Time-Dependent Simulations of Turbopump Flows

Cetin Kiris
Dochan Kwak
William Chan
NASA Ames Research Center

Robert Williams
Marshall Space Flight Center

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

- 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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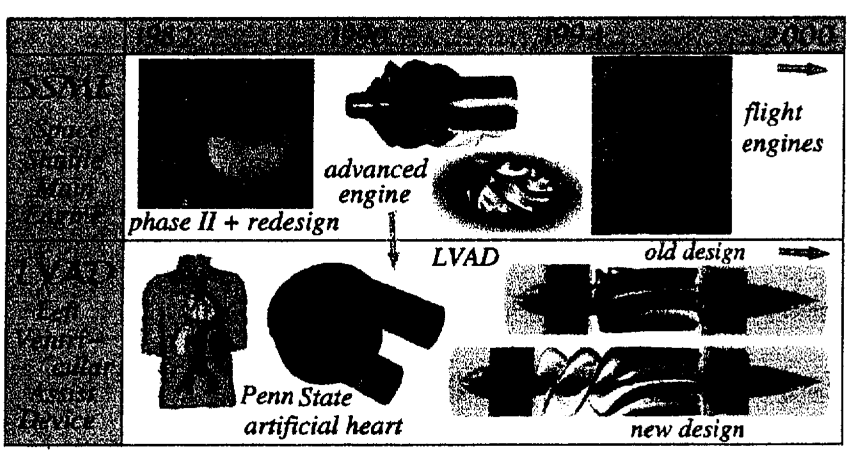
Objectives

- 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

** ***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

- 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.

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Artificial Compressibility Method

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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.**

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

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

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Impulsively Started Flat Plate at 90°

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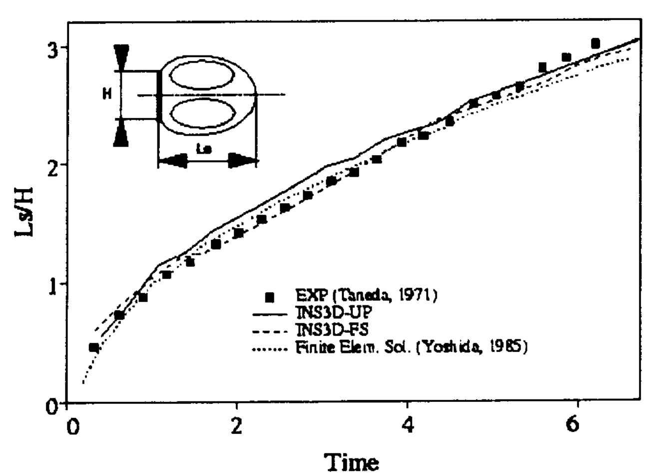
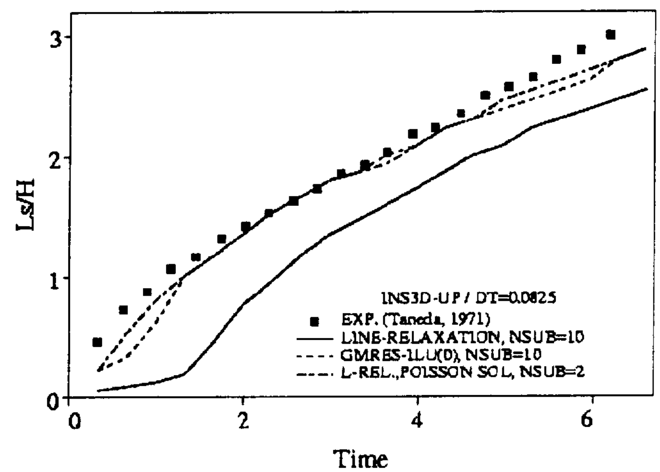
- Time History of Stagnation Point



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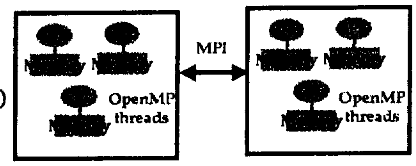
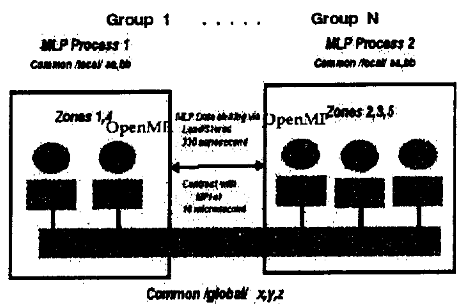
- INS3D-MPI
  (coarse grain)
  T. Faulkner & J. Dacles

- 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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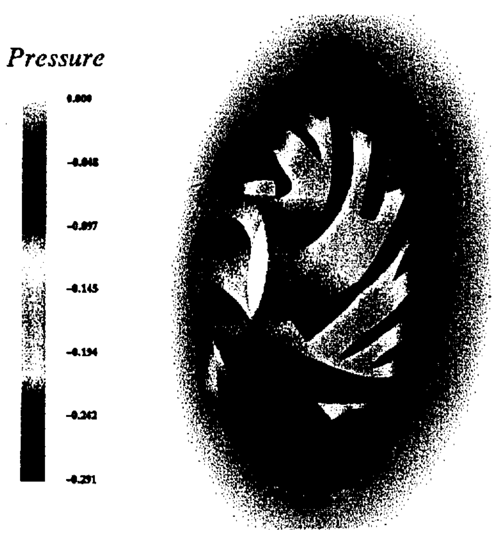

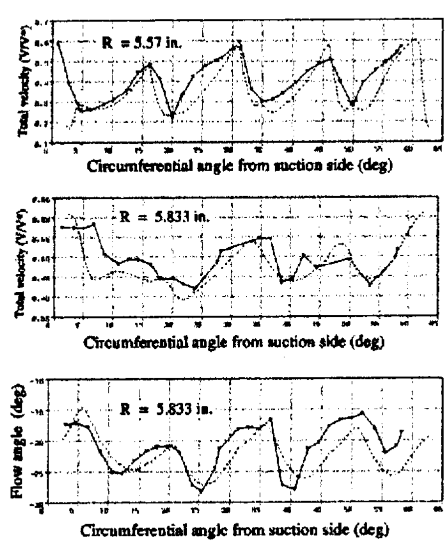

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Space Shuttle Main Engine Turbopump

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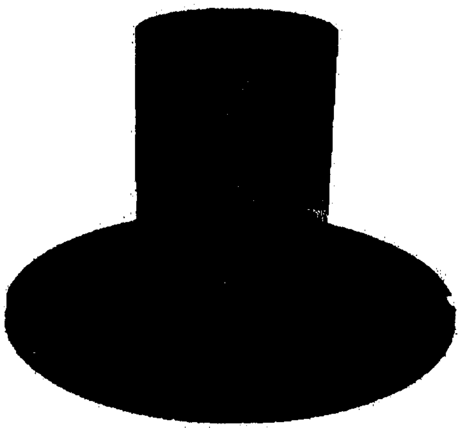

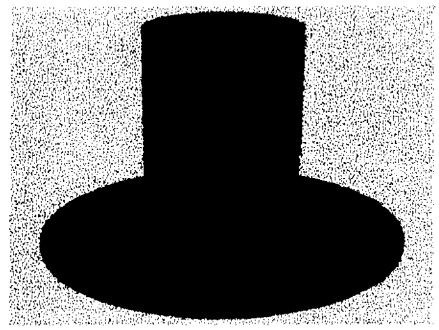

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INS3D Parallelization

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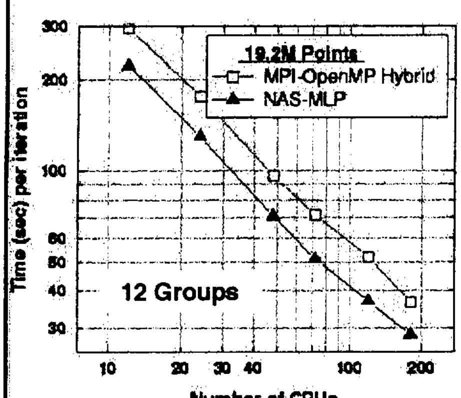
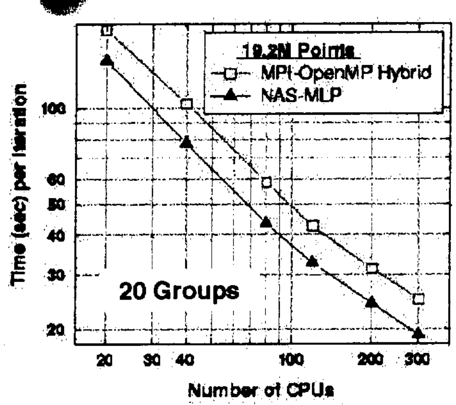
INS3D-MLP/OpenMP vs. -MPI/OpenMP

TEST CASE : SSME Impeller
60 zones / 19.2 Million points





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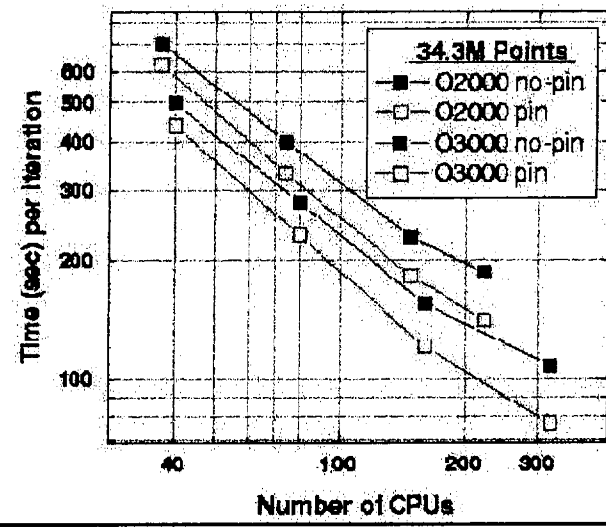
Parallel Implementation of INS3D

INS3D-MLP / 40 Groups

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



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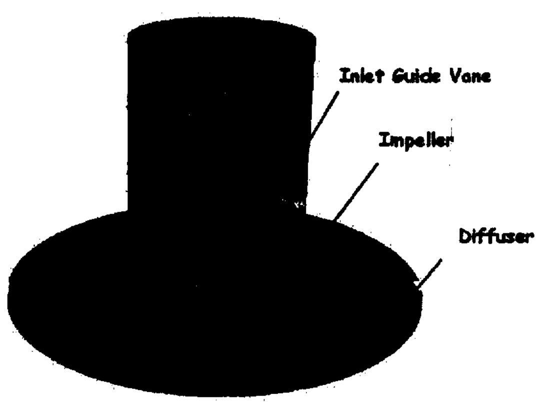
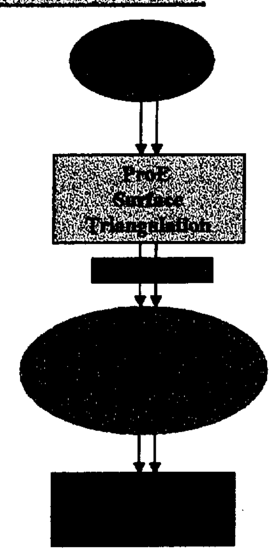
RLV 2nd Gen Turbopump (SSME Rig1)





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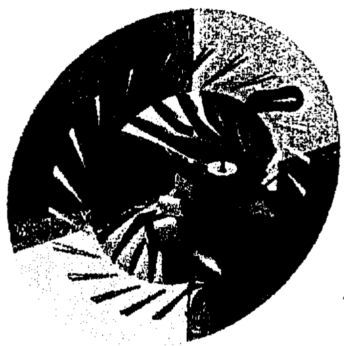
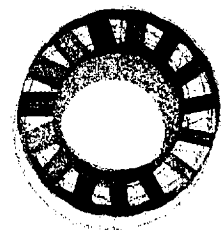
RLV 2nd Gen Turbopump

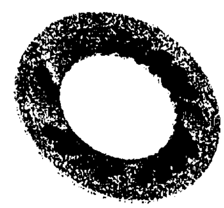
Overset Grid System



Inlet Guide Vanes
15 Blades
23 Zones
6.5 M Points



Diffuser
23 Blades
31 Zones
8.6 M Points



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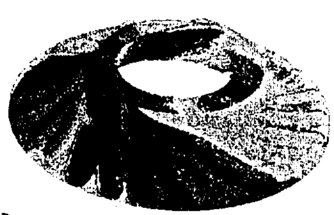
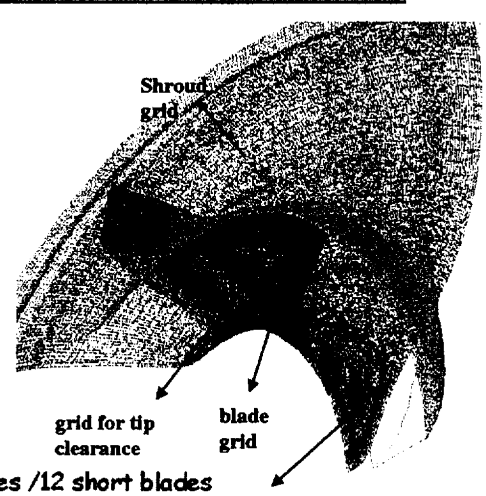
RLV 2nd Gen Turbopump





Unshrouded Impeller Grid :

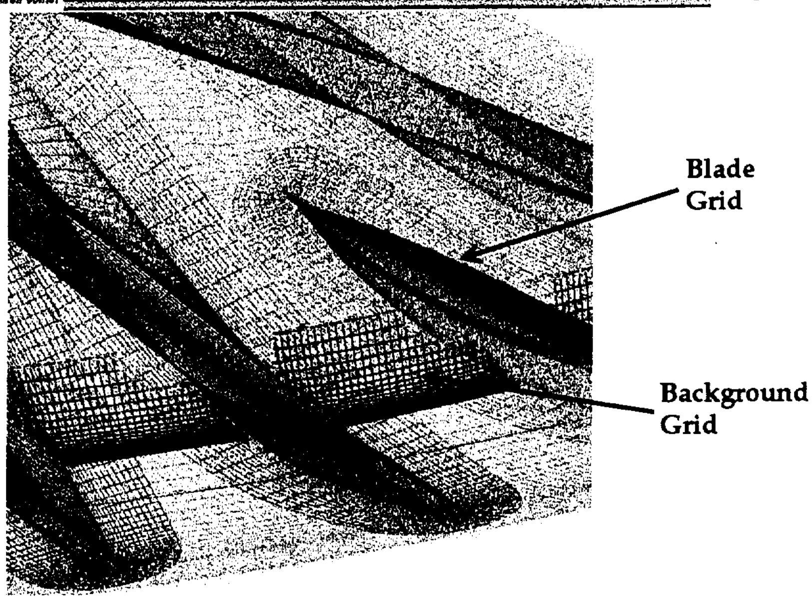
6 long blades / 6 medium blades /12 short blades

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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Scripting Capability

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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

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Scripting Capability

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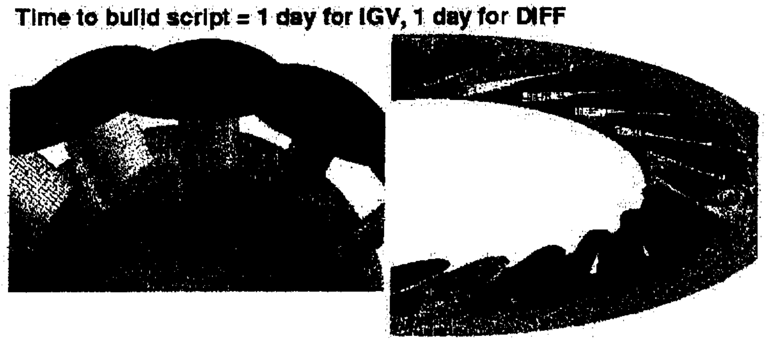
INLET GUIDE VANES AND DIFFUSER

	Old IGV	New IGV	Old DIFF	New DIFF
No. of points (million)	7.1	1.1	8.0	1.6
Time to build	1/2 day	10 sec.	1/2 day	8 sec.

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

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



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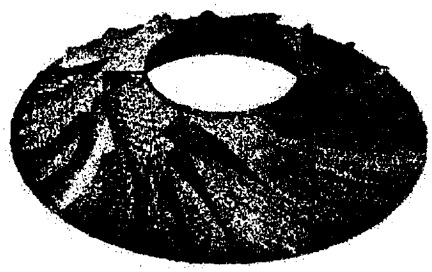
Scripting Capability

IMPELLER

	Old IMP	New IMP	Old TOT	New TOT
No. of points (million)	19.2	5.7	34.3	8.4
Time to build	~ 2 weeks	50 sec.		

Time to build IMP script : 3 to 4 weeks



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Scripting Capability

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

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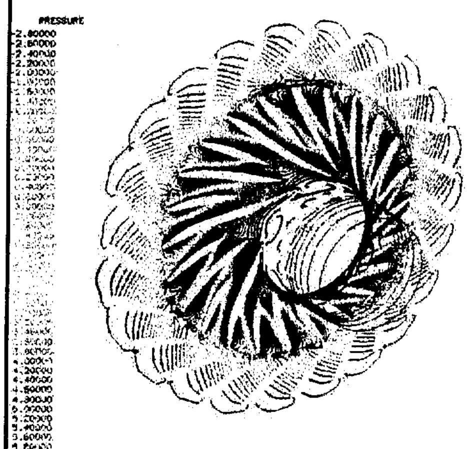
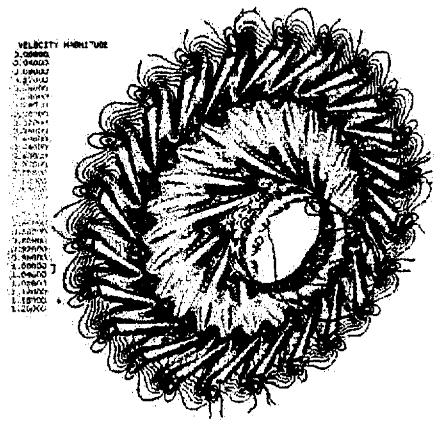
SSME-rig1 / Initial start

TIME STEP 18 / Impeller rotated 8-degrees at 100% of design speed





PRESSURE

VELOCITY MAGNITUDE

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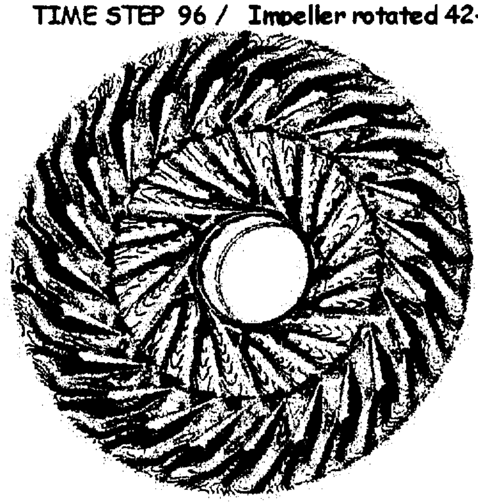
SSME-rig1 / Initial start

TIME STEP 96 / Impeller rotated 42-degrees



VELOCITY MAGNITUDE

- 34.3 Million Points
- 800 physical time steps in one rotation.

*One physical time-step requires less then 20 minutes wall time with 80 CPU's on Origin 2000. One complete rotation requires one-week wall time with 80 CPUs.
*Currently I/O is through one processor. Timing will be improved with parallel I/O since time-accurate computations are I/O intensive. With futher improvements several impeller rotations can be completed in one week.

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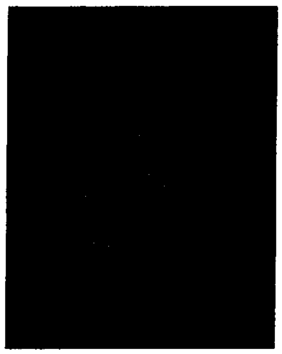
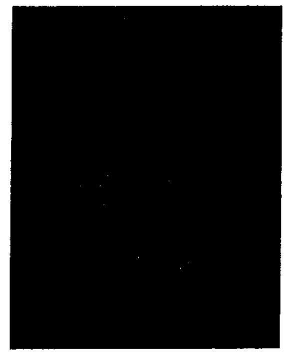
Data Compression using

Data compression by J. Housman & D.Lee





Before Compression

After Reconstruction

Grid File Compression

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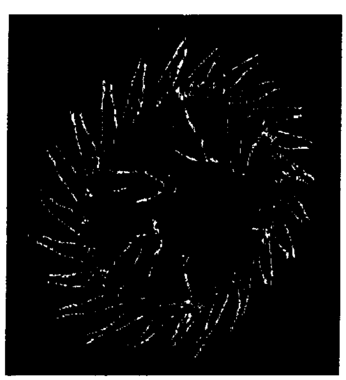
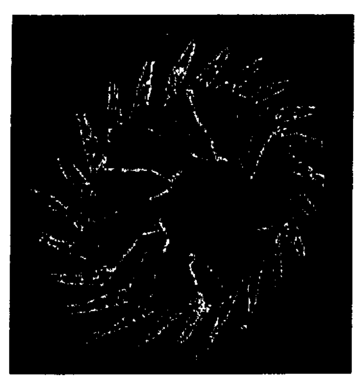
Data Compression

- Data compression by J. Housman & D.Lee





Before Compression

After Reconstruction

Total Velocity Contours

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STATIC/DYNAMIC STRESS ANALYSIS OF PROPULSION SYSTEMS

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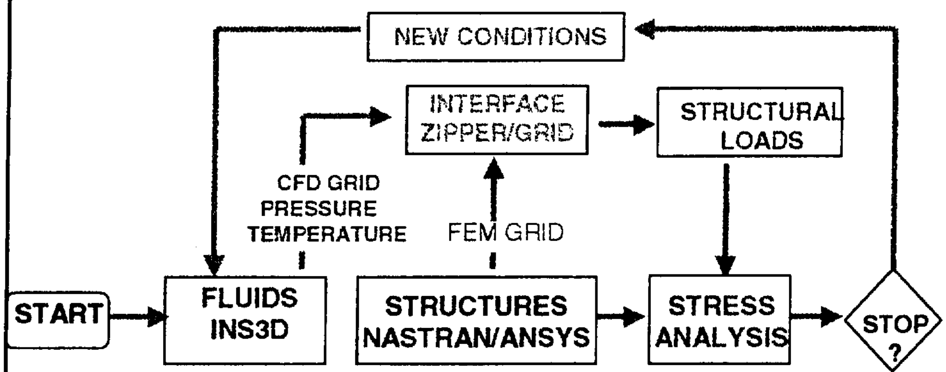

PROPOSED DEVELOPMENT UNDER CICT GC

TO BE IMPLEMENTED USING PSE/IPG TOOLS (GROWLER/SCIRUN/PUNCH)

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FLUID/STRUCTURE INTERFACE

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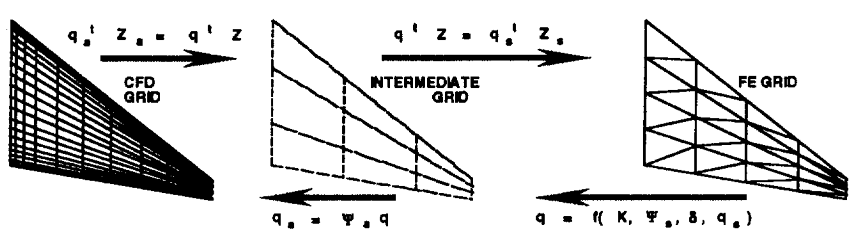
- **LUMPED LOAD APPROACH**
  - FAST, NEEDS FINE GRIDS, ADEQUATE FOR UNCOUPLED METHOD
- **CONSISTENT LOAD APPROACH (CONSERVES LOADS)**
  - ACCURATE FOR COUPLED METHODS, EXPENSIVE



CONSISTENT LOAD APPROACH USING VIRTUAL SURFACE VALIDATED IN ENSAERO

By Guru Guruswamy

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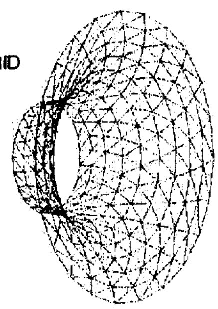
STRUCTURES

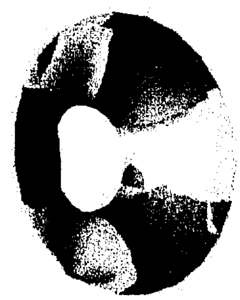
- STRUCTURES WILL BE MODELED USING BEAM, PLATE, SHELL AND SOLID FINITE ELEMENTS
- INHOUSE AND COMMERCIAL FEM CODES WILL BE USED

PRELIMINARY RESULTS FOR HUB USING 3D PLATE FEM

COARSE GRID
230 NODES
414 FE
1196 DOF



TYPICAL
STRUCTURAL
MODE AT 12KHz



By Guru Guruswamy

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Summary

- Unsteady SSME-rig1 one and half rotations are completed for 34.3 Million grid points model.
- Moving boundary capability is obtained by using DCF module.
- MLP shared memory parallelism has been implemented in INS3D, and benchmarked.
- 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.

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