Time-Accurate Simulations of Incompressible Flows with Moving Boundaries

Cetin Kiris
Dochan Kwak
Stuart E. Rogers
NASA Ames Research Center

Workshop on Numerical Simulations of Incompressible Flows
June 19-21, 2001 Half Moon Bay, CA

1

Outline

- INTRODUCTION
  - Status
  - Major Drivers of the Current Work
- OBJECTIVE
- SOLUTION METHODS
  - Formulation / Approach
  - Summary of Solver Development
  - Current Challenges
- HEC APPLICATIONS
  - Parallel Implementation
  - Application to SSME Turbopump
- DISCUSSION

2

Status from Applications Point of View

Ames Research Center

- Applications to Real-World Problems
  - N-S solution of full configuration was a big goal in the 80s
  - Numerical procedures and computing hardware have been advanced enabling simulation of complex configurations
- Some Examples of Successful Applications
  - Components of liquid rocket engine
  - Hydrodynamics (Submarines, propellers, ...)
  - Ground vehicles (automobile aerodynamics, internal flows...)
  - Biofluid problems (artificial heart, lung, ...)
  - Some Earth Science problems
- Current Challenges
  - For integrated systems analysis, computing requirement is very large
    ⇒ Analysis part is still limited to low fidelity approach
  - For high-fidelity analysis, especially involving unsteady flow, long turn-around time is often a bottle neck ⇒ Acceleration of solution time is required

3

Major Drivers of Current Work

Ames Research Center

- 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

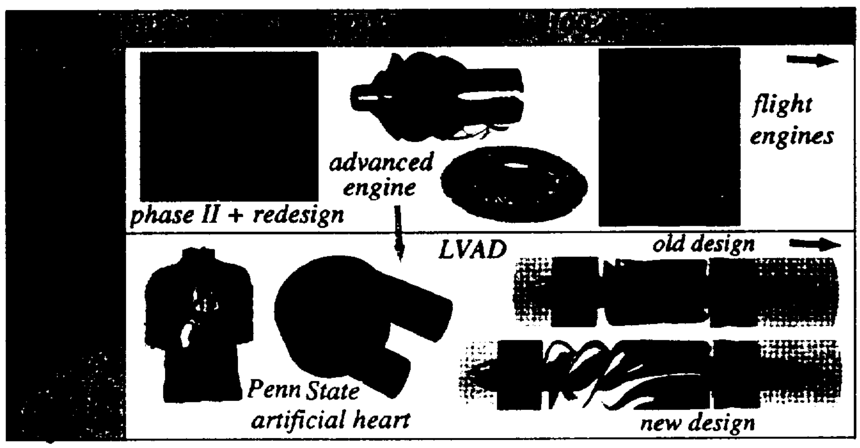
Turbo-pump component analysis ⇒ Entire sub-systems simulation

Computing requirement is large:
⇒The goal is to achieve 1000 times speed up over what was possible in 1992

4

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
- 3^{rd} and 5^{th}-order flux difference splitting for convective terms
- Central differencing for viscous terms
- One- and two-equations turbulence models
- Several linear solvers : GMRES, line-relaxation, LU-SGS, 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

6

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.

7

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.

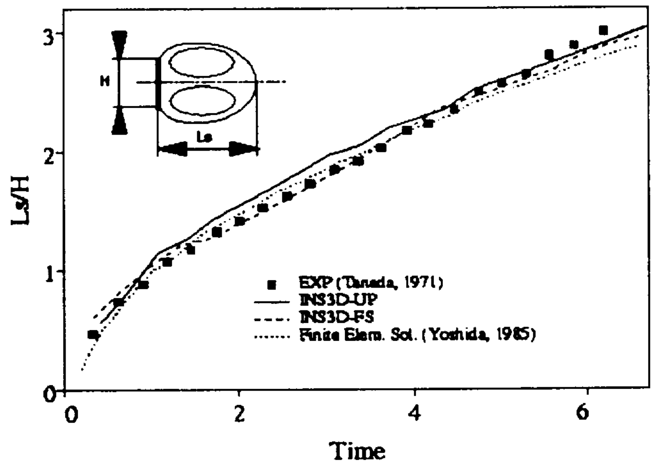
$$\frac{1}{\Delta \tau}(p^{n+1,m+1}-p^{n+1,m})=-\beta\nabla q^{n+1,m+1}$$

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

8

Impulsively Started Flat Plate at 90°

- Time History of Stagnation Point



Current Challenges

- Challenges where improvements are needed
  - Time-integration scheme, convergence
  - Moving grid system, zonal connectivity
  - Parallel coding and scalability

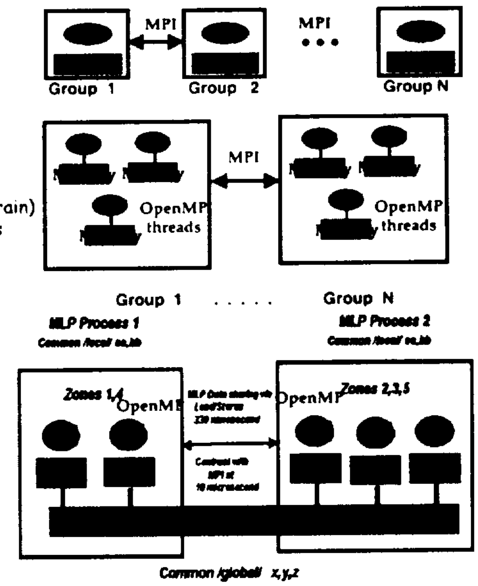
- As the computing resources changed to parallel and distributed platforms, computer science aspects become important such as
  - Scalability (algorithmic & implementation)
  - Portability, transparent coding etc.

- 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

10

INS3D Parallelization

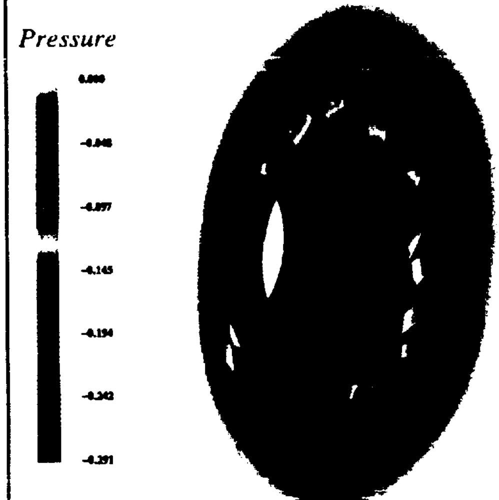
- INS3D-MPI
  (coarse grain)
  T. Faulkner & J. Dacles
- INS3D-MPI / Open MP
  MPI (coarse grain) + OpenMP (fine grain)
  Implemented using CAPO/CAPT tools
  H. Jin & C. Kiris
- INS3D-MLP
  C. Kiris

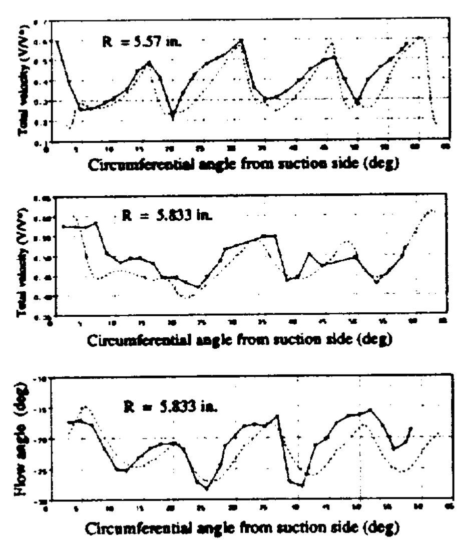


11

Previous Work (SSME Impeller)

Ames Research Center

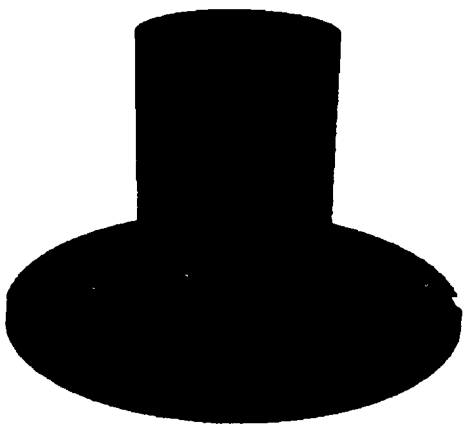




12

Space Shuttle Main Engine Turbopump

Ames Research Center



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

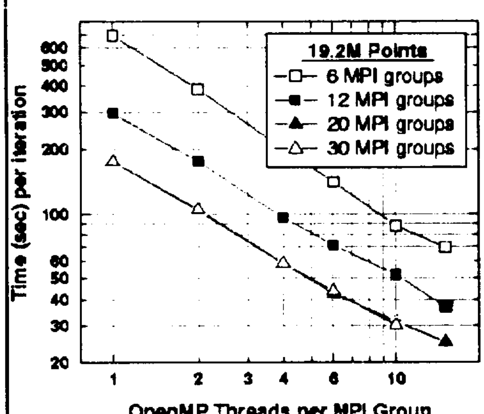
13

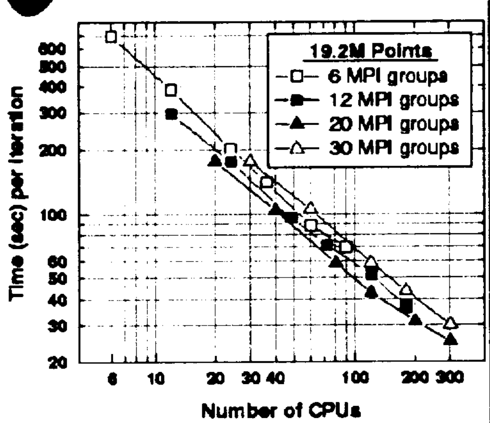
INS3D Parallelization

Ames Research Center

MPI coarse grain + OpenMP fine grain

TEST CASE : SSME Impeller
60 zones / 19.2 Million points



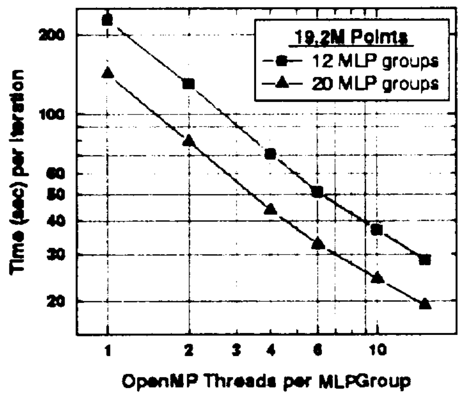


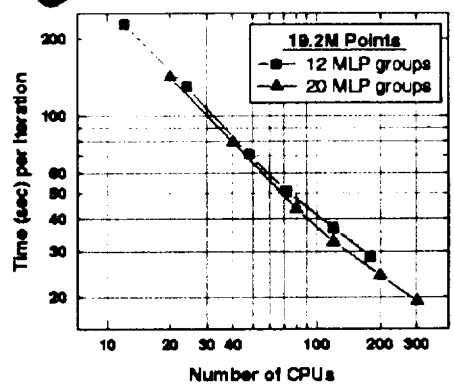
14

INS3D Parallelization

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

TEST CASE : SSME Impeller
60 zones / 19.2 Million points



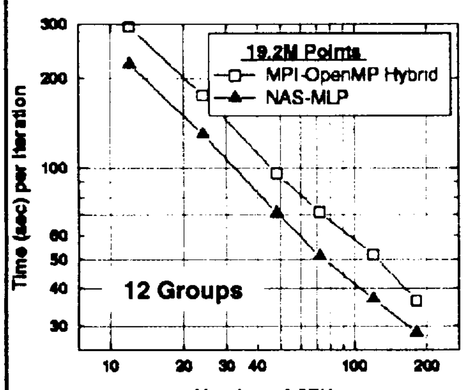


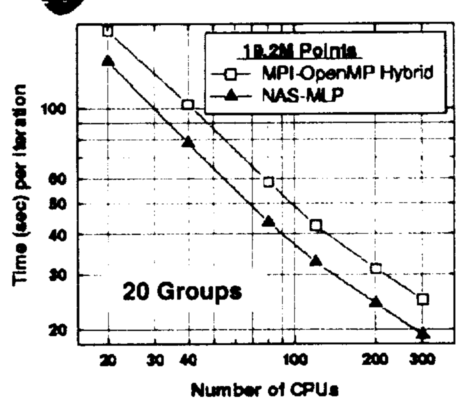
15

INS3D Parallelization

INS3D-MLP/OpenMP vs. -MPI/OpenMP

TEST CASE : SSME Impeller
60 zones / 19.2 Million points





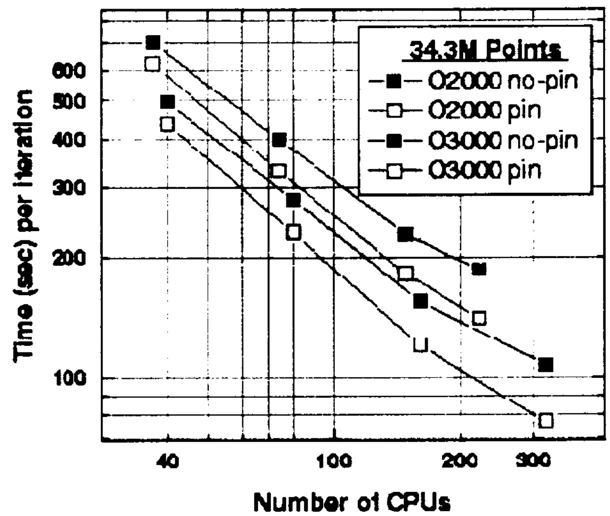
16

Parallel Implementation of INS3D

Ames Research Center

INS3D-MLP / 40 Groups

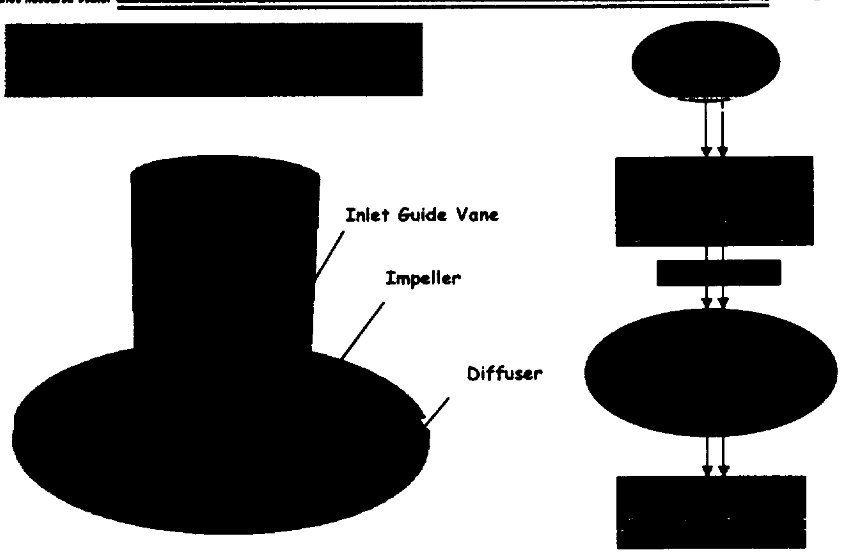
RLV 2nd Gen Turbo pump
114 Zones / 34.3 M grid points



17

RLV 2nd Gen Turbopump (SSME Rig1)

Ames Research Center

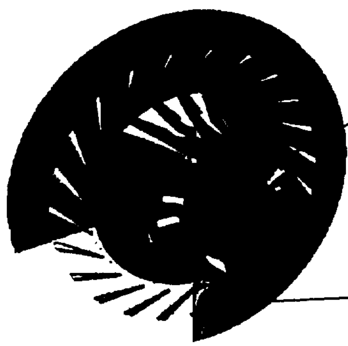


18

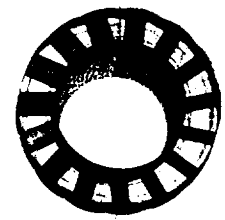
Shuttle Upgrade SSME-rig1

Ames Research Center

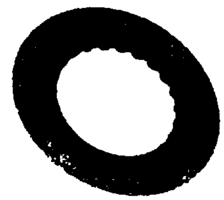
Overset Grid System



Inlet Guide Vanes
15 Blades
23 Zones
6.5 M Points



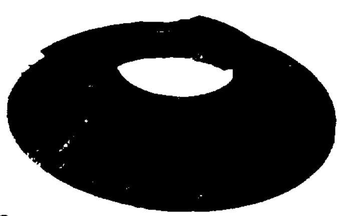
Diffuser
23 Blades
31 Zones
8.6 M Points

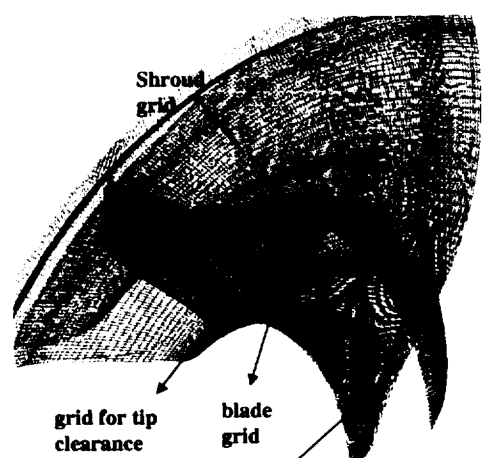


19

Shuttle Upgrade SSME-rig1

Ames Research Center





Unshrouded Impeller Grid :

6 long blades / 6 medium blades /12 short blades

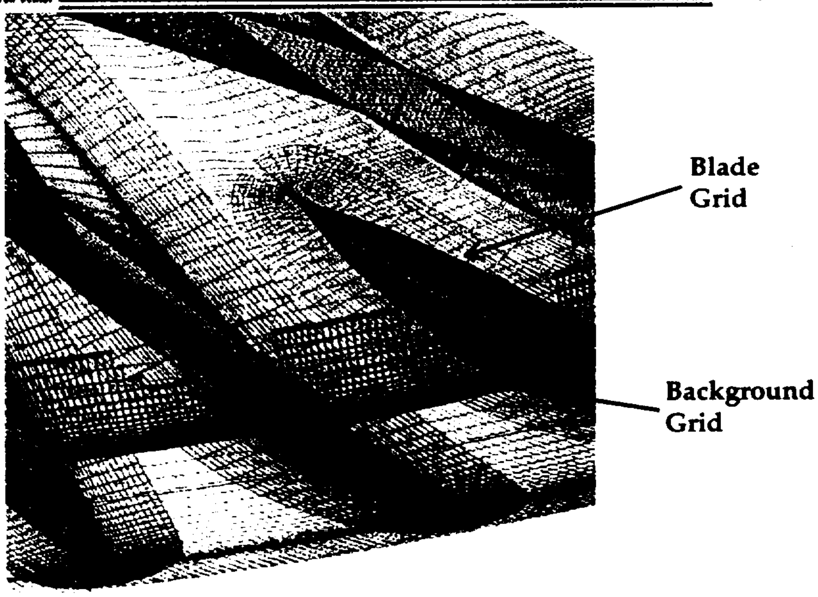
60 Zones / 19.2 Million Grid Points

Smallest zone : 75K /Largest zone : 996K **Overset connectivity : DCF (B. Meakin)**

Less than 156 orphan points.

20

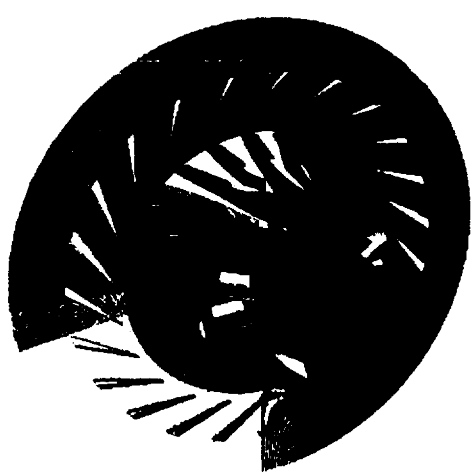
Impeller Overset Grid System

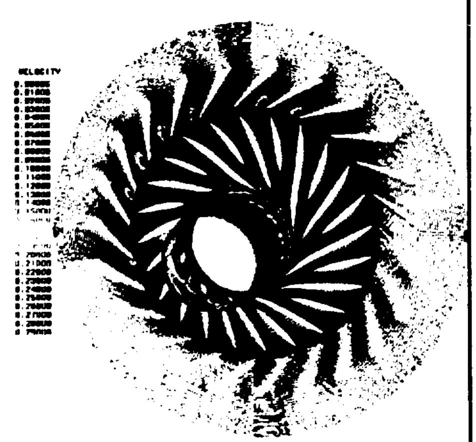


21

SSME-rig1/ Overset Grid System

Initial Start : flow at rest





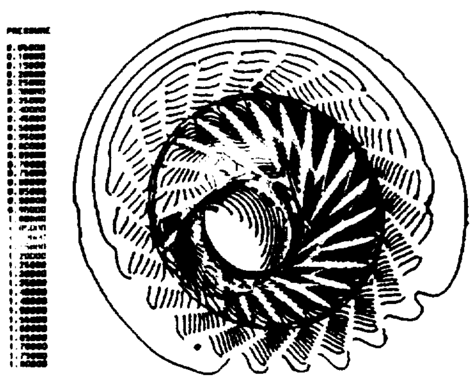
Velocity vectors at first physical time step.
Impeller started at 10% actual rotational speed.

22

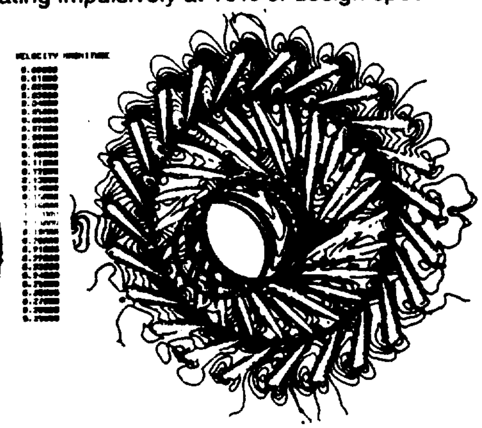
Ames Research Center

SSME-rig1 / Initial start

FIRST TIME STEP / Impeller starts rotating impulsively at 10% of design speed



PRESSURE



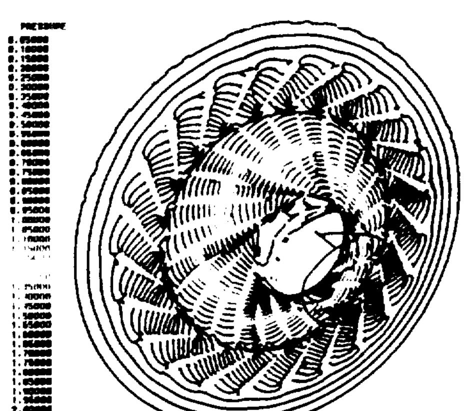
VELOCITY MAGNITUDE

23

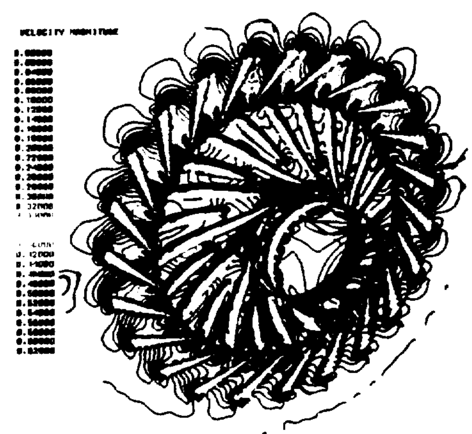
Ames Research Center

SSME-rig1 / Initial start

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



PRESSURE

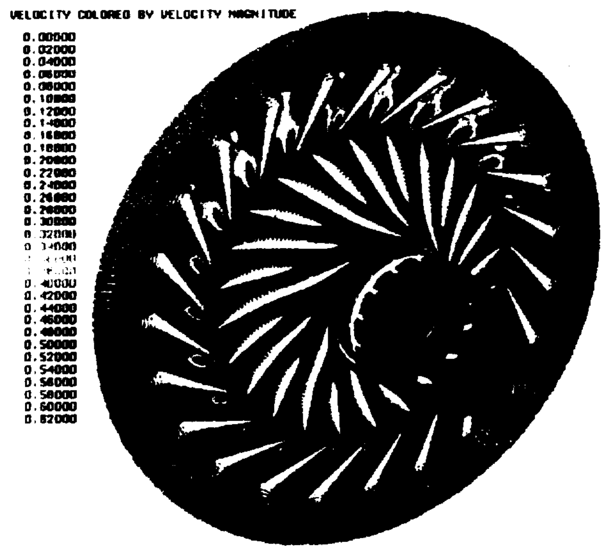


VELOCITY MAGNITUDE

24

SSME-rig1 / Initial start

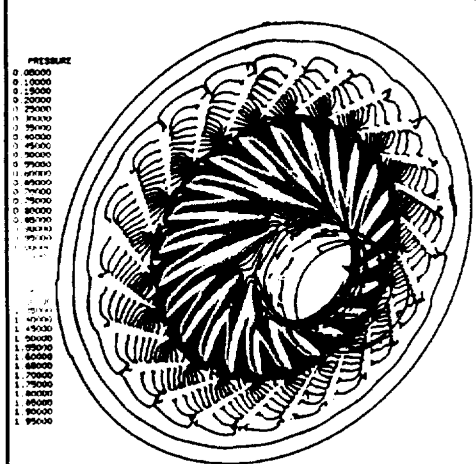
TIME STEP 5



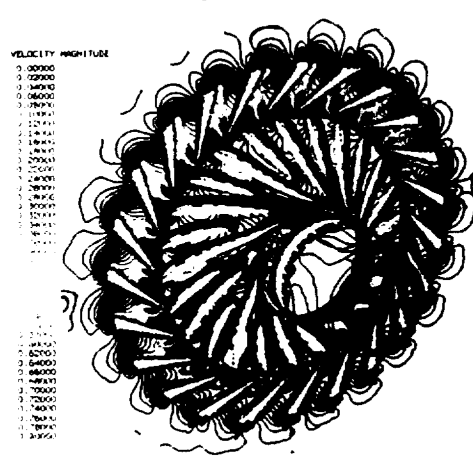
25

SSME-rig1 / Initial start

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



PRESSURE

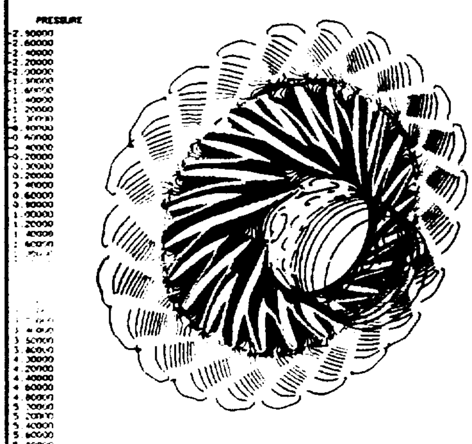


VELOCITY MAGNITUDE

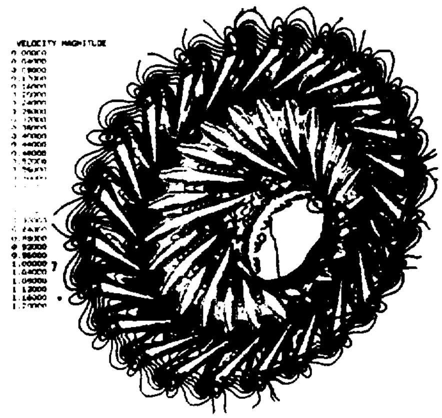
26

SSME-rig1 / Initial start

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



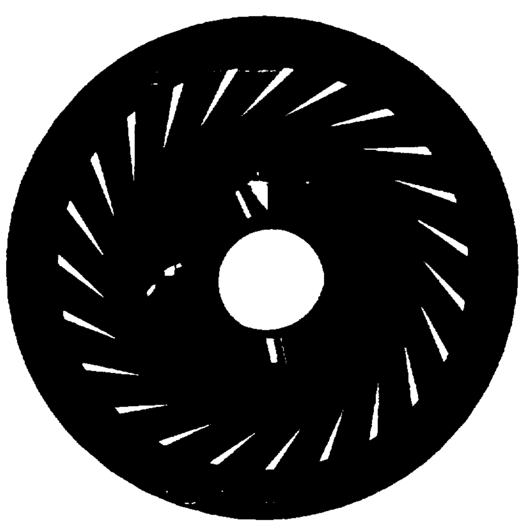
PRESSURE



VELOCITY MAGNITUDE

27

Shuttle Upgrade SSME-rig1



- **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.

28

Ames Research Center

Summary

NASA

- 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.

29