Summary of CFD Methods for Potential Extensions to Earth Simulation

Discussion with Scientists in Japanese Earth Simulator Project and Center for Climate Systems Research, University of Tokyo

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Dochan Kwak
Numerical Aerospace Simulation Systems
Applications Group
dkwak@mail.arc.nasa.gov
Tel: (650) 604-6743 / FAX: (650) 604-1095

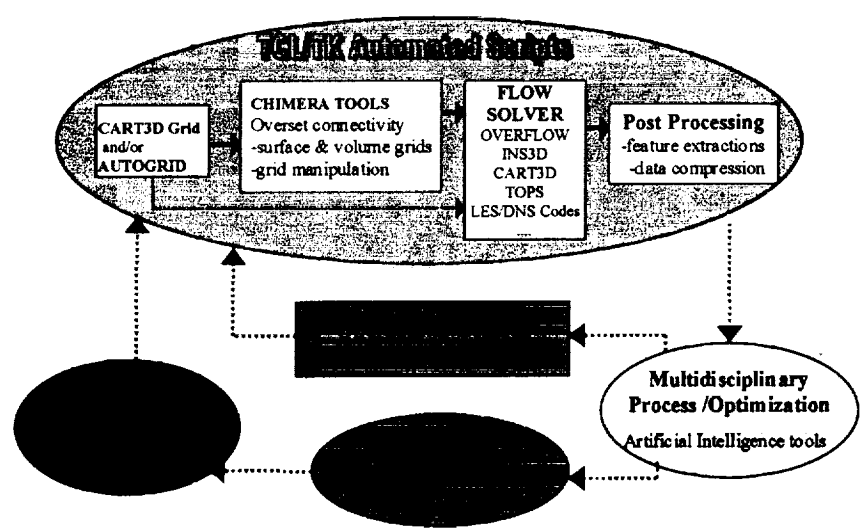
Outline

- Purpose of Selected Summary
- Historical Examples
- Current Tasks Extendable to Earth Simulation
- Tools Potentially Extendable to Earth Simulation
- Discussion

Tools Potentially Extendable to Earth Simulation

- INS3D
  High- fidelity steady and unsteady incompressible Navier-Stokes flow simulation
- Overset (Chimera) Tools
  Complex geometry Navier-Stokes simulation tool
- Cart3D
  Rapid Euler solver for conceptual and preliminary design
- Flow Data Compression Code
  CFD data compression compatible with the above codes

Simulation and Control Roadmap



Purpose of Selected Summary

- Review some recent activities in Ames' computational methods development area
- Place these in historical and current context
- Material selected is to be viewed as core capabilities for potential extension to earth science simulations
- This is intended for open discussion on issues and options

Historical Examples

- Grid generation Methods and Tools
  Developed elliptic, hyperbolic, unstructured point-insertion and local optimization, patched and overset (Chimera) grid procedures, Cartesian grid procedure.
  Resulting codes include: OVERGRID, 3D GRAPE, HYPGEN, DCF, SAGE, SURGRID, PRISIM, DELAUNAY, CART3D.
- CFD Algorithm Advances
  Developed following algorithms and disseminated throughout the US:
  MacCormack explicit algorithm
  Beam-Warming approximate factorization algorithm
  AF1/AF2 algorithm for small disturbance and potential flow
  Pulliam-Chaussee diagonalized ADI algorithm
  Steger-Warming flux-splitting algorithm
  Pseudo compressibility algorithm for viscous incompressible flow
  Linear-reconstruction unstructured scheme

Historical Examples

- Flow Solvers and Codes
  Small-disturbance, potential and BL: Bailey-Ballhaus, LTRAN2, BL3D
  TAIR/TWING, TOPS

Euler/Navier-Stokes:	ARC2D/3D, TNS, PNS, TIGER, CNS , OVERFLOW
Incompressible:	INS3D family of codes
Aero-elastic:	ENSAERO
Rotorcraft:	TURNS, OVERFLOW_Rtrcrft
Turbomachinery:	ROTOR, STAGE

- Post Processing and Scientific Visualization
  PLOT3D, FAST and others

Historical Examples

- Application Examples - Aerospace
  - Coupled aerodynamic-structured prediction of flutter
  - Full fighter aircraft performance predictions: transonic cruise (F-16), high alpha (F-18 with Dryden), STOVL (Harrier), F-15, F-16 ....
  - Full rotorcraft performance prediction (e.g. V-22)
  - Full simulation of the Space Shuttle stack performance (with JSC)
  - "Tip-to-tail" hypersonic aircraft performance prediction
  - Single- and multi-stage turbomachinery performance prediction
  - Simulation/ redesign of the Space Shuttle Main Engine Hot Gas Manifold
  - Space observation system,SOFIA
  - Space transportation vehicles: X-33, X-34, X-38, Shuttle crew escape module
- Application Examples - Non-Aerospace
  - First simulation of an Artificial Heart (Penn State)
  - Development of NASA/DeBakey Left Ventricular Assist Device
  - Simulation of naval vehicles (submarine and propeller with the navy)

Current Tasks Extendable to Earth Simulation

1.0 Geometry Definition and Grid Generation

- 1.1 CAD work
- 1.2 Overset grid generation
- 1.3 Topology determination
- 1.4 Auto-scripting
- 1.5 Internal flow gridding issues

2.0 Overset Grid Connectivity

- 2.1 Moving grid capability
- 2.2 Hole cutting problem
  Current tools need to be worked on
  DCF / Pegsus / X-ray DCF
- 2.3 Minimize CPU and wall clock time
- 2.4 Develop parallel version compatible with flow solvers

Current Tasks Extendable to Earth Simulation

3.0 Solver

- 3.1 Time-accurate algorithm
  Integration scheme
  High-accuracy compact schemes
  Convergence acceleration
- 3.2 Parallel codes
  MPI, OpenMP, MLP etc.
  Scalability, interoperability and other computer science issues

4.0 Intelligent Data Management

- 4.1 Feature extraction from unsteady data
- 4.2 Data compression for communication at remote sites and storage
- 4.3 Data base generation using experimental and computational data
  (soft computing tools to cover wide range of operations)

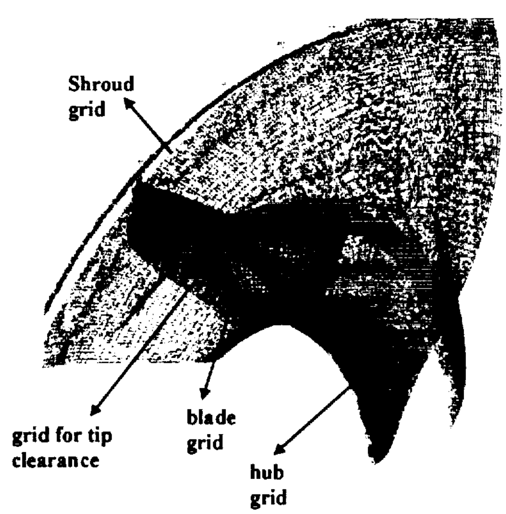
5.0 Systems analysis tool for entire rocket engine subsystems

INS3D - Incompressible Navier-Stokes Solver

- Description
  INS3D is a high- fidelity incompressible Navier-Stokes flow solver both for steady and unsteady flows. The objective is to provide CFD analysis capability on arbitrarily geometry involving complex flow phenomena.
- Overset and Block Grid Options
  - Easier grid generation : modularity, better local grid quality
  - Complex moving body problems
- Flow Solver
  - Includes different algorithm options
  - Parallel version is being developed
- Current work
  - Rapid, high fidelity procedure for unsteady turbopump system is being developed

POC: C. Kiris, kiris@nas.nasa.gov ; D. Kwak, kwak@mail.arc.nasa.gov

EXAMPLE GRID FOR INS3D
Shuttle Upgrade SSME-rig1



Unshrouded Impeller Grid :
6 long blades
6 medium blades
12 short blades

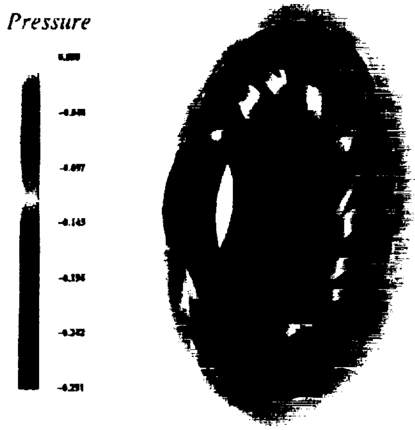
60 Zones
14.1 Million Grid Points

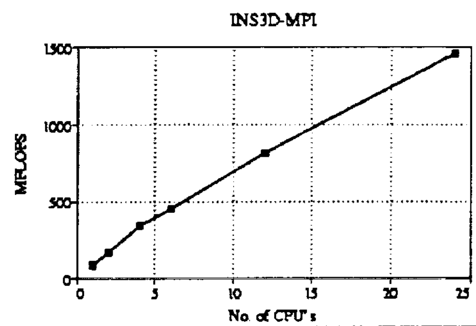
Smallest zone : 74,025
Largest zone : 899,248

Overset connectivity is currently underway by using PEGSUS.

Parallel Implementation of INS3D

INS3D-MPI - coarse grain
First release
T. Faulkner & J. Dacles
MPI course grain + Open MP
Debugging stage
H. Jin & C. Kiris
MLP (studying OVERFLOW-MLP)

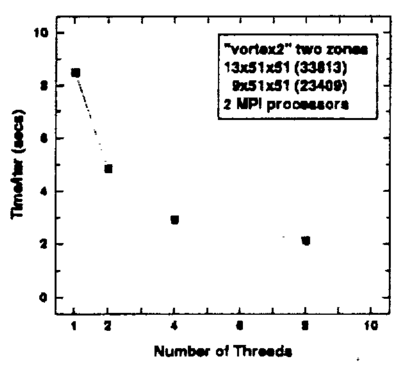




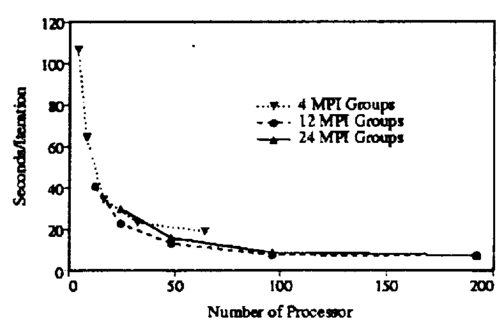
INS3D Parallelization

MPI coarse grain + Open MP

TEST CASE : 2 Zones Vortex



TEST CASE : SSME Impeller



No. of processors = No. of MPI * No. of threads

Cart3D - Cartesian Mesh Based Design Tool

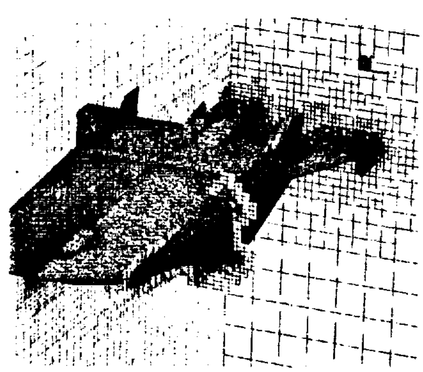
- DESCRIPTION
  High- fidelity inviscid analysis package is in demand for conceptual and preliminary design. The objective of Cart3D is to provide CFD analysis capability on arbitrarily complex, CAD- based geometry
- ACCOMPLISHMENTS
  - Mesh generation from CAD geometry is fully automated Cartesian cells which cut body are treated as general polyhedra
  - Fully automated Euler capability has been developed and demonstrated
- SIGNIFICANCE
  - Typical analysis cycle for completely new aerospace vehicle ~ 2 weeks

POC: M. Aftosmis, 4-4499, aftosmis@nas.nasa.gov

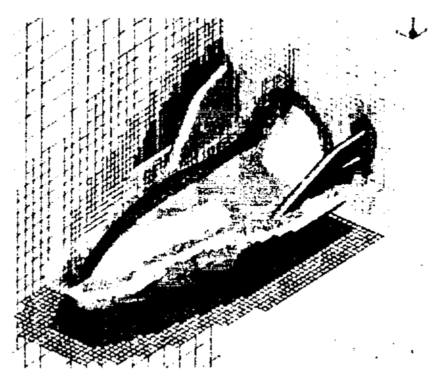
Cart3D - Advanced Aerospace Design Tool

- Example Meshes

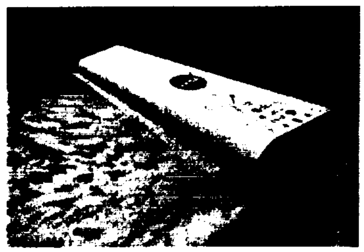
Generic SSTO : 1.2M Cells



X-38 : 1.6M Cells



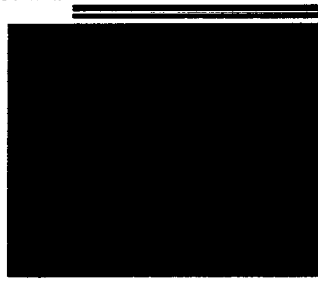
Cart3D : SHARP-L1 Reentry Vehicle Design

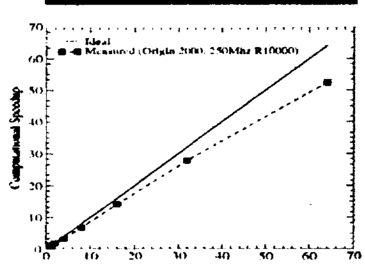


- Enables rapid conceptual design
  - 180 Cases delivered in 18 days using a desktop machine
  - Test matrix
    Mach 0.3 ~ Mach 5
    Alpha -5deg ~ +15deg
    beta -1deg ~ +1deg
    3 Asymmetric bodyflap deflections

Simulations performed by S. Pandya, Ames Research Center

Scalability of Parallel *Cart3D*





- Parallel Version of Cart3D
  - Parallelization through domain decomposition and explicit message passing.
  - Domain decomposition technique based upon space-filling curves permits domain decomposition to be performed in parallel and on-the-fly (at runtime)
  - Parallel speed-ups of ~53 on 64 processors.
  - Combined with robust multigrid to offer exceptionally fast convergence across the range of Mach numbers.
- Validation using Citation Twin-engine Business Jet
  - 1.42M cells, Mach 0.84 alpha 1.81deg

Overset Technology for Complex Configuration

Ames Research Center

- Overset (Chimera) Grid Approach
  - Easier grid generation : modularity, better local grid quality
  - Complex moving body problems
- OVERFLOW Flow Solver
  - Third-order upwind differencing
  - Spalart-Allmaras turbulence model
  - Multi-grid and low Mach number preconditioning
  - Performance: upto 12.3 GFLOPS on 256 node O2K
- Rapid, high fidelity solutions for complex geometries obtained:
  - Complete commercial high-lift airliner: within 50 days
    Predicted lift within 2% on approach for a complete Boeing 777-200 landing configuration in 48 days
  - Part-span flap Trap wing: 18 days
  - Transport aircraft flap redesign : 4 days

POC: S. Rogers, 4-4481, rogers@nas.nasa.gov

Overset Technology for Complex Configuration

Ames Research Center

- Overset (Chimera) Grid Approach
  NASA Ames Developed CFD Tools
  - OVERFLOW Navier-Stokes Flow Solver
  - Chimera Grid Tools: Pre- and Post Processing
  - Enabling flow simulation technology for complex configuration and unsteady flow involving bodies in relative motion

- OVERFLOW+CGT: 1998 NASA Software of the Year Honorable Mention
- PLOT3D Visualization Software
  1993 NASA Space Act Award
- FAST Visualization Software
  1995 NASA Software of the Year Award

Overset Technology for Complex Configuration

X38 B52
Drop

- Wide Range of Applications
  - Spacecraft ascent and descent
  - Propulsion
  - Aircraft
  - Hydrodynamics
- Current Development
  - Working toward fully automated grid generation
  - Steady and Unsteady capabilities
  - Bodies in Motion, 6 DOF
  - Non-equilibrium chemistry

Turbopump

Data Compression Using Multiresoultion Algorithm

- DESCRIPTION

  Numerical solution is, in general, only an approximation to the physical solution therefore for many purposes truncation of numerical data is acceptable. An efficient data compression algorithm for large 3-D data sets is desired for storage and transmission of data.
- ACCOMPLISHMENTS

  A prototype 3-D truncation compression code has been developed and demonstrated using CFD data. This code is based on Beam-Warming's supercompact multiwavelets extended from Harten's interpolatory method.
- SIGNIFICANCE

  Since most numerical flow solutions are smooth almost everywhere, this algorithm should provide efficient CFD data compression.

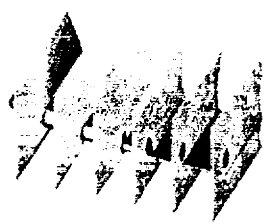
  Truncation even with high accuracy (e.g. 1×10^{-6} error) may allow significant compression thus reducing storage and transmission requirements
- WORK IN PROGRESS

  Develop a 2nd generation wavelets.

Wing Tip Vortex Data Compression

- Wing Tip Vortex Validation
  NACA0012, Wing Aspect Ratio=0.75, Re=4.6x106, α=10°
  INS3D Code, Baldwin-Barth Turbulence Model, 2.5M Grid (115x189x115)

BEFORE COMPRESSION



RECONSTRUCTED AFTER COMPRESSION

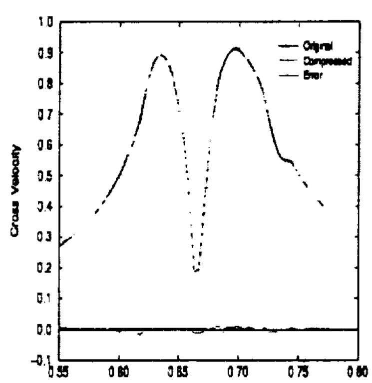
Compression Ratio : 40 (Pressure), 45 (Pressure & Velocities)
Error: 7.93×10^{-2} (Max Residual), 2×10^{-6} (L_{-2})

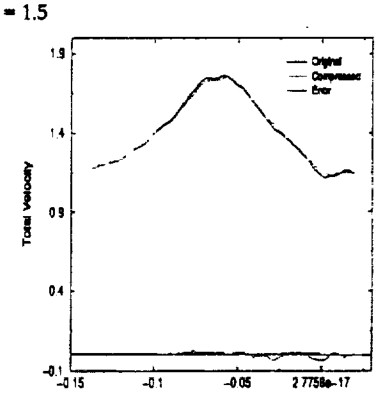
Computation by Jennifer Dacles-Mariani
Data Compression by Dohyung Lee

Wing Tip Vortex Data Compression

- Comparison of Velocity
  NACA0012, Wing Aspect Ratio=0.75, Re=4.6x106, α=10°
  INS3D Code, Baldwin-Barth Turbulence Model, 2.5M Grid (115x189x115)

x/c = 1.5





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Discussion

NASA

- ARC Strength
  CFD+IT
- Challenges
  Resources
  Technical
- Areas of Potential Collaboration
- Other Items