Time-Dependent Simulations of Turbopump Flows

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Thermal and Fluids Analysis Workshop  
September 10-14, Huntsville AL
Outline

- **INTRODUCTION**
  - Major Drivers of the Current Work
  - Objective

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

- **UNSTEADY TURBOPUMP FLOW**
  - Scripting Capability
  - Fluid / Structure Coupling
  - Data Compression

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

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

- Impact on system performance \(\Rightarrow\) More complete systems analysis using high-fidelity tools

- Target
  Turbo-pump component analysis \(\Rightarrow\) Entire sub-systems simulation

  Computing requirement is large:
  \(\Rightarrow\) The goal is to achieve 1000 times speed up over what was possible in 1992
To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially unsteady flow phenomena associated with high speed turbo pumps.
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
**Parallel version:**
- 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
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.
Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point

![Graph showing the relationship between Ls/H and time, with data points and curves representing different simulations and experiments.

Legend:
- EXP (Taneda, 1971)
- INS3D-UP
- INS3D-FS
- Finite Elem. Sol. (Yoshida, 1985)
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

Circumferential angle from suction side (deg)

R = 5.57 in.

Total velocity (V/Vw)

R = 5.833 in.

Circumferential angle from suction side (deg)

Flow angle (deg)

R = 5.833 in.
Inlet Guide Vane (IGV)
• 15 Blades
• Pitch, \( p = 24 \) degrees
• Blade Inlet Angle (mean), \( \beta_{IGV,1} = 90 \) degrees
• Blade Exit Angle (mean), \( \beta_{IGV,2} = 45 \) degrees

Clearance between IGV and Impeller, \( x = 0.12 \) inches

Impeller
• 6+6+12 Unshrouded Design
• Pitch, \( p = 60 \) degrees
• Blade Inlet Angle (mean), \( \beta_{imp,1} = 23 \) degrees
• Blade Exit Angle (mean), \( \beta_{imp,2} = 65 \) degrees
• Clearance between blade LE and Shroud, \( r = 0.0056 \) inches
• Clearance between blade TE and Shroud, \( x = 0.0912 \) inches

Clearance between Impeller and Diffuser, \( r = 0.050 \) inches

Diffuser
• 23 Blades
• Pitch, \( p = 15.652 \) degrees
• Blade Inlet Angle (mean), \( \beta_{dif,1} = 12 \) degrees
• Blade Exit Angle (mean), \( \beta_{dif,2} = 43 \) degrees
INS3D Parallelization

INS3D-MLP/OpenMP vs. -MPI/OpenMP

TEST CASE: SSME Impeller
60 zones / 19.2 Million points

19.2M Points
- MPI-OpenMP Hybrid
- NAS-MLP

Time (sec) per iteration vs. Number of CPUs

12 Groups

20 Groups

19.2M Points
- MPI-OpenMP Hybrid
- NAS-MLP
RLV 2nd Gen Turbopump (SSME Rig1)

Impeller Technology Water Rig
Baseline SSME/ATD HPFTP Class Impeller

ProE CAD Model

ProE Surface Triangulation

CART3D

OVERSET GRID
Chimera Grid Tools
- OVERGRID,
- DCF, ....

FLOW SOLVER
INS3D
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.
Impeller Overset Grid System

- Blade Grid
- Background Grid
Scripting Capability

SCRIPTING CAPABILITY FOR GRID GENERATION

> Require expertise to build scripts the first time
> Allow rapid re-run of entire grid generation process
> Easy to do grid refinement and parameter studies
> Easy to try different gridding strategies
> Documentation of gridding procedure
> Written in 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

Current example: one script for each component (IGV, Impeller and Diffuser)

Input

> profile curve 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
  - global surface grid spacing (on smooth part of geometry)
  - local surface grid spacing (leading/trailing edges, etc.)
  - normal wall grid spacing (viscous, wall function)
  - marching distance
  - grid stretching ratio
  - number of blades
  - ...

Output

> overset surface and volume grids for hub, shroud, blades
Scripting Capability

INLET GUIDE VANES AND DIFFUSER

<table>
<thead>
<tr>
<th></th>
<th>Old IGV</th>
<th>New IGV</th>
<th>Old DIFF</th>
<th>New DIFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of points (million)</td>
<td>7.1</td>
<td>1.1</td>
<td>8.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Time to build</td>
<td>1/2 day</td>
<td>10 sec.</td>
<td>1/2 day</td>
<td>8 sec.</td>
</tr>
</tbody>
</table>

Script timings on new grids based on SGI R12k 300MHz processor

Time to build script = 1 day for IGV, 1 day for DIFF
Scripting Capability

**IMPELLER**

<table>
<thead>
<tr>
<th>No. of points (million)</th>
<th>Old IMP</th>
<th>New IMP</th>
<th>Old TOT</th>
<th>New TOT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19.2</td>
<td>5.7</td>
<td>34.3</td>
<td>8.4</td>
</tr>
</tbody>
</table>

Time to build

~ 2 weeks          50 sec.

Time to build IMP script: 3 to 4 weeks
FUTURE PLANS FOR SCRIPTING

- Complete domain connectivity capability in scripts (X-ray maps and DCF input file creation)

- Flow solver input creation in scripts

- Perform more tests on different parameters

- Perform tests on different geometries, e.g., volute, inducer

- Improve robustness (error traps, wider range of cases)

- Generic template for each component

- Graphical interface front end
FIRST Rotation: Impeller rotated 30-degrees

VELOCITY MAGNITUDE

PRESSURE
FIRST Rotation: Impeller rotated 125-degrees

RLV 2nd Gen Turbopump (baseline)
RLV 2\textsuperscript{nd} Gen Turbopump (baseline)

FIRST Rotation: Impeller rotated 160-degrees

VELOCITY MAGNITUDE

PRESSURE
FIRST Rotation: Impeller rotated 230-degrees
- 34.3 Million Points
- 800 physical time steps in one rotation. One and a half impeller rotations are completed.
*One physical time-step requires less then 20 minutes wall time with 128 CPU's on SGI Origin platforms. One complete rotation requires one-week wall time.
*Code optimization is currently underway. For small case, 50% improvement is obtained by employing a better cash usage in the code. Less than 10 minutes per time step will be obtained by the end of September 2001.
Grid File Compression

After Reconstruction

Before Compression

Data compression by J. Houman & D. Lee

Data Compression using...
Data Compression

- Data compression by J. Housman & D. Lee

Before Compression

After Reconstruction

Total Velocity Contours
STATIC/DYNAMIC STRESS ANALYSIS FOR TURBOPUMP SUB-SYSTEMS

START

FLUIDS INS3D

NEW CONDITIONS

INTERFACE ZIPPER/GRID

CFD GRID PRESSURE TEMPERATURE

STRUCTURES NASTRAN/ANSYS

STEM ANALYSIS

STRUCTURAL LOADS

FEM GRID

STOP
FLUID/STRUCTURE INTERFACE

- **LUMPED LOAD APPROACH**
  - FAST, NEEDS FINE GRIDS, ADEQUATE FOR UNCOUPLED METHOD

- **CONSISTENT LOAD APPROACH (CONSERVES LOADS)**
  - ACCURATE FOR COUPLED METHODS, EXPENSIVE

\[ q_a^T Z_a = q^T Z \]

\[ q^T Z = q_s^T Z_s \]

CONSISTENT LOAD APPROACH USING VIRTUAL SURFACE VALIDATED IN ENSAERO

By Guru Guruswamy
STRUCTURES

- STRUCTURES WILL BE MODELED USING BEAM, PLATE, SHELL AND SOLID FINITE ELEMENTS

- INHOUSE AND COMMERCIAL FEM CODES WILL BE USED

PRELIMINARY RESULTS FOR HUB USING 3D PLATE FEM

COARSE GRID
230 NODES
414 FE
1196 DOF

TYPICAL STRUCTURAL MODE AT 12KHz

By Guru Guruswamy
Unsteady flow simulations for RLV 2nd Gen baseline turbopump for one and half impeller rotations are completed by using 34.3 Million grid points model.

MLP shared memory parallelism has been implemented in INS3D, and benchmarked. Code optimization for cash based platforms will be completed by the end of September 2001.

Moving boundary capability is obtained by using DCF module.

Scripting capability from CAD geometry to solution is developed.

Data compression is applied to reduce data size in post processing.

Fluid/Structure coupling is initiated.