20+ Years of Computational Fluid Dynamics for the Space Shuttle

Reynaldo J. Gómez III
EG/Aeroscience & Flight Mechanics
NASA Johnson Space Center
Houston, Texas
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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

**1982-2000**
- SSME: Space Shuttle Main Engine
- **1982**
  - **1990**
  - **1994**
  - **2000**
- Flight engines
- **Phase II + redesign**
- **Advanced engine**
- **STS-70 & subs**

**1973 Unitary Tests**
- OA-12 / IA9 1973

**1984 Bancroft & Merritt graphic**
- Cray X-MP solution
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.

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LH₂ @ -423 °F/20.4 K
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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

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LO₂ @ -297 °F/90.4 K
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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..

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 $2.5 \times 10^6$/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($\text{(Gomez & Ma, AIAA-94-1859)}$)
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)

- 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

AIAA-2006-0662

AIAA 2005-1223
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°, OB elevon = -4.39°

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°, OB elevon = -4.39°
Wind tunnel test pressure comparisons show good agreement with predictions.
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

Post flight Image

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

Insight into local flow properties
Parallel computing from prelaunch to landing

On-orbit Assessments

Hypervelocity Orbital Debris

Transonic airloads

Roll maneuver

AIAA-2003-1248

Contingency Abort

West/MSFC

Cetin Kiris/ARC

Entry Airloads
Timeline of Computing & Overset Space Shuttle Applications

1980
- NAS Begins
- Cray X-MP 0.2 Gflops
- ARC3D
- STS-51L
- 10^5 grid points

1985
- Cray 2 2 Gflops
- F3D
- OVERFLOW 1.6
- 10^6 grid points

1990
- Cray Y-MP 2.5 Gflops
- OVERFLOW 1.8
- 10^7 grid points

1995
- Cray C90 15 Gflops
- Chimera Grid Tools
- OVERFLOW 2.0
- 10^8 grid points

2000
- SGI Origin 2000 128 Gflops
- PEGASUS5
- OVERFLOW 2.1

2005
- SGI Altix 2.3 Tflops
- OVERFLOW 2.2

2010
- SGI Origin 3800 1.2 Tflops
- Columbia 67 Tflops

2011
- Pleiades 608 Tflops
- 772 Tflops

- STS-107

- 10^8 grid points
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

- Bipod Ramp Removal
- PAL Ramp Removal
- ±Z Aero-Vent Modification
- Modified Aft Longeron
- LO$_2$ feedline bracket redesigns
- STS-121
- RCS Tyvek® covers
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.