Large-Scale Applications for Aerodynamic Analyses using NASA TetrUSS on HPC

http:tetruss.larc.nasa.gov

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35th HPC User Forum
"Using HPC to Drive Economic Competitiveness"
Dearborn, Michigan
April 12 to 15, *2010*

Outline

- Introduction
- *TetrUSS "Tetrahedral Unstructured Software System"*
  - Key Capabilities
  - Recent Developments
- Applications
- Summary

The World We Live In
Applied Aerodynamics

Past Programs


Subsonic Transports


Personal Air Vehicles

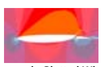

Supersonic Aircraft

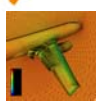

Uninhabited Air Vehicles


Runway Independent Air Vehicles

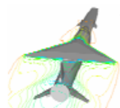

Abrupt Wing Stall (AWS)

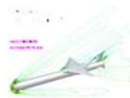

Mars Airplanes

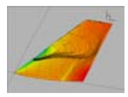

Transonic Slotted Wing


High Lift

911 Calls


X-43A (HyPER-X) Mishap & RTF


Pegasus XL RTF


Airbus AA587 Accident Investigation

Current Programs


Extreme Upset


Damaged Aircraft


Propulsion Airframe Acoustics

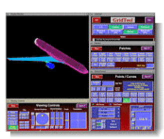

CLV/CEV

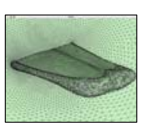
How do we provide credible and timely computational support to critical aerodynamic problems in a rapidly changing world?

TetrUSS Tetrahedral Unstructured Software System

A proven, stable, and reliable multi-platform system for unstructured Euler and Navier-Stokes CFD analysis.

- *Complete flow analysis system*
- *Well developed infrastructure*
- *In-house experts*
- *Broad outside collaborations*
- *Design via. CDISC/SUSIE*
- *Workhorse system with large experience/confidence base*


Geometry Setup
GridTool


Grid Generation
VGRID OpenGL

Flow Solver
USM3D


Visualization
SimpleView
(Commercial Packages)


Tools & Utilities

Key TetrUSS Capabilities (1)

Grids

- Advances in VGRID Tetrahedral/Prismatic grid generator
- Grid stretching & movement for sonic boom applications
- Wake-grid resolution (in progress)
- VGRID coupled with Calmar AGPS

Jet flows

- General jet BC prescription on unlimited numbers of jets
- Easy initialization of high-pressure plenum regions for startup

Design

- Knowledge-based design with CDISC
- Grid tools for efficient design (zonal design, quasi 2D)

Moving Body Problems

- Overset grids via. Noack's DirtLib
- 6DOF via. AEDC (G.Power's) FDCADRE
- Sinusoidal pitch/roll/yaw oscillations
- General prescribed motion capability available
- Static "constant-rate" roll capability

Key TetrUSS Capabilities (2)

Productivity

- Rapid grid generation
- Significant speedup of USM3D flow solver
- Production hardening of USM3D through extensive project application work
- Hands-off solution adapted grids, including grid-to-grid interpolation
- High-volume throughput via. script-based processes

Advanced Turbulence Models

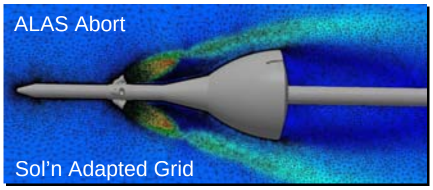
- Growing array of advanced turbulence models
- Cool and hot jet flows
- Massively separated flows

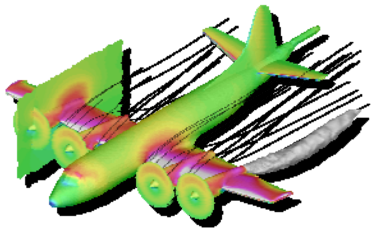
Post-Processing

- General component F&M integration
- General cutting-plane utility
- File conversions for TecPlot, FieldView, and Ensight
- ΔCp surface contour plots
- Sectional load plots

USM3D
Tetrahedral Flow Solver

- **Tetrahedral cell-centered, finite volume**
- **Euler and Navier-Stokes**
  - Compressible density based solver
  - Several 1- and 2-equation turbulence models
- **Time Integration**
  - LTS and 2nd order time stepping
- **Upwind spatial discretization**
  - FDS, AUSM, HLLC, LDFSS, FVS
  - Min-mod and Venkat limiters
- **Standard and special BC's**
- **Parallelized for clusters**
  - SGI, Sun, PC/Linux, Alpha/Linux, Mac OS X, IBM, HP
  - input/output files in global form





B. D. Goble and J. R. Hooker
Lockheed Martin Aeronautics Company

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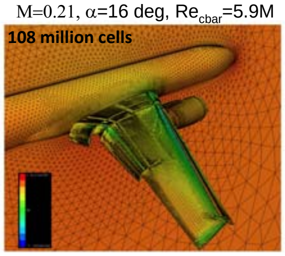
Speedup and Memory Reductions of USM3D

Previously would not even fit on NAS Columbia

High-Lift Landing Configuration

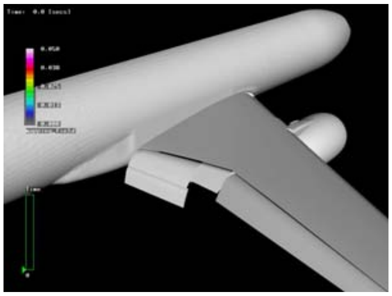
M=0.21, α=16 deg, Re_{cbar}=5.9M



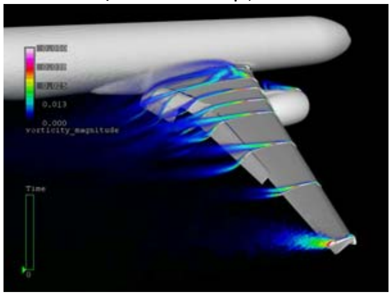
USM3D advances
- 5-times faster than May 2006 version

Large application - 108M cells
- SA with Detached Eddy Simulation (DES)
- 2000 Newton timesteps (14,000 iterations)
- 500 processors on NAS Columbia Altix
- 11 wall-clock hours
- potential for more speedup

USM3D SA: steady-unsteady URANS



USM3D SA/DES: 2000 timesteps, 11 hours

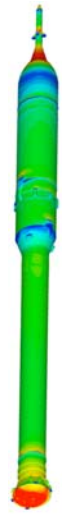


Taft/Pandya/Pirzadeh/Frink

USM3D Optimization for NAS Super Computers*

Mohagna Pandya and K. Abdol-Hamid

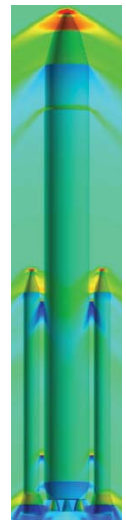
November 2008 – February 2009



- **Previous Bottlenecks**
  - Large memory footprint resulting in reduced efficiency beyond medium size cases (>20 million cells)
  - Solver-intrinsic grid pre-processing resulted in repetitive consumption of pre-processing CPU time for cases requiring multiple solutions, e.g, alpha-sweep, Mach-sweep
  - Very low throughput for large cases
  - Problem more pronounced for multi-core small memory machines like NAS Pleiades cluster

- **Accomplishments**
  - ✓ Demonstrated increased efficiency for cases up to 490 million cells by reducing USM3D's memory footprint
  - ✓ Preprocessing external to solver resulting in relatively less CPU time (30 mins for 490M Cells)
  - ✓ High throughput for large cases (I/O 15 mins for 490M Cells)
  - ✓ Projected upto 800 million cells (preprocessing limitation)

Benefits to ESMD Ares I, IX, V and Orion projects and ARMD projects



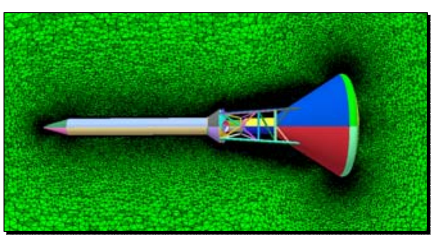
projected grid size 150 million cells

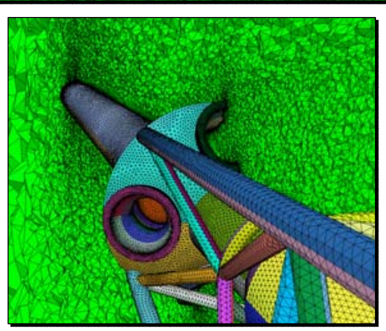
projected grid size 200 million cells

*Funding support provided by Ares I project

VGRID

Tetrahedral Grid Generator



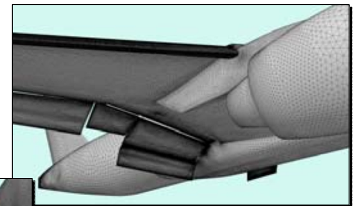


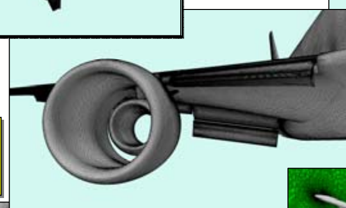
- Thin-layer viscous tetrahedra
- Elliptically smooth grids
- Anisotropic grid stretching on Computer-Aided Design (CAD) surfaces
- Robust viscous grid movement
- Solution adaptive grid (inviscid region)
- Easy control of grid spacing
- Robust, easy to use

Sample Navier-Stokes Grid
Apollo Launch Abort Vehicle
(generated by Ed Parlette, ViGYAN, Inc)

Shahyar.Z.Pirzadeh@nasa.gov

Work in Progress for Grid Generation
High-Lift Configuration

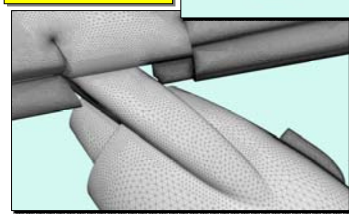


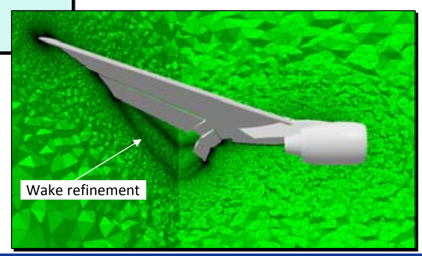


NS grid:
15 million nodes
86 million cells

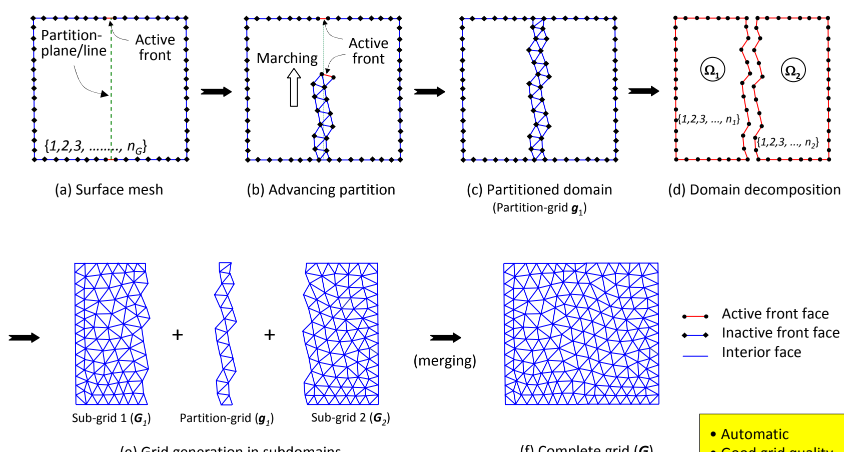
Parallel generation required for large grids

- wake refinement for accurate prediction of high-lift flows
- *surface* sources: enabling technology





Schematic of Domain Decomposition By the Advancing-Partition (AP) method



- Automatic
- Good grid quality
- Low overhead

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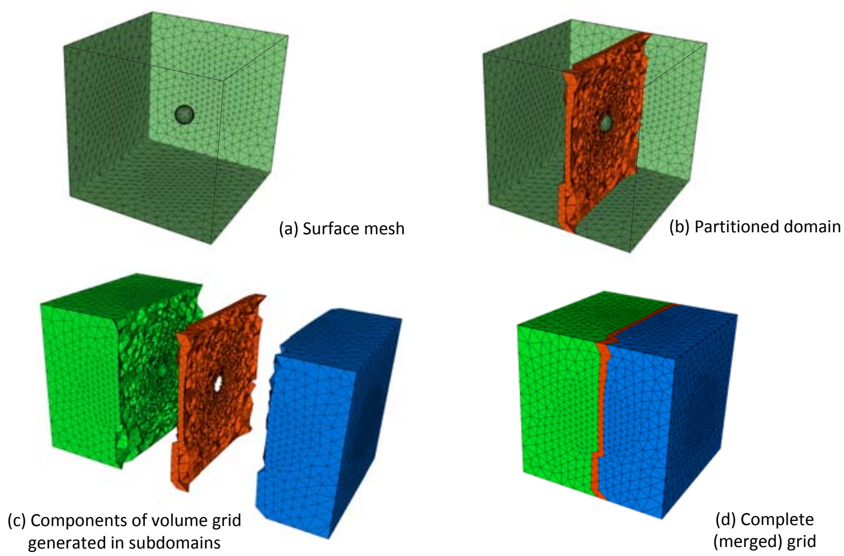
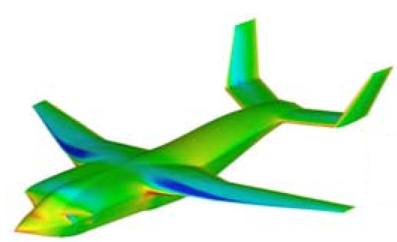
Domain Decomposition by the AP Method for a Sphere-in-Cube Configuration



CDISC Design Method

- Knowledge-based design applies prescribed flow/geometry sensitivity derivatives along stream-wise design stations
- Flow constraints automatically generate target pressure distributions from current analysis pressures
- Geometry constraints incorporate multidisciplinary influences and help ensure a practical design
- Modular Linux script approach allows easy coupling of CDISC with a wide range of flow solvers (USM3D, OVERFLOW, CFL3D, CART3D, CFD++,…)
- PREDISC GUI reduces case set-up time



- Design time ≈ analysis time (1-3 OM faster than optimization)
- Allows use of same level of geometric and flow physics fidelity in design and analysis

Current Drivers for TetrUSS Development

Aviation Safety Program

- Project: Integrated Resilient Aircraft Control (IRAC) Project
- Goal: Develop reliable computational tools for predicting and analyzing stability & control characteristics of aircraft in damaged or upset flight conditions.
- Technology Push in USM3D
  - Post-stall aerodynamics
  - Prediction of dynamic stability derivatives
  - Population of flight simulators

Constellation Program

- Project: Orion LAV & Ares 1&5 LV
- Goals:
  - Better prediction of aerodynamics at flight Reynolds numbers
  - Better prediction of surface heating from reaction control jets
- Technology Push in USM3D
  - Implementation of prismatic boundary-layer grid capability
  - Addition of gas chemistry capability

Current Drivers for TetrUSS Development

Subsonic Fixed Wing Project

- Project: Propulsion-Airframe Aeroacoustics (PAA)
- Goals:
  - Understand complex aeroacoustic phenomenon associated with PAA.
  - Develop jet noise and airframe noise reduction strategies.
- Technology Push in USM3D
  - Noise Prediction capability
  - Prediction of Hot Jet Flow mixing.
  - Adaptive Grid

TetrUSS Overview *Neal.T.Frink@nasa.gov*

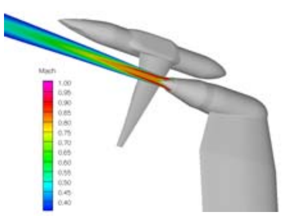
Three Typical Applications

- Propulsion-Airframe-Aeroacoustics
- LAV Abort Control Motor database
- ARES 1 Ascent Aerodynamic

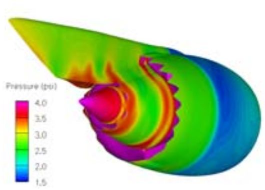
Propulsion-Airframe-Aeroacoustics: Concept to Flight

Using CFD & aerodynamics to drive noise prediction and design

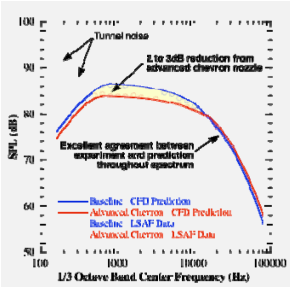
Concept: exploit favorable propulsion airframe interactions with tailored chevron design to reduce noise

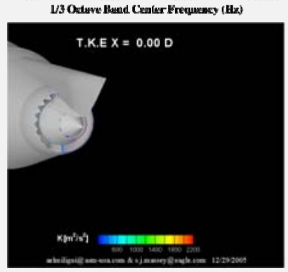


High fidelity propulsion/airframe simulation using TetrUSS (32 million unknowns)

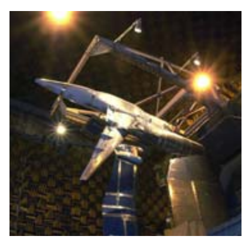


Computed nacelle/nozzle flows and loads for flight hardware design/fab using TetrUSS





Computed SPL and noise sources - Jet3D Acoustic Analogy with RANS CFD input



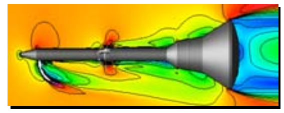
NASA/Boeing wind tunnel test (Boeing Low Speed Acoustic Facility)

Advanced chevron nozzle installed on B777 for NASA/Boeing QTD-2 flight test

2 dB community noise reduction demonstrated in flight!

Launch Abort Vehicle Aerodynamics

Abort Control Motor (ACM) Increments



Objective

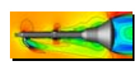
- Provide ACM plume increments for a Project Orion Launch Abort Vehicle (LAV) at flight conditions for LAV aero-database

Scope:

- Flow conditions consisted of Mach 0.3 to 0.7, and AOA -5 to 20 deg
  - Power levels corresponding to non-vacuum thrust ratios between TR=0.06 and 0.14 with wind-tunnel air plenum (γ=*1.4*), and power-off
  - All solutions at flight Reynolds numbers
  - 114 cases (66 high priority, 48 lower priority)
- Vehicle overall aerodynamics, loads and pressure distributions
- Detailed flow diagnostics and understanding of ACM influences
- Specific data delivery requirements for inclusion into LAV aero-database

USM3D Resource Statistics for LAV/ACM Database

NAS Columbia Altix

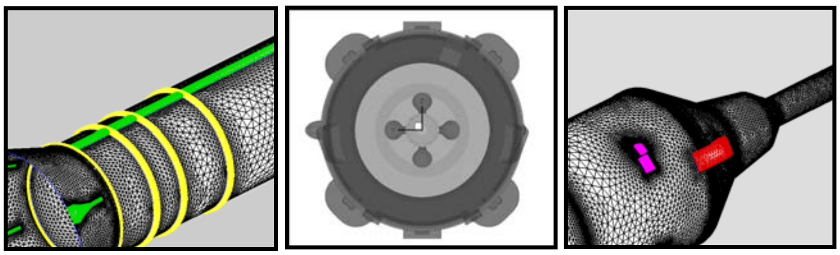


	Total CPU hrs	Average CPU hrs per case	Total iteration count	Avg # iterations per case	Average cell count
M=0.7 (30 cases)	46,831	1,561	281,862	9,395	28.65M
M=0.5 (54 cases)	90,183	1,670	565,779	10,477	27.20M
M=0.3 (30 cases)	94,648	3,155	604,381	20,148	26.47M
All cases (114 cases)	231,662	2,032	1,452,022	12,377	27.38M

ARES-1 Ascent Aerodynamics

Sample CFD Geometry/Grid Model

- ARES I is the crew launch vehicle component of the NASA Constellation Project
- The Ares I full stack consists of the LAS, crew escape, service module, the upper stage, frustum, first stage, and aft skirt
- Numerous protuberances on the vehicle add to the complexity of the CFD and/or wind-tunnel model geometry
- **Current grids range from 49M to 100M cells**



ARES-1 Ascent Aerodynamics

Objective

- Analyze the external flow aerodynamic performance of the evolving Ares–I configurations at representative flow conditions pertinent to the ascent phase of the trajectory.

•***Scope:*** ***Provide Navier-Stokes data/analysis for***

- Vehicle overall aerodynamics, loads and pressure distributions
- Quick assessments of the design changes and explore ideas to improved aerodynamic performance
- Detailed flow field diagnostics and understanding
- Access to an advanced/early CFD solution/analysis lead into a better wind-tunnel model design, efficient use of instrumentation and overall test matrix development
- Critical scaling between wind tunnel and flight Reynolds number
- ***The loads & pressure definitions for vehicle design are coming from CFD***

NASA Team

- Coordinated effort between NASA Langley, Ames, and Marshall
  - led by Dr. Khaled Abdol-Hamid (LaRC)
- Toolset: USM3D, OVERFLOW, Loci-Chem, FUN3D
- **Computational resource: NAS Columbia Altix**

ARES-1 Ascent Aerodynamics

TetrUSS/USM3D Contributions to Constellation

Productivity

- LaRC/USM3D Team 6 FTE, + 2 WYE
- Using 2000 CPU's per day
  - Average 15 solutions/day on 50M cell grids
- 2000 Ares-1 ascent aero solutions completed over last 3 years
- For Ares-1 (projection vehicle) & Ares-1X (demo vehicle) work as a whole within Configuration Aero Branch, over 3500 solutions computed to date
- Mass script-based post-processing completed at end of run series

Data Delivery

- Section loads & pressures through 3 design cycles
- CFD trade study to guide design of protuberances for improved vehicle aerodynamics and performance

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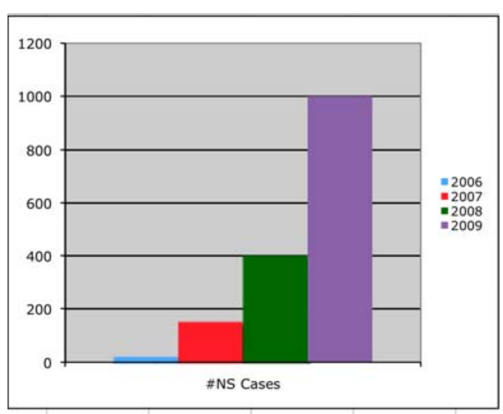
Improvement in Computational Resources 2006-2009

Advancement in grid generation (VGRID)

Faster Super Computer (Pleiades)

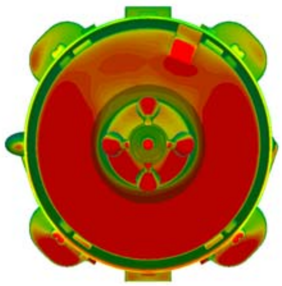


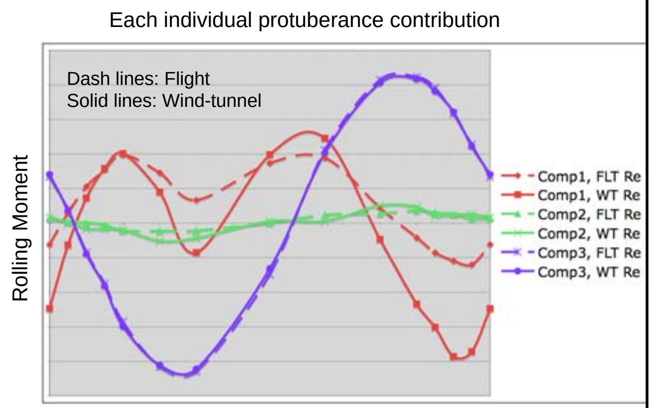
Faster CFD Methods (USM3D)

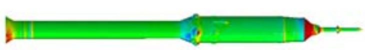
Semi-Automated Process

3000 CPUS = 12 cases/day

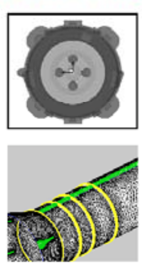
Sample Computed Flow Property With Roll Angle
ADAC-2A (A101)



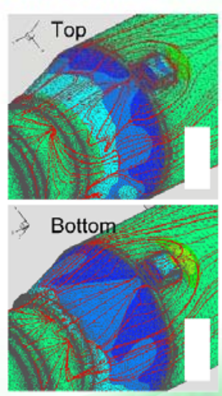




Ares I Ascent Aerodynamic Analysis using USM3D and OVERFLOW



Sample CFD geometry grid model.
Khaled S. Abdol-Hamid, NASA Langley



Sample flow diagnostics results. *Khaled S. Abdol-Hamid, NASA Langley*

Computational fluid dynamics (CFD) analyses are performed to assess the aerodynamic performance of evolving Ares I crew launch vehicle designs at flow conditions representative of the launch trajectory ascent phase. These analyses complement broader wind tunnel data to refine Ares ascent aerodynamic databases. In addition, CFD was used for exploratory parametric studies prior to any wind tunnel testing within the program, enabling quick assessments of design changes and revealing possible improvements for better aerodynamic performance. Early access to advanced CFD analyses led to better wind tunnel model design, more efficient use of instrumentation, and improved overall test matrix development.

Aerodynamic Data Analysis for Ares I Design Configurations:

- Completed over 400 solutions using 2,000,000 CPU-hours
- Quantified vehicle aerodynamics and structural load distributions for evolving design cycles
- Validated CFD consistency and accuracy through code-to-code and wind tunnel data comparisons
- Provided flow diagnostics and estimates for wind tunnel-to-flight Reynolds number scaling effects
- Addressed aerodynamic contributions from each individual protuberance detail towards overall vehicle performance and possible design trade-offs

Khaled S. Abdol-Hamid, NASA Langley

TetrUSS Contributors

Recent contributors

K. Abdol-Hamid - Turbulence modeling, large-scale applications
S. Bauer - Creative design applications
R. Campbell - Design, grid adaption/stretching/shearing utilities
N. Frink - Oversight, applications
C. Hunter - Mac port, applications
S. Massey - Scripting, key utilities for jet BC's and grid-to-grid sol'n interpolation
M. Pandya[1] - USM3D code expert/gatekeeper
P. Pao - adaptive-grid and solution cutting-plane utilities
E. Parlette[2] - SimpleView, GridTool, grid gen expert, TetrUSS training
S. Pirzadeh[2] - VGRID code expert/gatekeeper, applications
J.Taft - USM3D speedup/memory reduction
G. Power (AEDC) - Integration of USM3D into FD_CADRE framework

Caveats

- We have never had a formally funded "TetrUSS Team", but more of a "coalition of the willing" working from within various application projects

- The above list is not a code support team with the exception of
  - 1 WYE funded code expert supporting USM3D[1]
  - Approx 1 FTE/WYE funded code experts working on VGRID/GridTool[2]

- Some new utilities/capabilities are developed as needed by "contributors" within projects, and are not necessarily consolidated or well documented

Summary

- ***We live in the rapidly changing world of applied aerodynamics requiring flexible, high-fidelity CFD tools***
  - *complex geometries, complex flow physics, complex requirements, short schedules*

- ***TetrUSS has evolved into a prime workhorse for delivering on project needs in a timely fashion***
  - *having major impact on NASA programs because of key capabilities in grid generation, jet flows, design, moving bodies, productivity infrastructure, and advanced turbulence models*
  - *we have thrived through the synergistic interactions of a close-knit team of code experts immersed in an intense application-driven environment*

Thank You