Progress in Unsteady Turbopump Flow Simulations

Cetin Kiris
William Chan
Dochan Kwak
NASA Ames Research Center

Robert Williams
NASA Marshall Space Flight Center

JANNAF 2002 Meeting, Destin, FL
April 8-12, 2002

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
Major Drivers of Current Work

• To provide computational tools as an economical option for developing future space transportation systems (i.e. RLV subsystems development)

  Impact on component design ⇒ Rapid turn-around of high-fidelity analysis
  Increase durability/safety ⇒ Accurate quantification of flow
  (i.e. prediction of flow-induced vibration)

Impact on system performance ⇒ More complete systems analysis using high-fidelity tools

• Target
  Turbo-pump component analysis ⇒ Entire sub-systems simulation
  Computing requirement is large
  ⇒ The goal is to achieve 1000 times speed up over what was possible in 1992

  done already

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
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></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SSME</td>
<td>Shuttle Engine</td>
<td>phase II + redesign</td>
<td>flight engines</td>
</tr>
<tr>
<td>LVAD</td>
<td>Left Ventricular Assist Device</td>
<td>Penn State artificial heart</td>
<td>LVAD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>old design</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>new design</td>
</tr>
</tbody>
</table>

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

\[
\begin{bmatrix}
\frac{\partial U}{\partial \xi} + \frac{\partial V}{\partial \eta} + \frac{\partial W}{\partial \zeta}
\end{bmatrix}^{n+1} = 0 ; \quad \frac{3q^{n+1} - 4q^n + q^{n-1}}{2\Delta t} = -r_{n+1}^{n+1}
\]

- Introduce a pseudo-time level and artificial compressibility,

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

\[
\frac{1}{\Delta t} (p^{n+1}_{n+1} - p_{n+1}^{n+1}) = -\beta V q^{n+1}_{n+1}
\]

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

Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point
** Impulsively Started Flat Plate at 90° **

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

** 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**

**Previous Work (SSME Impeller)**

Pressure

- R = 5.57 in.
- R = 5.633 in.
- R = 5.833 in.
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.
INITIAL START: Impeller rotated 12-degrees

VELOCITY MAGNITUDE

PRESSURE
Particle traces and pressure surface at the end of first rotation.
- 34.3 Million Points
- Two and half 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
**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.

---

**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)

<table>
<thead>
<tr>
<th>No. of pts (million)</th>
<th>Manual</th>
<th>Script (fine)</th>
<th>Script (coarse)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.1</td>
<td>5.8</td>
<td>1.1</td>
</tr>
<tr>
<td>User time *</td>
<td>1 day</td>
<td>43 sec</td>
<td>20 sec</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Manual</th>
<th>Script (fine)</th>
<th>Script (coarse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.2</td>
<td>15.2</td>
<td>8.8</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Manual</th>
<th>Script (fine)</th>
<th>Script (coarse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>6.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

User time: 1 day, 37 sec., 22 sec.

(* from geometry def. to DCF input with SGI R12k 300MHz CPU)
**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.
- Fluid/Structure coupling is initiated.