Breaking CFD Bottlenecks in Gas-Turbine Flow-Path Design

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Bottlenecks in Design

• Simulations for design are at least an order of magnitude more challenging than their counterparts in analysis due to time constraints.

• Bottlenecks exist in all aspects of simulation:
  – Setup (model manipulation and grid generation)
  – Solution (accuracy and solution time)
  – Post-processing (visualization, engineering figures, etc.)

• Our R&D has been focusing on how to break some of these bottlenecks through:
  – Automation
  – Large-scale parallelization
  – Advanced modeling
Example Areas

• **Examples of bottlenecks for simulations used in design:**
  – Complex flow paths such as secondary-air and cooling systems
  – Complex aerothermal problems such as film-cooled, high-pressure turbines
  – Complex flows with mixing such as secondary/endwall flows

• **Similar bottlenecks exist in other Air Force, Navy, and NASA design problems**
  – Our intent is to show new ideas that might be used in a broad range of applications
IDEA

- Instead of generating a computational grid after the model is created, why not generate it at the same time and take advantage of the CAD operations???
CAD-Based Grid Generation

- For each CAD primitive, construct a grid inside and outside.
- When CAD operations are performed to construct a model, apply them to the computational grids as well.
- CAD operations consist of:
  - Union
  - Intersection
  - Difference
Application to Gas-Turbines
Secondary-Air System Flow Path

- For more details: AIAA-2009-3991
  “Automated Creation of Overset Grids Directly from Solid-Model Feature Trees”
• Why not use similar embedded, overset grid technology for multi-disciplinary problems such as conjugate heat transfer of film-cooled turbines???
Automated Model/Grid Generation of Turbine Airfoil Sections

- Conjugate heat transfer of various HPTs including TBC, cooling holes, walls, and plenums

Extension to 3D is relatively straightforward!

Overset film cooling holes grids can be changed for optimization without affecting remainder of grid

Every 4th grid point shown for clarity

Completely General: Can also be used for flow control
Stagnation Temperature Contours

- **Time-averaged Detached-Eddy Simulations are the Norm!**
  - Enables effects of self-excited unsteadiness on aerothermal performance to be predicted
  - Shown here: Instantaneous DES results

Diagram showing stagnation temperature contours with annotations indicating:
- Trailing-edge shedding effects on thermal mixing predicted
- Shedding subdued with trailing-edge blowing
Temperature Contours

- Interaction effects on both flow and wall temperature distributions are shown

- Effect of cooling flow on wall temperature can be easily seen

- Cooling flow “lift-off” can easily be seen

- Region of cooling effectiveness can easily be seen

- Wall hot spots can be easily seen

- Thermal barrier coating included
Wall Temperature Distribution

- Wall temperature distributions show extent of cooling effectiveness
For More Details

• See:
  AIAA-2010- “Conjugate Design/Analysis Procedure for Film-Cooled Turbine Airfoil Sections” to be published January 2010
  AIAA-2008-4407 “Transitional RANS/DES Computations of Turbine Heat Transfer”
• Why not use the latest parallel computing technology to turn around complex multi-disciplinary solutions fast enough for automated design optimization???
Let’s Use GPUs with CPUs!

• Graphical processing units (GPUs) have proven success for gaming applications
• We have recently shown GPUs to also be useful for scientific simulations

• GPU Costs:
  – ~$500 for 128 floating-point units
  – **Example**: Our GPU cluster in ECE
    • 8 nodes of single quad-cores (32 cores)
    • 1 GPU per core → 32 GPUs
    • 12 Teraflops of peak performance, ~$25,000-$30,000
  – Low space and power requirements

• **Cost Effective Means of Achieving our Goals!**
Our Latest Results

- Argonne National Laboratories 32 CPU/GPU cluster

GPU Cluster Speedup: MBFLO2

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Domain Size
- GPU (800K)
- CPU (800K)
- GPU (3.2M)
- CPU (3.2M)
- ideal GPU
- ideal CPU
Summary of Performance Gains

• For 32 CPU/GPU combined processors
  – MBFLO speed-up increased to ~146 over single CPU (66% improvement over 16 combined processors) on Argonne National Laboratory cluster.
    • A factor of 5.4 over 32 CPUs at 85% efficiency.
    • Over a factor of 30 in performance/price ratio!

• Greater speed-ups with larger data sets and more computing
  – Great performance for 3D turbulent computations!

• Goal to turn-around conjugate heat-transfer DES simulations in a few minutes so that automated optimization can be used
  – Currently at ~30 minutes solution time for TA’d DES
For More Details

• See:

Overall Summary

• New ideas are forthcoming to break existing bottlenecks in using CFD during design
  – CAD-based automated grid generation
  – Multi-disciplinary use of embedded, overset grids to eliminate complex gridding problems
  – Use of time-averaged detached-eddy simulations as norm instead of “steady” RANS to include effects of self-excited unsteadiness
  – Combined GPU/Core parallel computing to provide over an order of magnitude increase in performance/price ratio

• Gas-turbine applications are shown here but these ideas can be used for other Air Force, Navy, and NASA applications