High-Fidelity Aerospace Simulations in the Exascale Era

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Overview

• Overview of past progress in CFD for aerospace applications
• Assessment of future progress in Simulation Capabilities for aerospace applications
• Importance of contributing technologies
• Can we get there from here on our current path?
How do we measure Simulation Capability
Suboptimal may be expected
Is Super-Linear even possible?
Progress in Simulation Capabilities

- How do we measure Simulation Capability
- Suboptimal may be expected
- Is Super-Linear even possible?
  - Combination of algorithmic and hardware advances
Progress in Simulation Capabilities

- Moore’s Law is nominal: to be expected
Progress in Simulation Capabilities

• Moore’s Law is nominal: to be expected
• RANS Plateau probably looks like this
Progress in Simulation Capabilities

- Can we re-invigorate progress through increased investment in fundamental disciplines?
  - Will be required to meet CFD2030 Roadmap
Circa 1987

- 2\textsuperscript{nd} “Airplane” Paper
- Delaunay triangulation
- Unstructured mesh Euler solver
  - JST Scheme
  - Explicit Runge-Kutta
  - Implicit residual smoothing
  - Enthalpy damping
1987 Jameson Airplane Paper

- Unstructured tetrahedral mesh
  - 35,370 points, 181,959 tetrahedra
  - Mesh generation: 15 minutes
    - No mention of geometry issues
  - Flow solver: 1 hour on 1 processor of CRAY-XMP
    - Vectorized, later parallelized for CRAY-XMP/YMP
1987 Jameson Airplane Paper

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Circa 1999 (12 Years later)

- PETSc-FUN3D wins 1999 Gordon Bell prize
  Anderson, Keyes and Gropp
1999 High Lift Paper

- Coarse Mesh: 3 million points
- Fine mesh: 25 million points
- RANS simulation on up to 1500 CRAY-T3E processors
  - c/o Rob Vermelend
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- Reasonable agreement with experimental force data
- Easier take-off configuration
Evaluating Progress 1987-1999

• 12 years of Moore’s Law: $2^8 = 256$
  – 256 X 35,370 points = 9M points

• Actual Increase in Capability
  – 25M points/35,370 = 700
  – Euler to RANS
    • 10 to 50 times more computational requirements
  – Actual increase > 10,000
    • Equivalent to 20 years of Moore’s Law
  – Enabled by combination of hardware and algorithmic advances
    • Advancing layers mesh generation
    • Implicit/multigrid solvers
    • SA Turbulence model 1992
    • MPI as standard for parallel computing
1999 – 2017 (HLPW3)

- 1999 Fine Grid is ~ 2017 Medium Grid
- Finest 2017 grid ~ 10X finest 1999 grid
  - Only 5 years equivalent of Moore’s Law over actual 18 year period
## HL-CRM coefficient of variation
(Case 1a, “fine” grid)

<table>
<thead>
<tr>
<th>Case</th>
<th>Unstr “F” grid sizes</th>
<th>Cv for lift</th>
<th>Cv for drag</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiLiftPW-1, alpha=13</td>
<td>31-162 M points</td>
<td>0.014</td>
<td>0.021</td>
</tr>
<tr>
<td>HiLiftPW-1, alpha=28</td>
<td></td>
<td>0.017</td>
<td>0.020</td>
</tr>
<tr>
<td>HiLiftPW-2, alpha=7</td>
<td>73-177 M points</td>
<td>0.025</td>
<td>0.020</td>
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<tr>
<td>HiLiftPW-2, alpha=16</td>
<td></td>
<td>0.023</td>
<td>0.028</td>
</tr>
<tr>
<td>HiLiftPW-3, alpha=8</td>
<td>70-189 M points</td>
<td>0.022</td>
<td>0.020</td>
</tr>
<tr>
<td>HiLiftPW-3, alpha=16</td>
<td></td>
<td>0.023</td>
<td>0.023</td>
</tr>
</tbody>
</table>

No noteworthy decrease in Cv over the course of the 3 workshops (but the “F” grids have not gotten much finer, either!)

c/o C. Rumsey
HL-CRM $C_L$ statistics, Case 1a, alpha=16 deg.
Slow Growth in Grid Size

- Grid resolution demonstrated to reduce scatter

Why slow growth in grid size?
- Good enough for engineering
- Lack of computing resources
- Mesh generation does not scale
- Flow solver does not scale
- Flow solution not optimal $O(N)$
  - $O(N^2)$: 8x finer grid cost 64 times more to solve

Static technology: Inability to leverage Moore’s law (and new hardware)
Silver Linings from HLPW3

- Possible renaissance in new technology
  - GMGW Workshop
  - Anisotropic mesh adaptation
  - Transition prescription/prediction
  - New discretizations
    - Lattice Boltzmann, SUPG (p=1, p=2)
  - Strong solvers
    - More robust
      - but not scalable/optimal
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New Advocacy

• Capability stagnation has led to renewed advocacy
  – Importance of algorithmic developments in enabling capability advances
    • Numerical methods
    • Computer science
    • Physical modeling
Old Advocacy

- 10 years of Moore’s Law: 100x
- Evaluate capability growth since 2007
- Compare to other IT “technology” growth since 2007
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Petaflops Opportunities for the NASA Fundamental Aeronautics Program

Dimitri Mavriplis (University of Wyoming)
David Darmofal (MIT)
David Keyes (Columbia University)
Mark Turner (University of Cincinnati)
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Emergence of AI/ML
Science Runs on Red Storm

- SEAM (Spectral Element global Atmospheric Model) Simulation of the breakdown of the polar vortex used to study the enhanced transport of polar trapped air to mid latitudes.
- Record setting 20 day simulation, 7200 cpus for 36 hours. 1B grid points (3000x1500x300), 300K timesteps, 1TB of output.
- Spectral elements replace spherical harmonics in horizontal directions
- High order ($p=8$) finite element method with efficient Gauss-Lobatto quadrature used to invert the mass matrix.
- Two dimensional domain decomposition leads to excellent parallel performance.

c/o Mark Taylor, Sandia National Laboratories

18th AIAA Computational Fluids Dynamics Conference
25-28 June, 2007, Miami Florida
Performance of 4 fixed problem sizes, on up to 6K CPUs. The annotation gives the mean grid spacing at the equator (in km) and the number of vertical levels used for each problem.
Current State-of-the-Art HPC

Gordon Bell 2015: Earth Mantle simulation 1.6M cores

Wyoming in-house DG code (512³ mesh @p=4) using up to 1 million MPI ranks (2 per core) on Mira at Argonne

Factor 100 over 10 years held up at high end of HPC

Gordon Bell 2016: 10M-Core Scalable Fully-Implicit Solver for Nonhydrostatic Atmospheric Dynamics
NASA Computational Environment

• Columbia processes mostly $O(100)$ cpu jobs

• 2048 sub-system occupied with 512 jobs

• Few benchmarks above 512 cpus

• Some 2048 benchmarks (production ?)
Aerospace Computational Environment

- Does NASA Pleiades process mostly 10,000 core jobs?
  - x100 from 2007 Columbia
- DoD HPCMP Machines offer large job allocations
- In general production size jobs have not grown X100
  - Stagnation of grid sizes at HLPW3
- Computing is more ubiquitous
  - Larger number of jobs possible
- Heterogeneous architectures still not mainstream
Selected Grand Challenges

• Digital Flight
  – Static (and dynamic) aerodynamic data-base generation using high-fidelity simulations
  – Time-dependent servo-aero-elastic maneuvering aircraft simulations

• Transient Full Turbofan Simulation

• New frontiers in multidisciplinary optimization
  – Time dependent MDO
  – MDO under uncertainty

• Examples only (not all inclusive)
  – e.g. Aeroacoustics not mentioned
Design Optimization Challenges

• Unsteady Multidisciplinary Design Optimization:
  – Adjoint methods require backwards integration in time
  – Requires entire time-dependent solution set to be stored (to disk)

• Design under uncertainty
  – Ensemble averages for uncertainty estimation
  – Stochastic methods
Computational Requirements

• One analysis cycle
  – 100 million grid points, one revolution
  – ~30 hours on 100 cpus

• One design cycle (twice cost of analysis)
  – Forward time dependent simulation
  – Backwards time dependent adjoint solution

• 50 to 100 design cycles

• 30 to 60 hours on 10,000 cpus
Time Dependent Multi-Disciplinary Optimization

Unsteady adjoint optimization in FUN3D (2010-2013)

Far-field acoustic optimization of flexible rotor (Fabiano and Mavriplis (2016))
10m points on 4096 cores for 20 hours (largest to date)
Computational Requirements

• From M. D. Salas (2006): *Digital Flight: The last CFD Aeronautical Grand Challenge*
  – 60 seconds of flight = 1.5 days on 512 cpus
    • NASA codes, 50 million grid points, 50Hz time stepping

• Easily add:
  – Order of magnitude in grid resolution
  – Order of magnitude in time resolution
  – Multidisciplinary:
    • Structures, Heating, Flight control system
  – Overnight turnaround on 10,000 cpus

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Substantial Advances in Digital Flight

CREATE-AV

- Leveraged dynamic overset, AMR, higher order, multidisciplinary
- Digital fight for rotorcraft even more challenging
Wyoming Wind Energy Simulations

• Highly interdisciplinary
  – Aero, structures, controls, atmospheric turbulence
• Technology enablers
  – Unstructured mesh solvers
  – Dynamic adaptive meshing
  – Dynamic overset meshes
  – High-order (DG) off-body
  – LES modeling
  – Atmospheric boundary layer modeling
• Exascale problem
  – 10 orders of magnitude range of scales
48 Wind Turbine Simulation

1.5B dof's
22K cores
1.28 revs in 12 hours
Scales: 10 km to 7 microns

Good weak scaling from 6 – 96 turbines

<table>
<thead>
<tr>
<th>Turbine Count</th>
<th>Efficiency</th>
<th>Revs</th>
<th>Near-Body Cores</th>
<th>Off-Body Cores</th>
<th>Total Cores</th>
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</thead>
<tbody>
<tr>
<td>6</td>
<td>1.0000</td>
<td>1.374</td>
<td>2,088</td>
<td>720</td>
<td>2,808</td>
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<tr>
<td>12</td>
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<td>1.360</td>
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<td>24</td>
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<td>48</td>
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<td>5,760</td>
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<tr>
<td>96</td>
<td>0.8686</td>
<td>1.194</td>
<td>33,408</td>
<td>11,520</td>
<td>44,928</td>
</tr>
</tbody>
</table>
Summary

• **Difficult Problems**
  – Our ability (at UW) to simulate $C_{L_{\text{max}}}$ is about as good as it was 15 years ago: **Not very good**
  – $C_{L_{\text{max}}}$ for HL will require advances in:
    • Geometry modeling
    • Grid generation/adaptivity
    • Solver technology
    • Physical modeling
      – Transition, Turbulence modeling (RANS, LES)

• **Substantial advances can be made simultaneously in other areas**
  – Multidisciplinary simulations
  – Optimization technology
  – Uncertainty quantification
  – Automated/Robust Data-base fill-in
Conclusions

• Advances in complementary fundamental disciplines are required to **simply keep pace** with Moore’s Law
  – Offer the possibility of outperforming Moore’s Law
• Even more true with increasing computational power
  – Asymptotically arguments most powerful at large scale
• Required to meet the CFD 2030 Vision
Acknowledgements

• Mike Brazell, Behzad Aharabi, Zhi Yang, Andrew Kirby, HLPW3 Committee
• University of Wyoming Advanced Research Computing Center (ARCC)
• NCAR-Wyoming Supercomputer Alliance