Time-Dependent Simulations of Incompressible Flow in a Turbopump Using Ovreset Grid Approach

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Outline

- INTRODUCTION
  - Major Drivers of the Current Work
  - Objective
- SOLUTION METHODS
  - Summary of Solver Development
  - Formulation / Approach
  - Current Challenges
- PARALLEL IMPLEMENTATION
- UNSTEADY TURBOPUMP FLOW
- DISCUSSION

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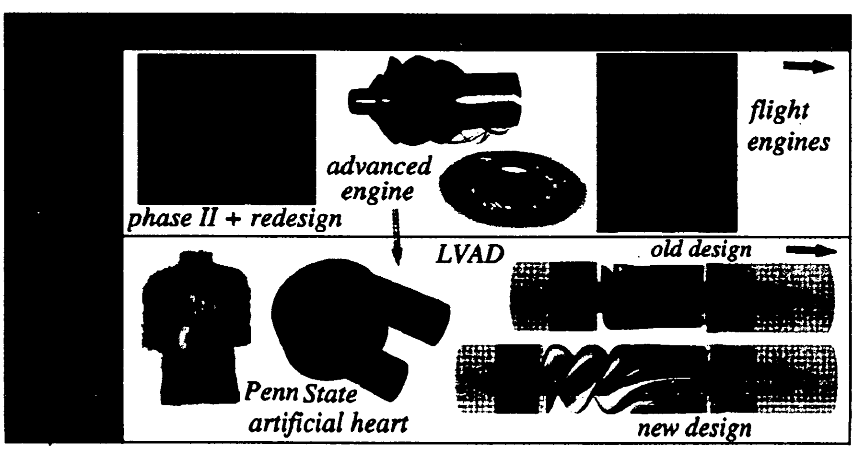
- To enhance incompressible flow simulation capability for developing aerospace vehicle components, especially, unsteady flow phenomena associated with high speed turbo pump.



INS3D - Incompressible N-S Solver

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** *Parallel version : Based on INS3D-UP*
- MPI and MLP parallel versions
- Structurel, 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

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

Time-Accurate Formulation

- Discretize the time term in momentum equations using second-order three-point backward-difference formula

$$\left(\frac{\partial U}{\partial \xi}+\frac{\partial V}{\partial \eta}+\frac{\partial W}{\partial \zeta}\right)^{n+1}=0 \qquad \frac{3q^{n+1}-4q^{n}+q^{n-1}}{2\Delta t}=-r^{n+1}$$

- 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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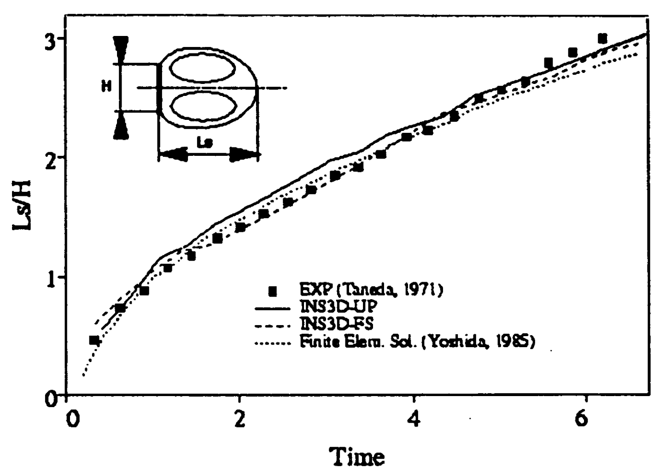
Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point



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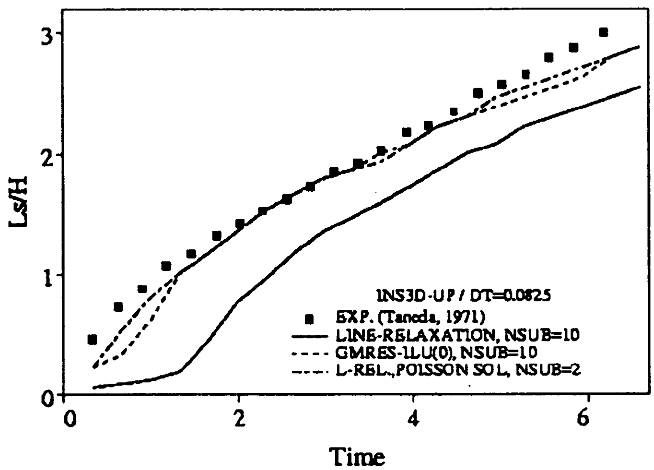
Impulsively Started Flat Plate at 90°

NASA

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



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Impulsively Started Flat Plate at 90°

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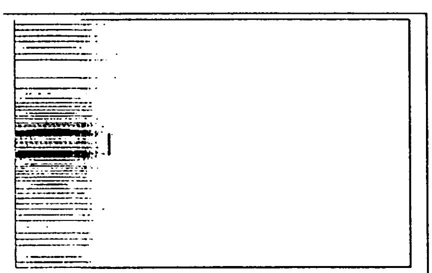
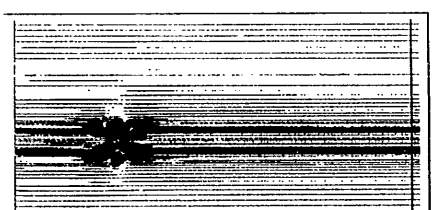
- VELOCITY VECTORS T=0.33

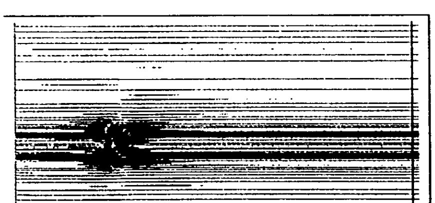
Flow is at rest and
U=1 imposed at inflow at T=0.0



INS3D-UP line-relaxation
10 subiteration at each time-step



INS3D-UP / GMRES-ILU
10 subiteration at each time-step



INS3D / line-relaxation
Poisson solver is incorparated
2 subiteration at each time-step

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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 such as
  - 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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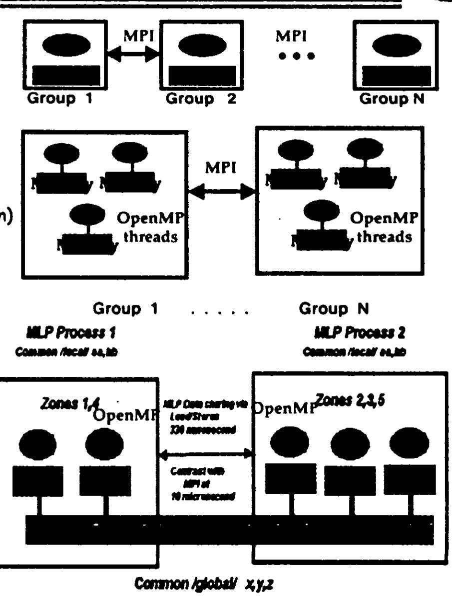
INS3D Parallelization

- 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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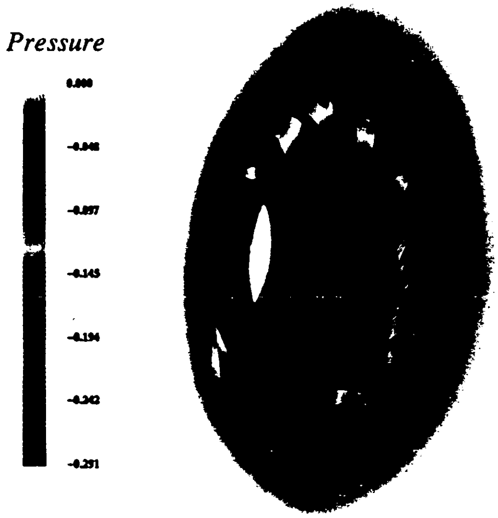

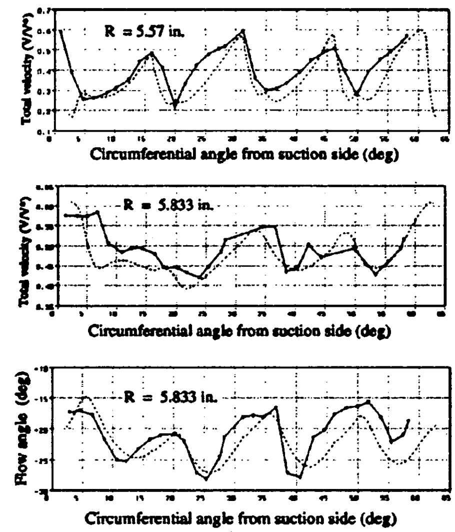

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RLV 2nd Gen Turbopump (SSME Rig1)

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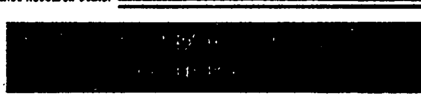

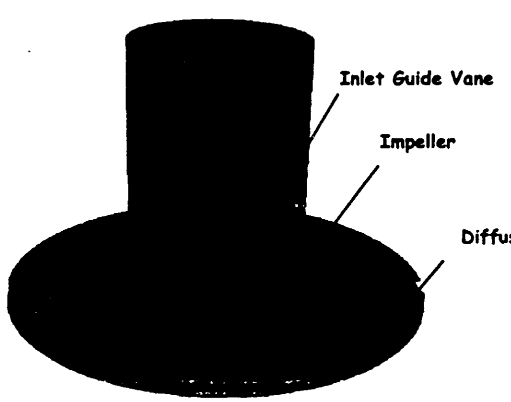

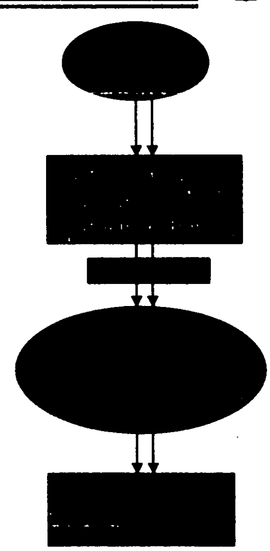

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INS3D Parallelization

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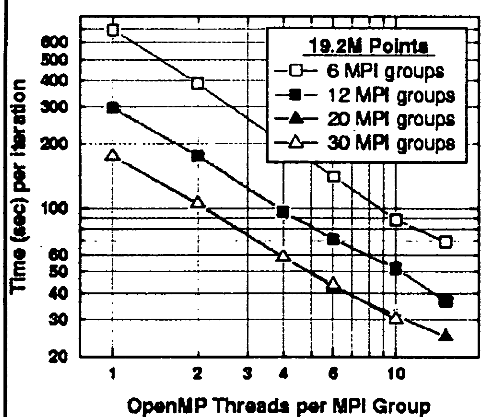
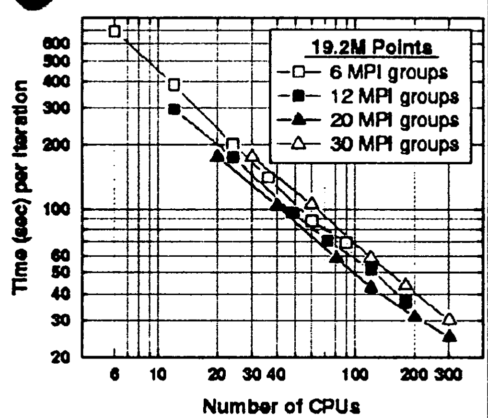
MPI coarse grain + OpenMP fine grain

TEST CASE : SSME Impeller
60 zones / 19.2 Million points





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INS3D Parallelization

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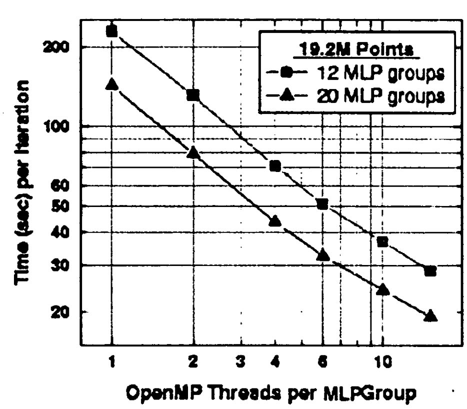
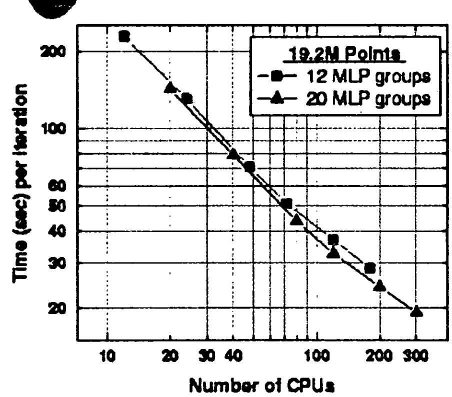
INS3D-MLP (NAS MLP no pin-to-node) / OpenMP

TEST CASE : SSME Impeller
60 zones / 19.2 Million points





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INS3D Parallelization

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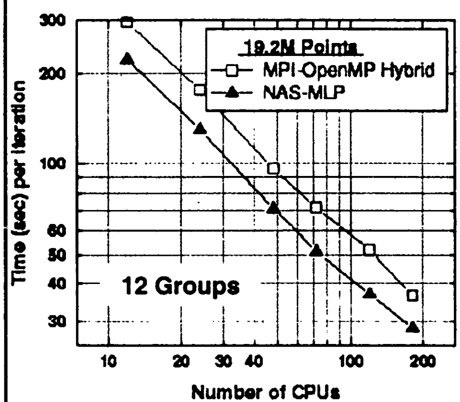
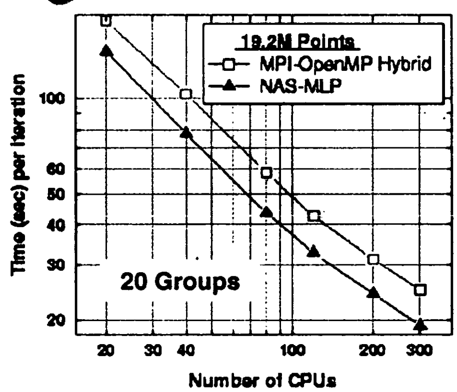
INS3D-MLP/OpenMP vs. -MPI/OpenMP

TEST CASE : SSME Impeller
60 zones / 19.2 Million points





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Parallel Implementation of INS3D

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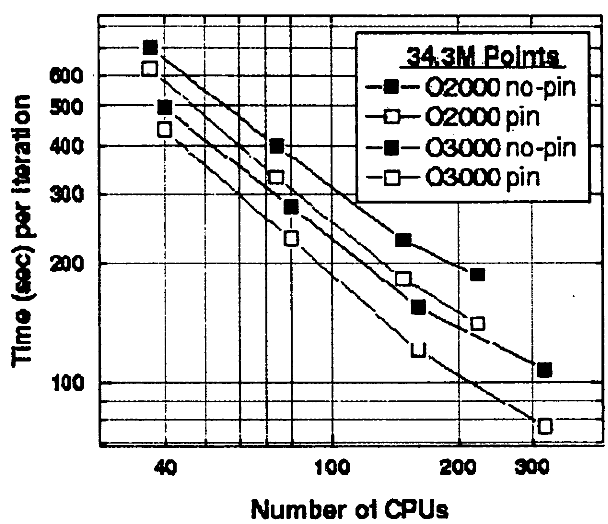
INS3D-MLP / 40 Groups

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



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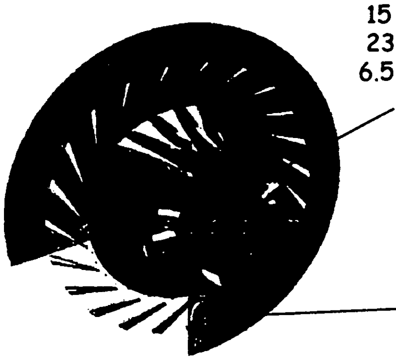
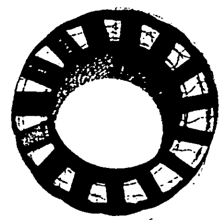
Shuttle Upgrade SSME-rig1

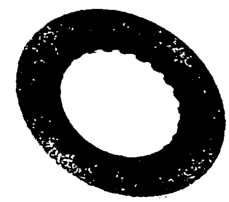
Overset Grid System



Inlet Guide Vanes
15 Blades
23 Zones
6.5 M Points



Diffuser
23 Blades
31 Zones
8.6 M Points



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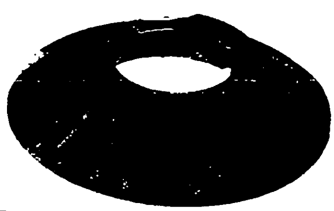
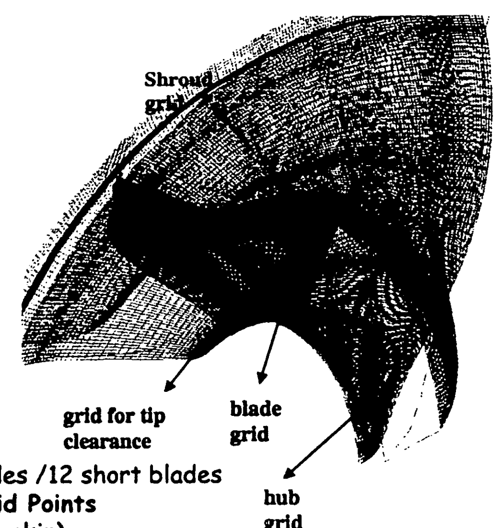
Shuttle Upgrade SSME-rig1





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.

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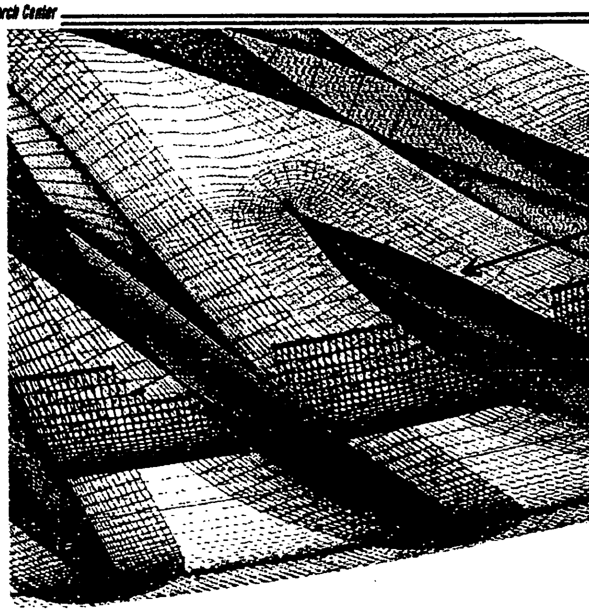
Impeller Overset Grid System



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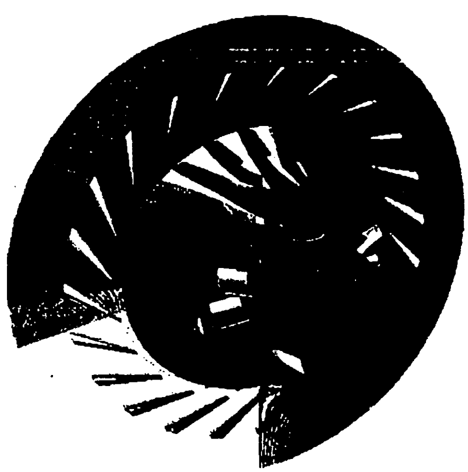
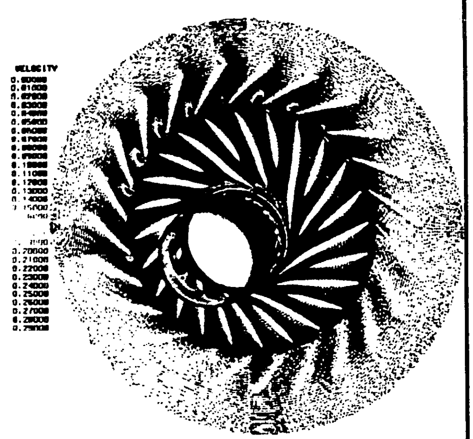
SSME-rig1/ Overset Grid System

Initial Start : flow at rest





Velocity vectors at first physical time step.
Impeller started at 10% actual rotational speed.

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SSME-rig1 / Initial start

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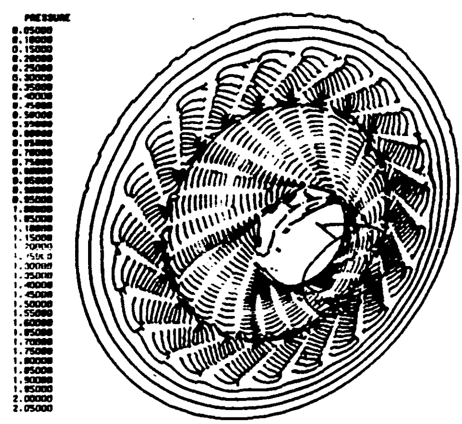
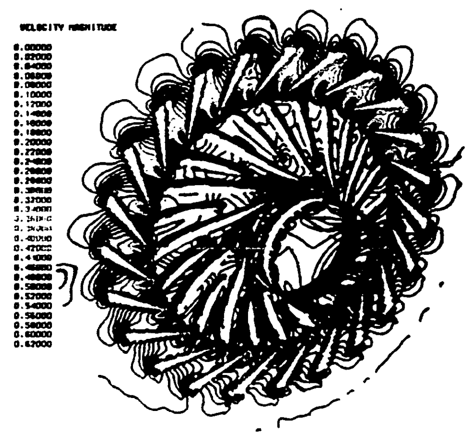
TIME STEP 5 / Impeller rotated 2.25-degrees at 10% of design speed





PRESSURE

VELOCITY MAGNITUDE

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SSME-rig1 / Initial start

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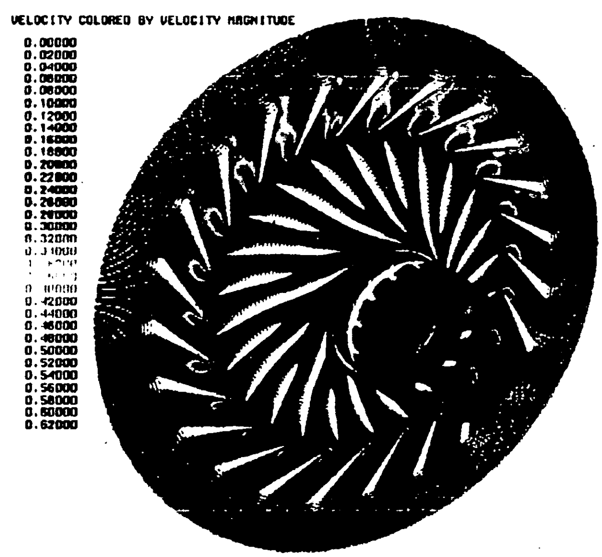
TIME STEP 5



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SSME-rig1 / Initial start

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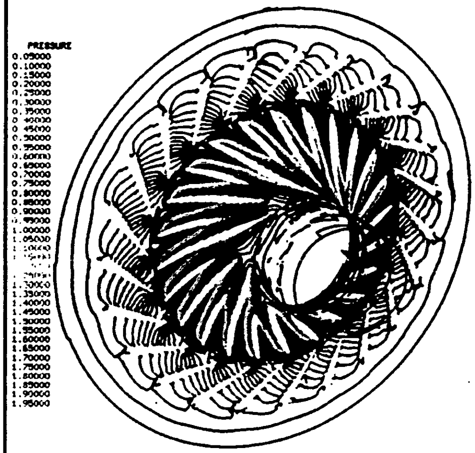
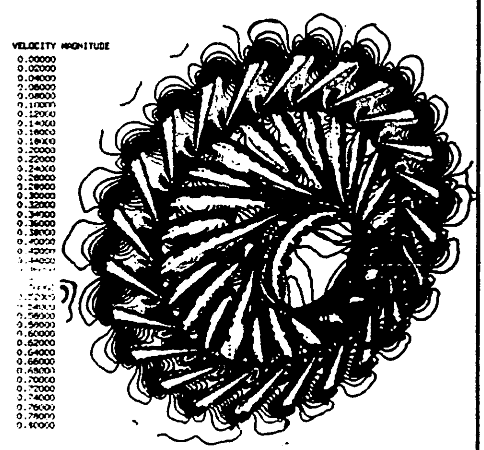
TIME STEP 7 / Impeller rotated 3-degrees at 30% of design speed





25 PRESSURE

VELOCITY MAGNITUDE

SSME-rig1 / Initial start

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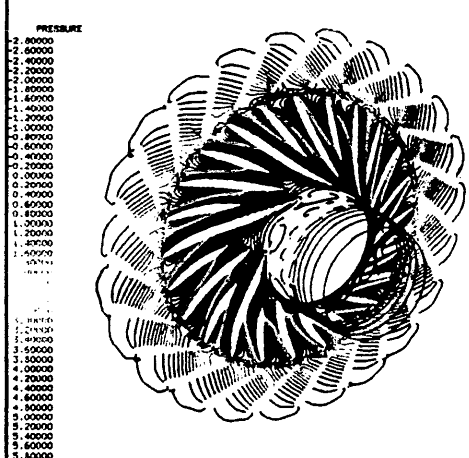
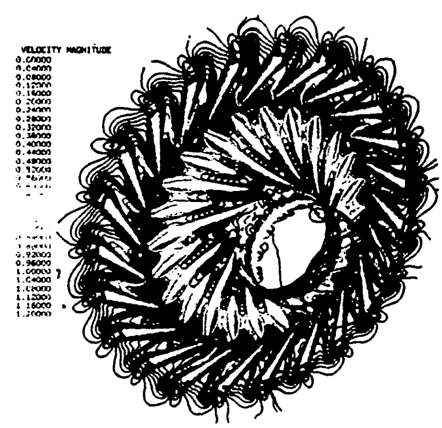
TIME STEP 18 / Impeller rotated 8-degrees at 100% of design speed





26 PRESSURE

VELOCITY MAGNITUDE

SSME-rig1 / Initial start

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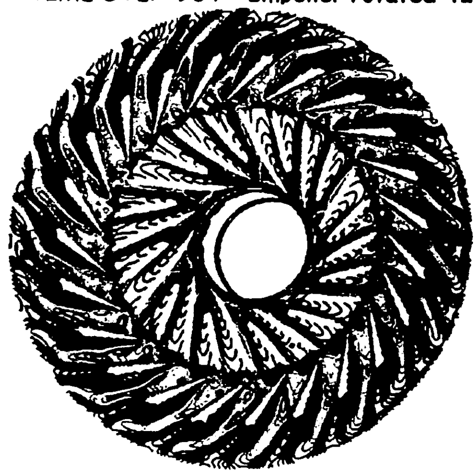
TIME STEP 96 / Impeller rotated 42-degrees



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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Summary

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- Unsteady SSME-rig1 start-up procedure from the pump at rest has been initiated by using 34.3 Million grid points.
- Computational model for the SSME-rig1 is completed. Moving boundary capability is obtained by using DCF module in OVERFLOW-D.
- MPI /Open MP hybrid parallel code has been benchmarked.
- MLP shared memory parallelism has been implemented in INS3D, and benchmarked.
- MLP/OpenMP version requires 19-25% less computer time than MPI/OpenMP version. Pin-to-node for MLP version is implemented. 40% less computer time is required in the new version.
- Time-accurate features of methods designed for 3-D applications are evaluated. An efficient solution procedure is obtained.

- Work currently underway
  - Unsteady SSME-rig1 simulations by using 34.3 Million grid points.
  - Experimental measurements at NASA-MSFC.

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