Panel Discussion:
Perspectives on the Future of CFD

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Topics for Discussion

- What have we accomplished?
- Is CFD mature enough?
- Where can we go from here?

Progress to Date

- CFD has pioneered the field of flow simulation for
  - Obtaining engineering solutions involving complex configurations
  - Understanding physics (critical to mission success)
- CFD has progressed as computing power has increased
  - Numerical methods have been advanced as CPU and memory increases
  - N-S solution of full configuration was a big goal in the 80s
  - Complex configurations are routinely computed now
  - DNS/LES are used to study turbulence
- As the computing resources changed to parallel and distributed platforms, computer science aspects become important such as
  - Scalability (algorithmic & implementation)
  - Portability, transparent codings etc

Examples of Current Capability

- Algorithmic advances include
  - Discrete models :
    Various artificial dissipation models
    Unified formulations, e.g. preconditioning
    Unstructured methodology
    Various gridding strategies
  - Solution methods:
    Explicit/Implicit
    Preconditioning, dual-time
    Multi-grid
- Successful application of CFD to engineering problems
  - High-lift configurations
  - Multiple bodies in relative motion
  - Components of propulsion system (both aero & space)
  - Maneuvering vehicle
  - .....
  - List goes on

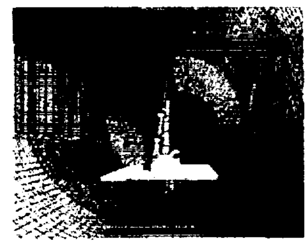
Examples of Current Capability: OVERSET CFD Tools

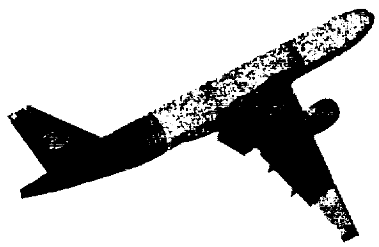
- EXAMPLE LANDING CONFIGURATION
  - 22.4M mesh points
  - 79 zones
  - 201 C90 hours for convergence (Lift within 2% of experiment)

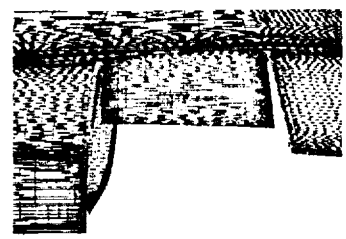
⇒ Small geometric variations have a major impact, particularly near maximum lift

⇒ Grid density study was performed

⇒ Accuracy of physical modeling needs further assessment



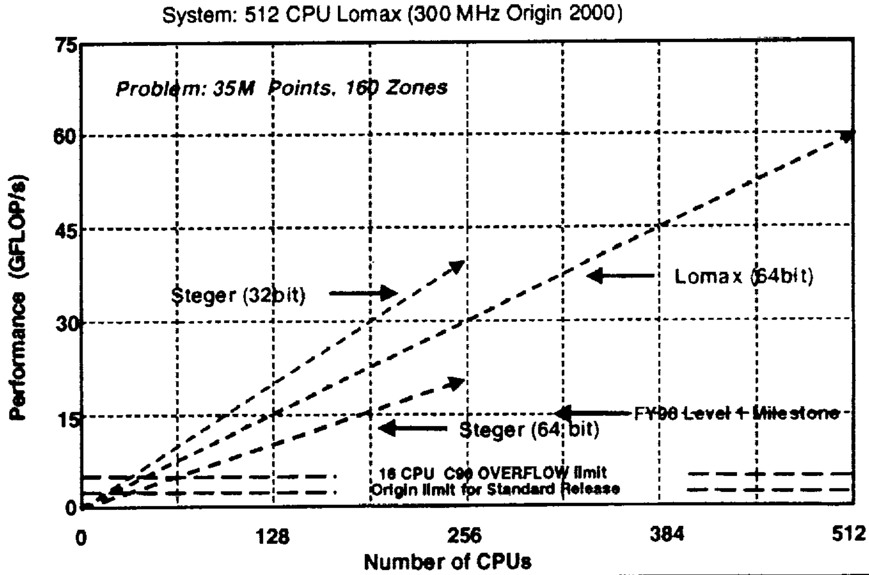




Stuart Rogers, NASA Ames - AST/IWD High Lift

Examples of Current Capability: OVERFLOW-MLP Performance

System: 512 CPU Lomax (300 MHz Origin 2000)



Examples of Current Capability: OVERFLOW-MLP Performance

- Origin 2000 (64 bit) performance is dramatically better than full C90
  - OVERFLOW 16 CPU C90 = 4.6 GFLOP/s
  - OVERFLOW 256 CPU O2K (250MHz) = 20.1 GFLOP/s
  - OVERFLOW 512 CPU O2K (250MHz) = 37.0 GFLOP/s (cluster)
  - OVERFLOW 512 CPU O2K (300MHz) = 60.0 GFLOP/s
- Striking Performance/Cost Advantage of Steger/Lomax over C90
  - OVERFLOW = 256 CPUs are 4.4x faster @ 4.5x Cheaper = 23x
  - OVERFLOW = 512 CPUs are 13.0x faster @ 2.6x Cheaper = 33x
- Dramatic performance gains for small changes in code
  - ~1000 lines of changes (<1% of total code)

Are we done with development?

"Can do it all" message was propagated in the past, but
CFD did not replace Wind Tunnel ⇒ CFD was oversold!

Of course, we are not done and further research will create advances with across the board benefits;

- Algorithm
  Convergence acceleration, Robustness, Error estimation
  Grid related issues, adaptive grids ....
- Physical modeling issues
  Turbulence, Combustion, Multiphase, Spray, Plasma etc.
- Solution Procedures
  Automation: CAD-Grid-Solution-Feature extraction
- Applications
  Rapid turn around for complex configurations
  Design and product development - we still need trained CFDers
  ⇒ Outsourcing makes sense

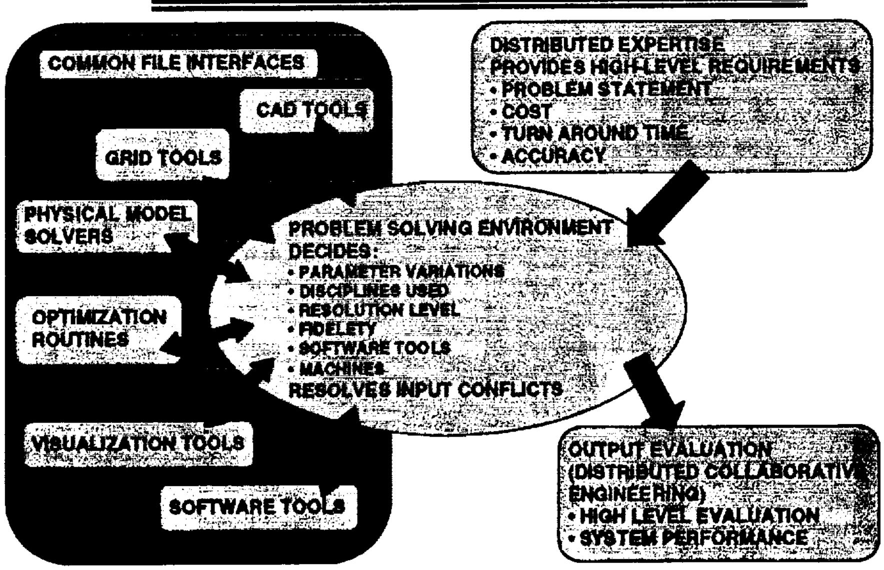
However, sponsors are likely to view these as "incremental advances."

Where do we go from here?

- Work environment is different now
  - Tremendous information is available
  - Single-handed code development is rapidly becoming outdated (CFD discipline as defined in the past is disappearing)
  - Problem solving environment is more collaborative

    ⇒ Requires software engineering to mitigate risks:
    Legacy software handling tools
    Visualization
    Data base handling tools

PROBLEM SOLVING ENVIRONMENTS



Examples of Potential Future (or Current) Challenges

Ames Research Center

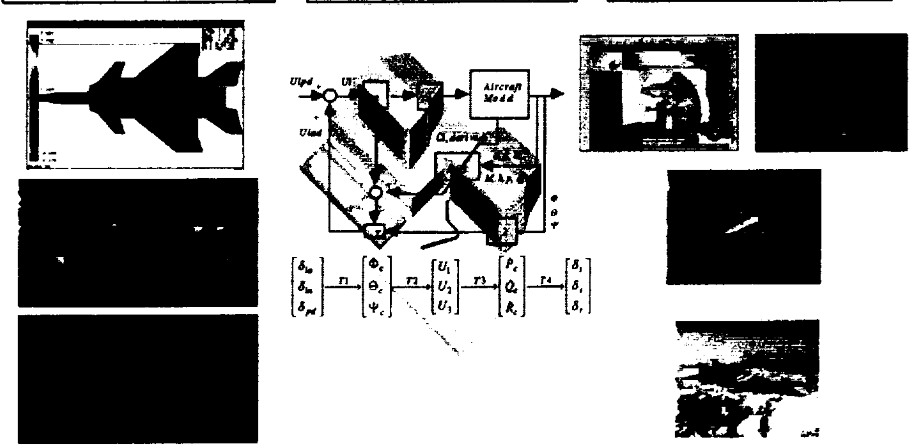
- Risk Assessment
  - What are the risks of designing flow devices using CFD+IT tools?
  - Can we manage uncertainties?
  - Uncertainties can from many different sources:
    e.g. methods, software engineering ...
- There is a limit on heuristic model
  ⇒ Can benefit from Scientific + Engineering approach, for example,
  - Compute transport properties to model real gas effect
  - LES to predict nozzle+jet noise, maximum lift of high-lift configuration
    e.g. flow+structure+combustion

  ⇒ Can we use LES for wall-bounded flow, if we have 100x faster computer today?
  Do we need to invest more in LES method?
  or, take different approaches?
- CFD+IT Tools
  - CFD for information generation and control (a part of IT element)
    e.g. Virtual flight

Example of Current Challenges: Integrated Vehicle Modeling Environment (IVME)

Ames Research Center

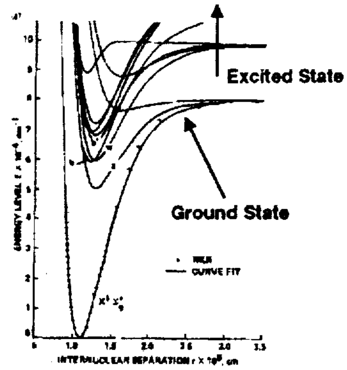
Step 1	Step 2	Step 3
Vortex, Wind Tunnel, or CFD Analyses for Configuration Specific Aerodynamics	NeuroEngineering Lab for Flight Control/Interface Integration	Flight Simulation and Virtual Reality to Evaluate Vehicle Control Concepts & Handling Qualities



Karen Gundy-Burlet NASA Ames

Example: Real Gas Effect Model

ELECTRONIC STATE FOR N2



- Current Model

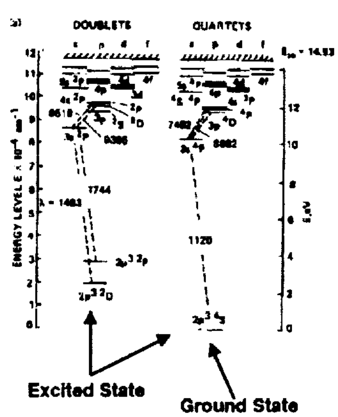
  Euler :
  - Do not require knowledge of internal internal molecular structures and intermolecular potentials

  Navier-Stokes :
  - Molecules are structureless
  - Transport properties are based on a single intermolecular potential
  - Collisions are assumed to be elastic

  Non-equilibrium flow equations:
  - EOS for each species is based on equil distributions over many internal states
  - Reaction rates account for ground states
  - Empirical intermolecular potential is used

Example: Real Gas Effect Model

ELECTRONIC STATE FOR N ATOM



- Proposed Approach

  Based on more accurate solution of known microscopic equations, develop better macroscopic equations:

  - Derive micro eqs and constitutive eqs from Bloltzman eq (inelastic collision)
  - Obtain state-to-state rates and product-state distribution functions

  ⇒Provide macro properties to be used in CFD codes

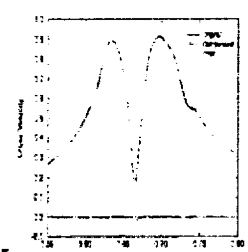
- Impact
  - The results are more accurate physics-based representation of macroscopic properties (from current curve fitting)
  - Applicable to high-speed planetary reentry / RLV in descend

Example of Data Base Management Tool: Data Compression Using Multi-resolution

- Wing Tip Vortex Validation
  NACA0012, A R=0.75, Re=4.6x106, α=10°
  INS3D Code, 2.5M Grid (115x189x115)

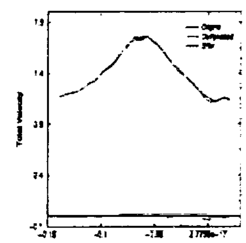
IMAGES BEFORE AND RECONSTRUCTED FROM COMPRESSED DATA ARE INDISTINGUISHABLE

CROSS FLOW VELOCITY



X/C=1.5

TOTAL VELOCITY



Compression Ratio :
40 (Pressure), 45 (Pressure & Velocities)
Error: 7.93×10^{-2} (Max Residual), 2×10^{-6} (L_2)

Computation by Jennifer Dacles-Mariani
Data Compression by Dohyung Lee

Where do we go from here?

- integrated solution for assessing the total system performance, life cycle and safety can very well be the next challenge
  e.g. Need a more complete picture of entire design space not just one design

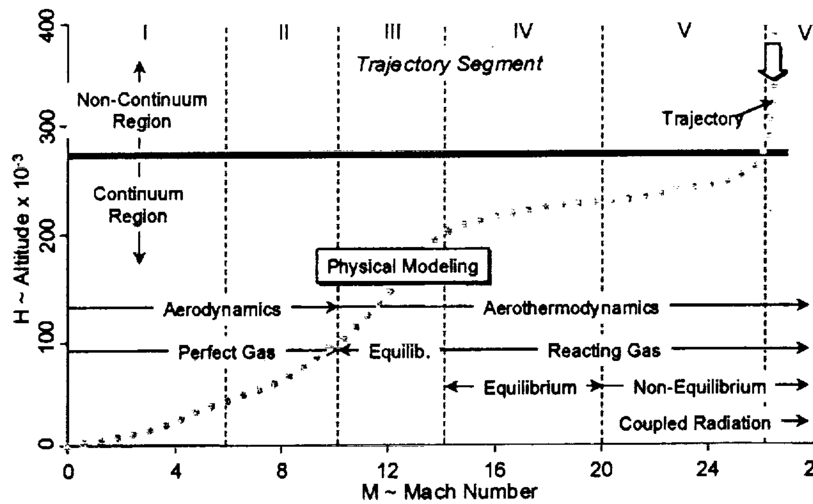
Some challenges specific to CFD are:

- Physics-based simulation for more predictive capability
- Integrated analysis
  e.g. multi-discipline, performance for entire flight envelope
- IT tools can be used to integrate CFD, experiments and flight tests
  e.g. virtual flight
  ⇒ Requires : Many simulations which will be put into data base, and data base management tools, query tools to extract desired info

- Validation is an issue

Example: Impact of Real Gas Effect Model

Typical RLV Descent Trajectory for Aerodynamics Analyses



What are some of Target Problems?

- Bottom line for research is "money"
- We can target some of the unsolved challenges in flow devices
  - Compressor rotational stall
  - Turbopump system in rocket engine
  - Jet noise
  - Maximum lift of high-lift system
  - Rotor-based propulsion system
  - .....
- There are a wide range of challenging applications in non-aerospace
  - Climate prediction
  - Flow-related problems in human body; e.g. heart, lung, hemodynamics....
  - Automobile
  - Naval hydrodynamics
  - Chemical engineering
  - ....

Example of Target Problems: Rotor-Based Propulsion System (Army AFDD)

V-22 Tiltrotor

- Issues:
  High Cycle Fatigue: Unsteady loads associated with rotor-based propulsion systems are the primary driver of high cycle fatigue of system components.
  Whirl-Flutter: Interaction between structural dynamics of wing and rotational motion and vortical flow of propulsion system can lead to catastrophic structural failure.
- Potential Impact:
  High Cycle Fatigue: High fidelity simulation and analysis capability for aero-elastic effects for propulsion systems.
  Whirl-Flutter: Confirm existing theory or define improved design standards.

Bob Meakin: Army AFDD/ Nasa Ames

Where do we go from here?

We need the next level of BIG CFD goals.

Where do we go from here?

Potential Topics

- Tough Problems:
  Physics-Based Scientific Computing + CFD
- Big Impact on Aerospace Engineering :
  for Developing 3rd Gen RLV

Strategy