Progress in Unsteady Turbopump Flow Simulations Using Overset Grid Systems

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Outline

• INTRODUCTION
  - Major Drivers of the Current Work
  - Objective

• SOLUTION METHODS
  - Summary of Solver Development
  - Formulation / Approach
  - Parallel Implementation

• UNSTEADY TURBOPUMP FLOW
  - Overset Grid System
  - Scripting Capability
  - Results

• SUMMARY
Objectives

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

<table>
<thead>
<tr>
<th>Year</th>
<th>SSME</th>
<th>LVAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1982</td>
<td>Space Shuttle Main Engine</td>
<td>LVAD Left Ventricular Assist Device</td>
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<tr>
<td>1990</td>
<td>advanced engine</td>
<td>Penn State artificial heart</td>
</tr>
<tr>
<td>1994</td>
<td>phase II + redesign</td>
<td>new design</td>
</tr>
<tr>
<td>2000</td>
<td>flight engines</td>
<td></td>
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Current Challenges

- Challenges where improvements are needed
  - Time-integration scheme, convergence
  - Moving grid system, zonal connectivity
  - Parallel coding and scalability

- As the computing resources changed to parallel and distributed platforms, computer science aspects become important.
  - Scalability (algorithmic & implementation)
  - Portability, transparent coding, etc.

- Computing resources
  - "Grid" computing will provide new computing resources for problem solving environment
  - High-fidelity flow analysis is likely to be performed using "super node" which is largely based on parallel architecture
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.

INS3D - Incompressible N-S Solver

** Parallel version is based on INS3D-UP:
  - MPI and MLP parallel versions
  - Structured, overset grid orientation
  - Moving grid capability
  - Based on method of artificial compressibility
  - Both steady-state and time-accurate formulations
  - 3rd and 5th-order flux difference splitting for convective terms
  - Central differencing for viscous terms
  - One- and two-equations turbulence models
  - Several linear solvers: GMRES, GS line-relaxation, LU-SGS, GS point relaxation, ILU(0), ...

** HISTORY
  ** 1982-1987 Original version of INS3D - Kwak, Chang
  ** 1988-1999 Three different versions were developed:
    INS3D-UP / Rogers, Kiris, Kwak
    INS3D-LU / Yoon, Kwak
    INS3D-FS / Rosenfeld, Kiris, Kwak
INS3D Parallelization

- INS3D-MPI (coarse grain)

- INS3D-MPI / Open MP
  MPI (coarse grain) + OpenMP (fine grain)
  Implemented using CAPO/CAPT tools

- INS3D-MLP

Group 1

Group 2

Group N
INS3D Parallelization

TEST CASE: SSME Impeller
60 zones / 19.2 Million points

Number of CPUs

INS3D-MLP/OpenMP vs. MPI/OpenMP

12 Groups

20 Groups

Number of CPUs

RLV 2nd Gen Turbopump (SSME Rig1)

Inlet Guide Vane

Impeller

Diffuser

ProE Surface Triangulation

Baseline SSME/ATD HPFTP Class Impeller

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RLV 2nd Gen Turbopump

Overset Grid System

Inlet Guide Vanes
15 Blades
23 Zones
6.5 M Points

Diffuser
23 Blades
31 Zones
8.6 M Points

Unshrouded Impeller Grid:
6 long blades / 6 medium blades / 12 short blades
60 Zones / 19.2 Million Grid Points
Overset connectivity: DCF (B. Meakin)
Less than 156 orphan points.

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Impeller Overset Grid System

Blade Grid

Background Grid

RLV 2nd Gen Turbopump

Particle traces and pressure surface at the end of first rotation.
Three impeller rotations are completed.

One complete rotation requires less than 3.5 days by using 128 CPUs on SGI Origin 3000. When 512 CPUs are utilized, one rotation can be completed less than 1.5 days. In 1999, one impeller rotation would take 42 days by using 32 CPUs on SGI Origin 2000 platform.
Diffuser blade needs to be corrected to compare with experiments

Original geometry used in computations

Diffuser used in experiments
**Scripting Capability**

**Motivation**
Significant user's effort needed in complex process from geometry to flow solver.

**Objective**
Develop script system to:
- generate grids
- create domain connectivity input
- create flow solver input for different components automatically

**Approach**
Develop one script for each component with ring interface between components => easy plug in for different designs and combinations of components.

**Script Generation**

**Disadvantages**
- Require expertise to build scripts the first time

**Advantages**
- Allow rapid re-run of entire process
- Easy to do grid refinement and parameter studies
- Easy to try different gridding strategies
- Documentation of gridding procedure
- Tcl scripting language
- Works on UNIX, LINUX and WINDOWS
- Integer and floating point arithmetic capability
- Modular procedure calls
- Easy to add GUI later if needed
Scripting Capability

INPUT AND OUTPUT

Input

- profile curves for hub and shroud in PLOT3D format (rotated by script to form surface of revolution)
- blade and tip surfaces in PLOT3D format
- Parameters that can be changed
  - number of blades and sections
  - global surface grid spacing $\Delta s$ (on smooth regions)
  - local surface grid spacing, some independent and some expressed as multiples of $\Delta s$ (leading/trailing edges, etc.)
  - normal wall grid spacing (viscous, wall function)
  - marching distance
  - grid stretching ratio
-...

Output

- overset surface and volume grids for hub, shroud, blades
- object X-rays for hole cutters using DCF
- domain connectivity namelist input for OVERFLOW-D

INLET GUIDE VANES (N repeated blades, no tip clearance)

No. of pts (million) 7.1 5.8 1.1
User time * 1 day 43 sec. 20 sec.

(* from geometry def. to DCF input with SGI R12k 300MHz CPU)
Scripting Capability

IMPELLER
(M sections, N different blades in each section, tip clearance)

Manual               Script (fine)              Script (coarse)
No. of pts (million)  19.2                15.2                8.8
User time *          ~2 weeks              319 sec.              234 sec.
(* from geometry def. to DCF input with SGI R12k 300MHz CPU)

DIFFUSER (N repeated blades, no tip clearance)

Manual               Script (fine)              Script (coarse)
No. of pts (million)  8.0                  8.4                  1.6
User time *          1 day                 37 sec.              22 sec.
(* from geometry def. to DCF input with SGI R12k 300MHz CPU)
Scripting Capability

RING INTERFACE BETWEEN COMPONENTS

- IGV out ring
- > 9-point overlap between rings
- > no impeller points beyond last plane of IGV ring
- > no IGV points beyond first plane of impeller ring

FUTURE PLANS FOR TURBOPUMP SCRIPTING

- Flow solver input creation in scripts
- Develop master script for connecting different components
- Develop script for other components, e.g., volute, inducer
- Perform more tests on different parameters
- Improve robustness (error traps, wider range of cases)
- Graphical interface front end
- Geometry and operating conditions obtained on January 24, 2002
  (M. Williams @ Boeing, and D. Dorney NASA-MSFC)
- Impeller: 6 long blades/6 short blades
- Diffuser: 13 blades

- Rotational speed: 6322 RPM / Mass Flow Rate: 1210 gallons/min.
- Re: 1.37x10^7 / \( L_{ref} = 4.5225 \) inches, \( V_{ref} = V_{up} = 249.5 \) ft/sec
- 39 Million grid points / 41 zones in overset grid systems

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Consortium Impeller-Diffuser

- Impeller inflow ring
- Impeller diffusion
- Impeller hub
- Diffuser outflow ring
- Diffuser blade
- Impeller-diffuser interaction rings
Consortium Impeller-Diffuser

diffuser blade collar grids

impeller blades collar grids

Consortium Impeller-Diffuser

Impeller - diffuser interaction
INITIAL START / Impeller started rotating at design speed
pressure contours and surfaces

First Rotation : Impeller rotated 90 degrees.
pressure surfaces total velocity surfaces
Consortium Impeller-Diffuser

First Rotation: Impeller rotated 160 degrees.
- Pressure surfaces
- Total velocity surfaces

First Rotation: Impeller rotated 240 degrees.
- Pressure surfaces
- Total velocity surfaces
Consortium Impeller-Diffuser

First Rotation: Impeller rotated 360 degrees.
- Pressure surfaces
- Total velocity surfaces

Consortium Impeller-Diffuser

Second Rotation: \( t/T = 1.2 \)
- Pressure surfaces
- Total velocity surfaces
Second Rotation: $t/T = 1.2$ velocity vectors near diffuser blade
Summary

- Unsteady flow simulations for RLV 2nd Gen baseline turbopump for three impeller rotations are completed by using 34.3 Million grid points model.
- MPI/OpenMP hybrid parallelism and MLP shared memory parallelism has been implemented in INS3D, and benchmarked.
- For RLV turbopump simulations more than 30 times speed-up has been obtained.
- Moving boundary capability is obtained by using DCF module.
- Scripting capability from CAD geometry to solution is developed.
- Unsteady flow simulations for advanced consortium impeller/diffuser by using 39 Million grid points model are currently underway. 1.2 impeller rotations are completed.
- Fluid/Structure coupling is initiated.