Unsteady Turbopump Flow Simulations

Cetin Kiris
Dochan Kwak
NASA-Ames Research Center, Moffet Field, CA 94035

ABSTRACT

The objective of the current effort is two-fold: 1) to provide a computational framework for design and analysis of the entire fuel supply system of a liquid rocket engine; and 2) to provide high-fidelity unsteady turbopump flow analysis capability to support the design of pump sub-systems for advanced space transportation vehicle. Since the space launch systems in the near future are likely to involve liquid propulsion system, increasing the efficiency and reliability of the turbopump components is an important task. To date, computational tools for design/analysis of turbopump flow are based on relatively lower fidelity methods. Unsteady, three-dimensional viscous flow analysis tool involving stationary and rotational components for the entire turbopump assembly has not been available, at least, for real-world engineering applications. Present effort is an attempt to provide this capability so that developers of the vehicle will be able to extract such information as transient flow phenomena for start up, impact of non-uniform inflow, system vibration and impact on the structure. Those quantities are not readily available from simplified design tools.

In this presentation, the progress being made toward complete turbo-pump simulation capability for a liquid rocket engine is reported. Space Shuttle Main Engine (SSME) turbo-pump is used as a test case for the performance evaluation of the hybrid MPI/Open-MP and MLP versions of the INS3D code. Relative motion of the grid system for rotor-stator interaction was obtained by employing overset grid techniques. Time-accuracy of the scheme has been evaluated by using simple test cases. Unsteady computations for SSME turbopump, which contains 106 zones with 34.5 Million grid points, are currently underway on Origin 2000 systems at NASA Ames Research Center. Results from these time-accurate simulations with moving boundary capability and the performance of the parallel versions of the code will be presented.
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Cetin Kiris
Dochan Kwak

NAS Applications Branch
NASA Ames Research Center

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David Taylor Model Basin
"Hydrodynamics Colloquium"
April 12, 2001, Bethesda, MD
INTRODUCTION
- Major Drivers of the Current Work
- Objectives

APPROACH / PROGRESS
- Formulation and Solution Method
- Computational models
- Code parallelization
- Unsteady SSME-rig1 turbopump simulation

SUMMARY

Major Drivers of the Current Work

- TOOLS FOR AEROSPACE DESIGN
  Decrease design cycle time ⇒ Rapid turn-around
  Increase design/process fidelity ⇒ High accuracy and low variation
  Increase discipline integration ⇒ Increased range of options via IT

Turbo-pump component analysis ==> Entire turbo pump simulation

- Computing time requirement is large:
  To achieve 1000 times speed up by 2001 over what was possible in 1992.
Objectives

- To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially, unsteady flow phenomena associated with high-speed turbo pump.

[Diagram showing timeline and various components]
Time Accurate Formulation

- Time-integration scheme

Artificial Compressibility Formulation

- Introduce a pseudo-time level and artificial compressibility
- Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

Pressure Projection Method

- Solve auxiliary velocity field first, then enforce incompressibility condition by solving a Poisson equation for pressure.
Artificial Compressibility Method

Time-Accurate Formulation

- Discretize the time term in momentum equations using second-order three-point backward-difference formula

\[
\left( \frac{\partial U}{\partial \xi} + \frac{\partial V}{\partial \eta} + \frac{\partial W}{\partial \zeta} \right)_{n+1} = 0
\]

\[
\frac{3q^{n+1} - 4q^n + q^{n-1}}{2\Delta t} = -r_{n+1}
\]

- Introduce a pseudo-time level and artificial compressibility,

- Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

\[
\frac{1}{\Delta t} (p_{n+1,m+1} - p_{n+1,m}) = -\beta N q_{n+1,m+1}
\]

\[
\frac{1.5}{\Delta t} (q_{n+1,m+1} - q_{n+1,m}) = -r_{n+1,m+1} - \frac{3q_{n+1,m} - 4q^n + q^{n-1}}{2\Delta t}
\]

Impulsively Started Flat Plate at 90°

- GRID
  Thickness of plate = 0.3H

- VELOCITY MAGNITUDE

  T=0.4
  T=1.2
  T=2.0
  T=4.0
Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point
  Artificial compressibility incorporated with Poisson solver

Boost Pump Computational Model

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Space Shuttle Main Engine Turbopump

COMPUTATIONAL CHALLENGES:
- Cost due to time-accurate flows
- Moving grid system
- Code parallelization

Shuttle Upgrade SSME-rig1

Inlet Guide Vanes
15 Blades
17 Zones / 4.5 M Points

Diffuser
23 Blades
24 Zones / 6.5 M Points
Shuttle Upgrade SSME-rig1

Unshrouded Impeller Grid:
6 long blades / 6 medium blades / 12 short blades
60 Zones / 19.2 Million Grid Points
Smallest zone : 75K / Largest zone : 996K
Overset connectivity is obtained by using DCF module OVERFLOW-D

Impeller Overset Grid System
Shuttle Upgrade SSME-rig1

SSME-rig1
- 114 Zones
- 34.3 Million Points
- 800 physical time steps in one rotation.
- XINTOUT for each position is saved.
- Less than 192 orphan points.

INS3D Parallelization

INS3D-MPI - coarse grain
Implemented by T. Faulkner & J. Dacles
INS3D Parallelization

INS3D-MPI/OpenMP
MPI (coarse grain) + OpenMP (fine grain)

Implemented by using CAPO/CAPT tools - Henry Jin at NASA-Ames

MPI

OpenMP threads

Group 1

Group N

INS3D Parallelization

MPI coarse grain + OpenMP fine grain

TEST CASE: SSME Impeller
24 zones / 2.8 Million points

Time (sec) per iteration

OpenMP Threads per MPI Group

Number of CPUs

2.8M Points

4 MPI groups

12 MPI groups

24 MPI groups

2.8M Points

4 MPI groups

12 MPI groups

24 MPI groups

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INS3D Parallelization

MPI coarse grain + OpenMP fine grain

TEST CASE: SSME Impeller
60 zones / 19.2 Million points

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Number of CPUs

- Time (sec) per iteration

1 OpenMP Thread

---

INS3D Parallelization

OpenMP with two different solver

TEST CASE: SSME Impeller
60 zones / 19.2 Million points

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Number of OpenMP Threads

- Time (sec) per iteration

19.2M Points / OpenMP
- Gauss-Seidel Line Rel.
- GMRES Solver

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