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Time-Dependent Simulations of Turbopump Flows

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Thermal and Fluids Analysis Workshop
September 10-14, Hunstville AL

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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

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Major Drivers of Current Work

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- 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

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Objectives

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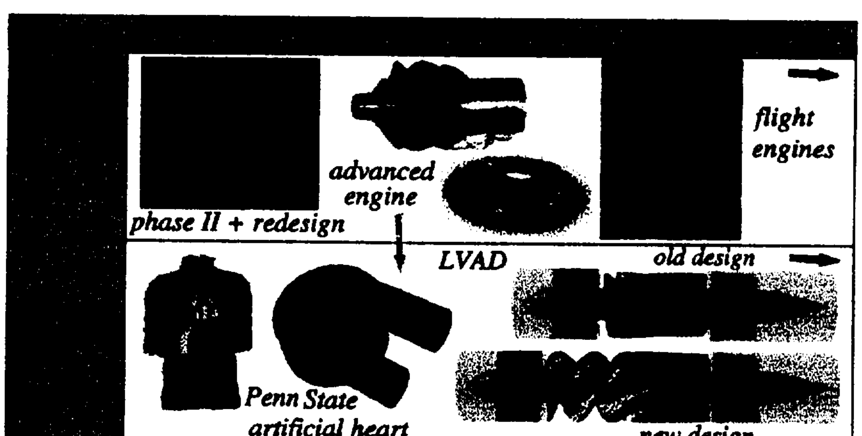
- To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially, unsteady flow phenomena associated with high speed turbo pump.



INS3D - Incompressible N-S Solver

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** ***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 devoped :

  INS3D-UP / Rogers, Kiris, Kwak

  INS3D-LU / Yoon, Kwak

  INS3D-FS / Rosenfeld, Kiris, Kwak

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Time Accurate Formulation

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- Time-integration scheme

  Artificiai 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.

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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.**

$$\frac{1}{\Delta\tau}(p^{n+1,m+1}-p^{n+1,m})=-\beta\nabla q^{n+1,m+1}$$

$$\frac{1.5}{\Delta t}\left(q^{n+1,m+1}-q^{n+1,m}\right)=-r^{n+1,m+1}-\frac{3q^{n+1,m}-4q^{n}+q^{n-1}}{2\Delta t}$$

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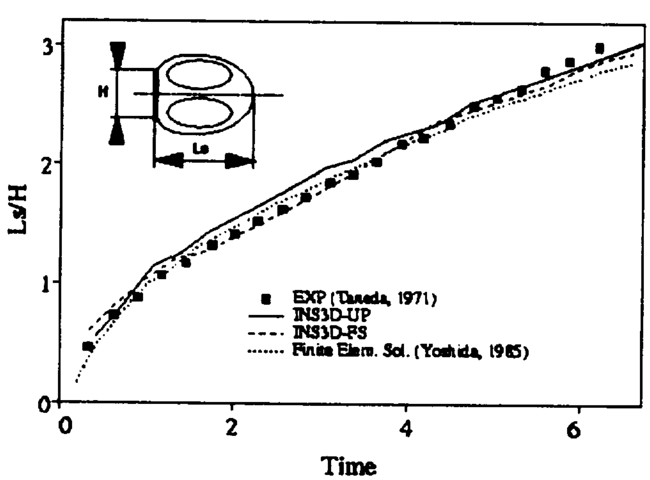
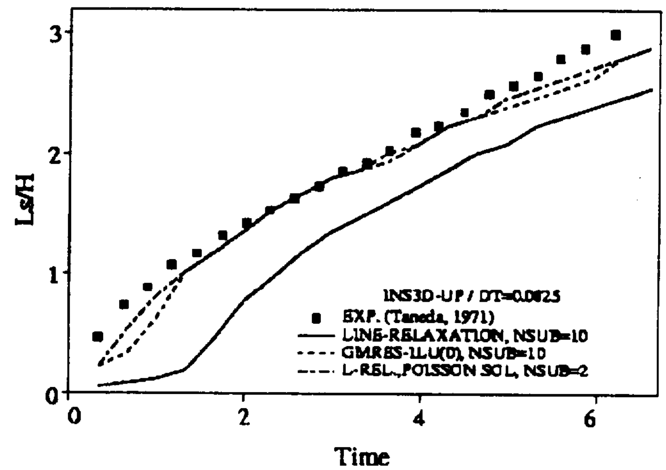
Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point



Impulsively Started Flat Plate at 90°

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



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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**

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INS3D Parallelization

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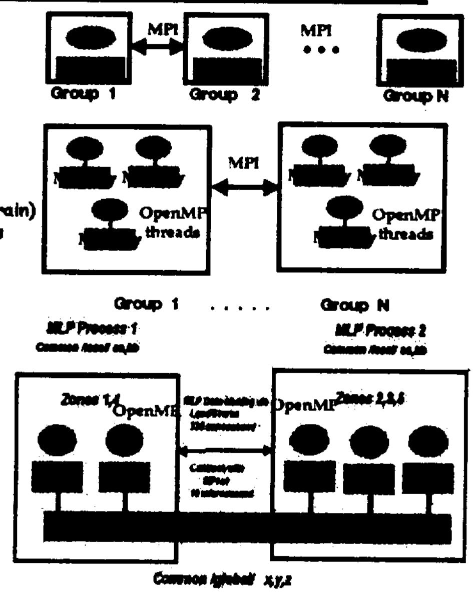
- **INS3D-MPI**
  (coarse grain)
  T. Faulkner & J. Dacles
- **INS3D-MPI / Open MP**
  MPI (coarse grain) + OpenMP (fine grain)
  Implemented using CAPO/CAPT tools
  H. Jin & C. Kiris
- **INS3D-MLP**
  C. Kiris



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Previous Work (SSME Impeller)

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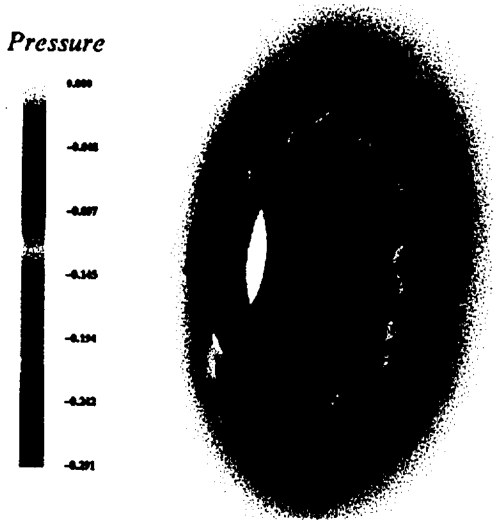

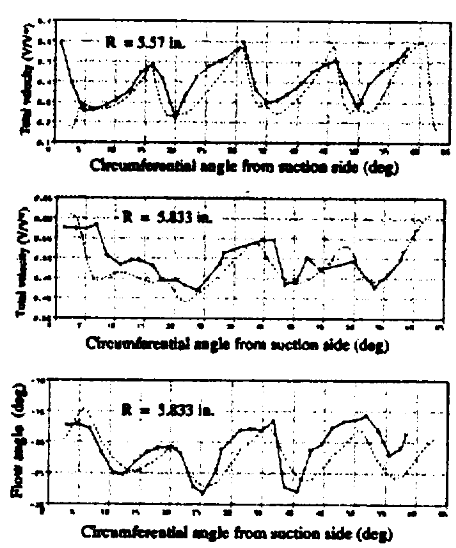

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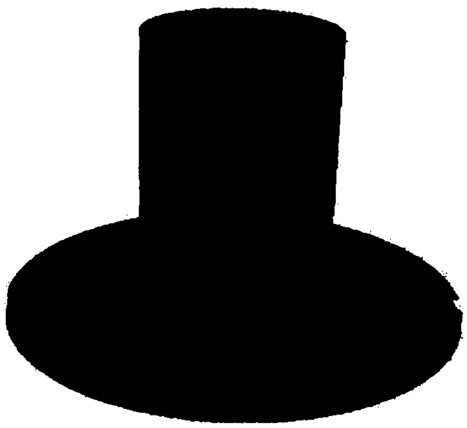
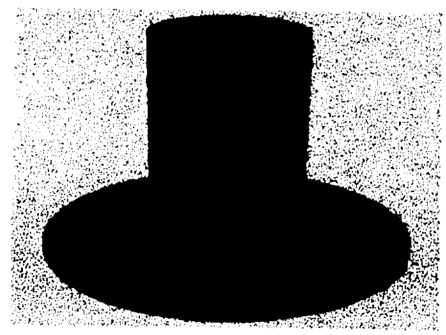
Space Shuttle Main Engine Turbopump





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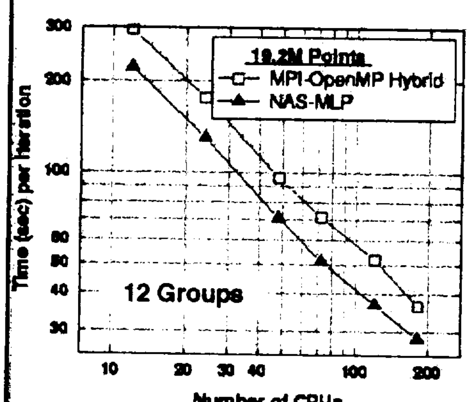
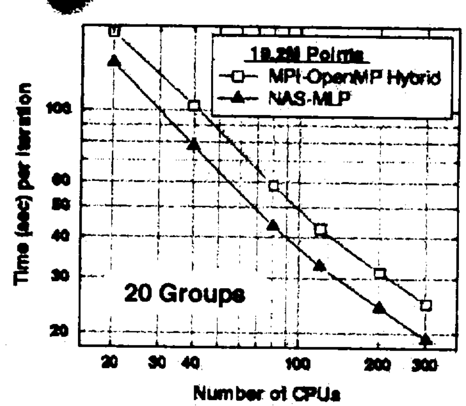
INS3D Parallelization

INS3D-MLP/OpenMP vs. -MPI/OpenMP

TEST CASE : SSME Impeller
60 zones / 19.2 Million points





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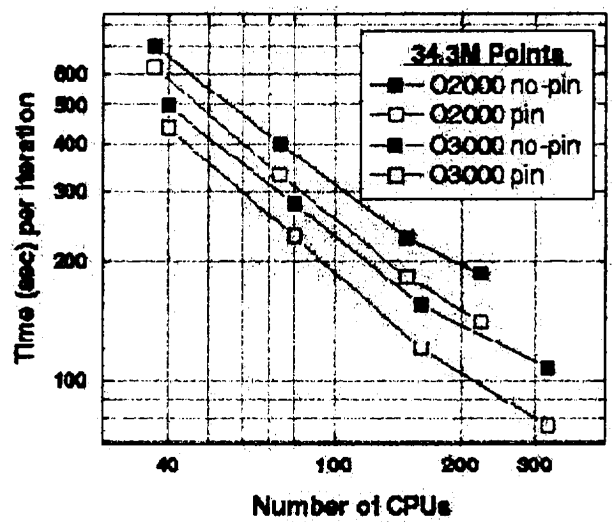
Parallel Implementation of INS3D

INS3D-MLP / 40 Groups

RLV 2nd Gen Turbo pump
114 Zones / 34.3 M grid points



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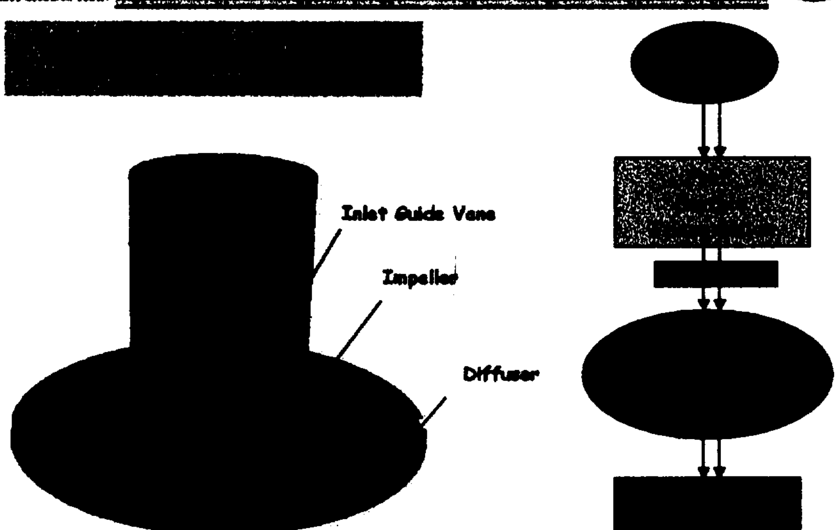
RLV 2nd Gen Turbopump (SSME Rig1)



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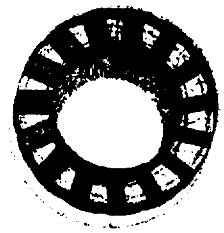
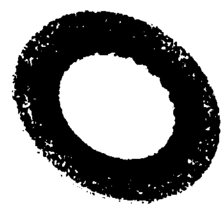
RLV 2nd Gen Turbopump

Overset Grid System

Inlet Guide Vanes
15 Blades
23 Zones
6.5 M Points



Diffuser
23 Blades
31 Zones
8.6 M Points



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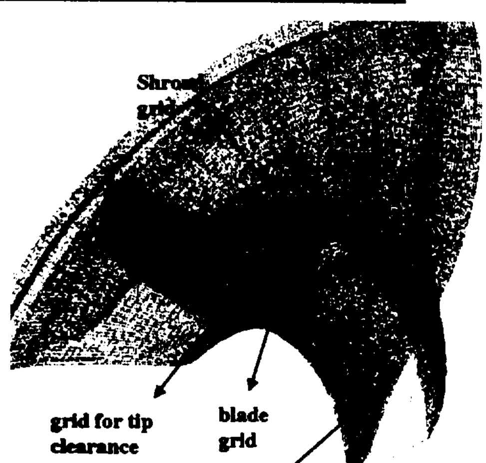
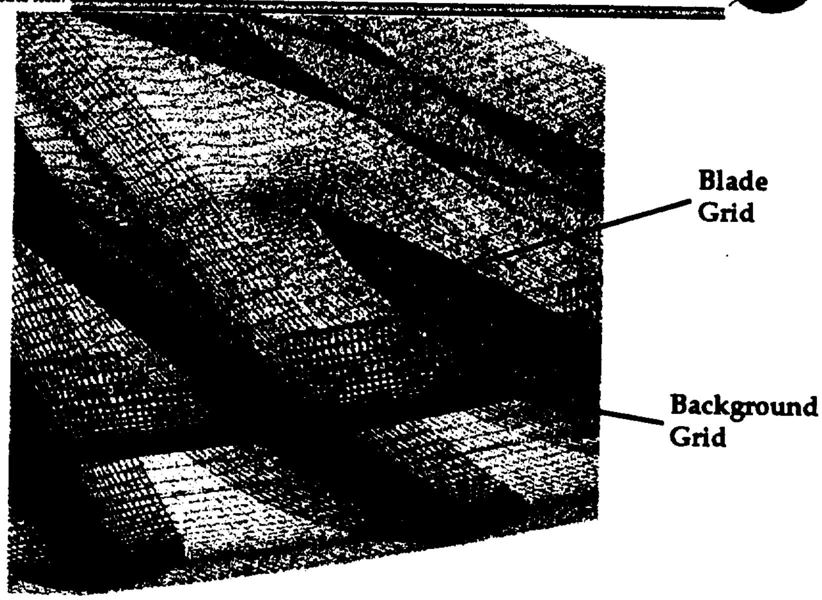
RLV 2nd Gen Turbopump



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



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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

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