</td>
<td>Pleiades</td>
<td>608 Tflops</td>
<td>OVERFLOW 2.2</td>
<td>OVERFLOW 2.2</td>
</tr>
<tr>
<td>2010</td>
<td>2011</td>
<td>Pleiades</td>
<td>772 Tflops</td>
<td>STS-107</td>
<td>10^8 grid points</td>
</tr>
</tbody>
</table>
We went to the moon without CFD or parallel computers. Why do we need them now?

- Reduce number of physical tests and improve relevance when you run test
- Nearly 100,000 hours (11 years) of Shuttle wind tunnel testing
- Many facilities have shut down or been mothballed
- Provides flight increments/environments that cannot be obtained from other sources.
Overset CFD was a key part of many External Tank redesign assessments and debris assessments.

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

Diagram annotations:
- RCS Tyvek® covers
- Bipod Ramp Removal
- ±Z Aero-Vent Modification
- Modified Aft Longeron
- LO₂ feedline bracket redesigns
- STS-121 PAL Ramp Removal
But there is still more work to be done...

STS-134, STS-135?

Some STS-1 flight anomalies are still beyond current CFD tool capabilities, e.g.

- Acoustics and heating on complex configurations with strong shock wave-boundary layer interactions
- Physical models (turbulence, chemistry, multiphase flows,...) are key limitations that need to be improved.

Future programs will need 10s to 100s of millions of CPU-hours to characterize external environments

- There is evidence that we need 10x more resolution and 10x more solutions than we can currently produce to generate grid converged solutions and populate databases.