20+ Years of Chimera Grid Development for the Space Shuttle

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Outline – The Early Years (1987-1994)

• Introduction
• Shuttle problems
• Initial tools & grid system
• Collar grids & improved geometric fidelity
• Moving grid development
• State-of-the-art, ca. 1994
Introduction

• Post-Challenger time-frame
  – Re-examining many Shuttle issues

• JSC/Ames collaboration
  – Funded effort for technology development

• Rockwell Downey effort
  – Dan Dominik (group lead)
  – USA code from Rockwell Science Center

• Group members (1987-1994)
  – **Ames**: Joe Steger (group lead), Yehia Rizk, Bob Meakin, Pieter Buning, Ing-Tsau Chiu, Shigeru Obayashi, Maurice Yarrow, William Chan, Kevin Renze, Shmuel Ben-Shmuel (Rockwell)
  – **JSC**: Fred Martin (group lead), Steve Parks, Steve Labbe, Jeff Slotnick, Max Kandula, Dan Pearce, Ray Gomez, Ed Ma, Scott Stanley, Jay Le Beau, Thomas Wey
Shuttle Group Visit to KSC, 1988

(LEFT TO RIGHT) Escort, Bill Riba, Bob Meakin, Ing-Tsau Chiu, Pieter Buning, Yehia Rizk, Shigeru Obayashi, Joe Steger, Jeff Slotnick, Fred Martin, Escort.
Shuttle Problems

- Fast-sep abort
- STS-1 trajectory lofting
- 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.

Lockheed Engineering & Sciences Company

Jeff P. Slotnick / March 8, 1989
PAYLOAD BAY DOOR PRESSURE COMPARISONS
ORBITER X-STATION (X0) = 905 inches

DATASETS:
- △ IVBC-3PL
- ○ STS-5 TAP V07P9126 (X0=885)
- ◇ STS-5 TAP V07P9128 (X0=915)

NASA/Ames CFD

BURST (-CP)
CRUSH (+-CP)
Initial Tools and Grid System

• **Grid generation**: HYGRIIID
  – Hyperbolic equations for marching out from surface

• **Grid connectivity**: PEGSUS
  – Jack Benek, Joe Steger, Carroll Dougherty, Pieter Buning, AEDC-TR-85-64
  – Grid hierarchy; grid surfaces form hole-cutting boundary

• **Flow solver**: F3D
  – Susan Ying, Joe Steger, AIAA-86-2179
  – Flux split in streamwise direction, central differencing in cross-flow directions

• **Surface grids**: Hand-coded
Initial Grid System: 3 grids, 250K points (AIAA-88-4359)
STS ASCENT CONFIGURATION

OIL FLOW COMPARISON

TWT 655 FA27 Wind Tunnel Test with F3D/Chimera Navier–Stokes Solver

Mach 2
Alpha -4 deg

Wind Tunnel

Computation

NASA Ames Space Shuttle Flowfield Group

PRELIMINARY
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)

Computation

Wind Tunnel

NASA Ames Space Shuttle Flow Simulation Group

PRELIMINARY

2/12/88
STS ASCENT CONFIGURATION

COMPARISON OF PRESSURE COEFFICIENT

IA105A Wind Tunnel Test with F3D/Chimera Navier–Stokes Solver

Mach 1.05
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Wind Tunnel

Computation

NASA Ames Space Shuttle Flow Simulation Group

PRELIMINARY

2/12/88
Added Components

- Elevon deflections (sheared grid)
- SRB attach ring and Integrated Electronics Assembly (IEA box)
- Forward and aft Orbiter/ET attach hardware
Previous ET/Orbiter Aft Attach Models

Preliminary (Symmetric) Grid System

IA–613 Wind Tunnel Model
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 JSC Space Shuttle Flow Simulation Group
PRELIMINARY 3/3/90
Collar Grids, Improved Geometric Fidelity

- Steve Parks, Collar Grid Tools (AIAA-91-1587)
  - Intersection lines, hyperbolic surface grid generation, surface projection
  - Orbiter vertical tail
  - Orbiter aft bulkhead (OMS pods, SSME’s)
  - Orbiter/ET attach hardware
  - ET/SRB attach hardware
New Aft Attach Model vs Flight Hardware
Surface Grid Topology of Aft Attach Region
Domain Decomposition of Volume
Moving Grid Development

• Original 2D store separation work
  – Carroll Dougherty, Jack Benek, Joe Steger, NASA TM 88193 (1985)

• Modification of PEGSUS for moving body problems
  – Bob Meakin and Norm Suhs (AEDC), AIAA-89-1996

• Development of DCF3D
  – Bob Meakin, Ing-Tsau Chiu, AIAA-91-1586, 95-0854

• Cartesian off-body grid generation and adaption
  – Bob Meakin, AIAA-95-1722

• Much further development including X-ray hole cutting and OVERFLOW-D
  – Bob Meakin et al., through the Army Rotorcraft CFD group
SRB Separation Sequence, Mach 4.5
3 grids, 350K points, 500 time-steps
(from Meakin and Suhs, AIAA-89-1996)
State-of-the-Art, ca. 1994

• Surface and volume grid generation
  – HYPGEN/HGUI William Chan, Joe Steger, Ing-Tsau Chiu, AIAA-91-1588
  – Collar Grid Tools Steve Parks, Buning, Chan, Steger, AIAA-91-1587
  – SURGRD William Chan, AIAA-94-2208

• Overset grid assembly
  – DCF3D Bob Meakin, Ing-Tsau Chiu, AIAA-91-1586, 95-0854
  – PEGSUS 4.0 Norm Suhs, Bob Tramel, AEDC-TR-91-8

• Flow Solver
  – OVERFLOW Pieter Buning, Renze, Slotnick, Kandula et al., AIAA-92-0437, 93-0521, 94-2357
  – OVERFLOW-D Bob Meakin, Wissink, Potsdam, Chan, AIAA-2001-0593

• Post-processing
  – FOMOCO William Chan, AIAA-95-1681
## Flow Solver and Computer Time

<table>
<thead>
<tr>
<th>Date</th>
<th>Code &amp; computer improvements</th>
<th>Speed up</th>
<th>Date</th>
<th>Grid Size, number of steps</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>F3D, Cray 2 (1 proc)</td>
<td>1</td>
<td>1987</td>
<td>¼ Mpts, 850 steps</td>
<td>1</td>
</tr>
<tr>
<td>1990</td>
<td>Cray Y-MP (1 proc)</td>
<td>2</td>
<td>1989</td>
<td>¾ Mpts</td>
<td>3</td>
</tr>
<tr>
<td>1991</td>
<td>OVERFLOW (Pulliam-Chaussee diag)</td>
<td>3</td>
<td>1991</td>
<td>1.6 Mpts</td>
<td>2</td>
</tr>
<tr>
<td>1992</td>
<td>Cray Y-MP (5/8 proc)</td>
<td>5</td>
<td>1993</td>
<td>3000 steps (flight Re, plumes)</td>
<td>3.5</td>
</tr>
<tr>
<td>1994</td>
<td>Cray C-90 (7/16 proc)</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>OVERFLOW time-step improvement</td>
<td>2</td>
<td>1994</td>
<td>16 Mpts</td>
<td>10</td>
</tr>
</tbody>
</table>

200x 200x
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)

Wingspan Location (inches)
Mach 1.25, STS-50 flight conditions
Surface: pressure coefficient
Flow-field: Mach number
NASA JSC Aeroscience Branch
Image Credit: Reynaldo Gomez
20+ Years of Chimera Grid Development for the Space Shuttle

STS-107, Return To Flight, End of the Program

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NASA Johnson Space Center
Houston, Texas
September 2010
STS-107 Debris  AIAA 2005-1223

Cart3D
Trajectory
Results

Outline of RCC panels
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.
Aerodynamic Tools

Modeling & Simulation

Ground Test

Flight Test
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
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.

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

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

AIAA 2004-2226
Wind tunnel test pressure comparisons show good agreement with predictions.
Detailed comparisons along the LO₂ feedline were key to understanding protuberance airloads.
Proposed ice/frost ramp configuration, tested but not flown.
Offbody and integrated validation was required to support debris transport tools.

Pressure sensors vs. CFD ≈ 0.01 Cp
Integrated Loads vs. CFD ≈ 5% of flt
Pressure Sensitive Paint
Particle Imaging Velocimetry ± 20 ft/sec
Grid generation automation enabled recreation of previous grid systems and generation of a range of configurations.

**GlobalDefs.tcl**

```tcl
set Configuration OrbiterET
set ShockGrid 0
set PlumeGrid 0
set ETGrid 1
set BprGrid 1
set YokeGrid 1
set FwdIFRamps 0
set AftIFRamps 0
set BflapDeflection 0.000
set ObLeftElevonDefl 0.000
set IbLeftElevonDefl 0.000
set IbRightElevonDefl 0.000
set ObRightElevonDefl 0.000
set Gimbal(pitch, ssmet) 16.000
set Gimbal(pitch, ssme1) 10.000
set Gimbal(pitch, ssmer) 10.000
set Gimbal(pitch, lsrb) 0.000
set Gimbal(pitch, rsrb) 0.000
set Gimbal(yaw, ssmet) 0.000
set Gimbal(yaw, ssme1) 3.500
set Gimbal(yaw, ssmer) -3.500
set Gimbal(yaw, lsrb) 0.000
set Gimbal(yaw, rsrb) 0.000
set TunnelRoll -31.185
set TunnelPitch -11.646
set InitialWallSpaceing 1.6e-4
```

**Configuration Options**

- **Intra-Configuration Options**
- **Global Configuration**
- **Control Surface Deflections**
- **Engine Gimbals**
- **Tunnel Controls**
- **Viscous Spacing**

**Overall build script:**

```bash
% BuildControlSurf
% BuildGimbNoz
% BuildVol
% BuildPeg5i
% addmanual.pl
% pegasus5 < peg.i.mod
% BuildMixsuri
% BuildOveri
```
Configuration examples

All
OrbiterET

AllShort
External Tank

Orbiter
IA700A
Scripted control surface motion is a key part of automation.
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:
- RCS Tyvek® covers
- Bipod Ramp Removal
- ±Z Aero-Vent Modification
- Modified Aft Longeron
- LO₂ feedline bracket redesigns
- STS-121 PAL Ramp Removal

Reynaldo J. Gomez III NASA/JSC/EG3
Other applications

Shuttle Carrier Aircraft
Mach = 0.3, $\alpha = 3^\circ$
G. Schauerhamer

Entry Calculations
Mach = 0.8, $\alpha = 17^\circ$
L. Marek/JSC
Overset Legacy

Advanced Subsonic Transport 1992-2000
Chimera Grid Tools, tcl scripting, turbulence modeling, PEGASUS 5

DoD High Performance Computer Modernization Project 1992-present
OVERGRID, OVERFLOW-D, rotorcraft applications.

Space Launch Initiative 2000-2002
OVERFLOW 2.0, moving body tools

Constellation 2004-2010
OVERFLOW 2.1, robustness improvements for high gradient plume driven unsteady flows.

SSLV 1987-1994
Initial OVERFLOW development, collar grids, complex geometry issues, plumes

Many individuals and groups contributed to this effort including NASA ARC, JSC, LaRC, MSFC and AEDC.
Timeline of Computing & Overset Space Shuttle Applications

- **1980**: NAS Begins
- **1985**: Cray 2
  - **0.2 Gflops**
- **1990**: Cray C90
  - **15 Gflops**
  - Chimera Grid Tools
- **1995**: SGI Origin 2000
  - **128 Gflops**
- **2000**: SGI Origin 3800
  - **1.2 Tflops**
  - Pegasus5
  - **Overflow 1.8**
  - **Overflow 2.0**
- **2005**: SGI Altix
  - **2.3 Tflops**
  - **Overflow 2.1**
  - **Overflow 2.2**
  - Pleiades
  - **608 Tflops**
- **2010**: Columbia
  - **67 Tflops**

- **ARC3D**, **INS3D**, **F3D**, **ST5-1L**, **STS-107**

- **10^5** grid points
- **10^6** grid points
- **10^7** grid points
- **10^8** grid points
After 20+ years was overset a good choice?

Weaknesses

‣ Relatively steep learning curve for new users.
‣ Double valued surface issues.

Strengths

‣ Accuracy - Structured grids without block zonal constraints
‣ Efficiency - Structured grids, grid scripts
‣ Flexibility - Nearly ideal for Shuttle redesign work.

Overall overset was a pragmatic choice for our application.
But there is still more work to be done...

STS-133, 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.