Time-Dependent Simulations of Turbopump Flows

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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
  - Scripting Capability
  - Fluid / Structure Coupling
  - Data Compression
- 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)

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<th>Impact on component design</th>
<th>Rapid turn-around of high-fidelity analysis</th>
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<tr>
<td>Increase durability/safety</td>
<td>Accurate quantification of flow</td>
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<td>(i.e., prediction of flow-induced vibration)</td>
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- 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

**Objectives**

- To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially, unsteady flow phenomena associated with high speed turbo pump.
** Parallel version: 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, Kirby, Kwak
- INS3D-LU / Yoon, Kwak
- INS3D-FS / Rosenfeld, Kirby, Kwak

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**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

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

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

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

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

Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point

\[
\text{EXP (Tomita, 1971)} \quad \text{INDX-U} \quad \text{INDX-PS} \quad \text{Point Elec. Sol. (Tomita, 1945)}
\]
Impulsively Started Flat Plate at 90°

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

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
**INS3D Parallelization**

- **INS3D-MPI**
  - (coarse grain)
  - T. Faulkner & J. Doakas

- **INS3D-MPI / Open MP**
  - MPI (coarse grain) + OpenMP (fine grain)
  - Implemented using CAPO/CAPT tools
  - H. Jin & C. Kirke

- **INS3D-MLP**
  - C. Kirke

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**Previous Work (SSME Impeller)**

Pressure

- **R = 5.17 ln.**
- Circumferential angle from suction side (deg)

- **R = 5.833 in.**
- Circumferential angle from suction side (deg)

- **R = 5.833 in.**
- Circumferential angle from suction side (deg)
Parallel Implementation of INS3D

INS3D-MLP / 40 Groups
RLV 2nd Gen Turbo pump
114 Zones / 34.3 M grid points

34.3M Points
- O2000 no-pin
- O2000 pin
- O3000 no-pin
- O3000 pin

Time (sec) per iteration

Number of CPUs

RLV 2nd Gen Turbopump (SSME Rig1)

Inlet Guide Vane
Impeller
Diffuser

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RLV 2nd Gen Turbopump

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

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