A THREE-DIMENSIONAL PARALLEL TIME-ACCURATE TURBOPUMP SIMULATION PROCEDURE USING OVERSET GRID SYSTEMS

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The objective of the current effort is to provide a computational framework for design and analysis of the entire fuel supply system of a liquid rocket engine, including high-fidelity unsteady turbopump flow analysis. This capability is needed to support the design of pump sub-systems for advanced space transportation vehicles that are likely to involve liquid propulsion systems. To date, computational tools for design/analysis of turbopump flows are based on relatively lower fidelity methods. An unsteady, three-dimensional viscous flow analysis tool involving stationary and rotational components for the entire turbopump assembly has not been available for real-world engineering applications. The present effort provides developers with information such as transient flow phenomena at start up, and non-uniform inflows, and will eventually impact on system vibration and structures. In the proposed paper, the progress toward the capability of complete simulation of the turbo-pump for a liquid rocket engine is reported. The Space Shuttle Main Engine (SSME) turbo-pump is used as a test case for evaluation of the hybrid MPI/Open-MP and MLP versions of the INS3D code. CAD to solution auto-scripting capability is being developed for tubopump applications. The relative motion of the grid systems for the rotor-stator interaction was obtained using overset grid techniques. Unsteady computations for the SSME turbo-pump, which contains 114 zones with 34.5 million grid points, are carried out on Origin 3000 systems at NASA Ames Research Center. Results from these time-accurate simulations with moving boundary capability are presented along with the performance of parallel versions of the code.

INTRODUCTION

Until recently, the high performance pump design process was not significantly different from that of 30 years ago. During the past 30 years a vast amount of experimental and operational experience has demonstrated that there are many important features of pump flows, which are not accounted for in the semi-empirical design process. Pumps being designed today are no more technologically advanced than those designed for the Space Shuttle Main Engine (SSME). During that same time span huge strides have been made in computers, numerical algorithms, and physical modeling.

Rocket pumps involve full and partial blades, tip leakage, and exit boundary to diffuser. In addition to the geometric complexities, a variety of flow phenomena are encountered in turbopump flows. These include turbulent boundary layer separation, wakes, transition, tip vortex resolution, three-dimensional effects, and Reynolds numbers effects. In order to increase the role of Computational Fluid Dynamics (CFD) in the design process, the CFD analysis tools must be evaluated and validated so that designers gain confidence in their use. As a part of extending the CFD technology to pump design work, INS3D code has been validated for pump component analysis using data from a rocket pump inducer, and pump impellers[1,2].

When rotating and stationary parts are included as shown in Figure 1, unsteady interactions between stationary and rotating components need to be included. To resolve the complex geometry in relative motion, an overset grid approach is employed in the current effort. In this approach, a geometrically complex body is decomposed into a number of simple grid components. In order to solve the entire configuration including inlet guide vanes, impeller blades, and diffuser blades, an overset grid system was constructed using 34.3 Million grid points with 114 zones. Since neighboring grids may overlap arbitrarily, these grids can be created independently from each other. Thus it is easier to generate high quality and nearly orthogonal grids using this approach. Connectivity between neighboring grids is established by interpolation at the grid outer boundaries. Addition of new components to the system and simulation of arbitrary relative motion between multiple bodies are achieved by establishing new connectivity without disturbing the existing grids.

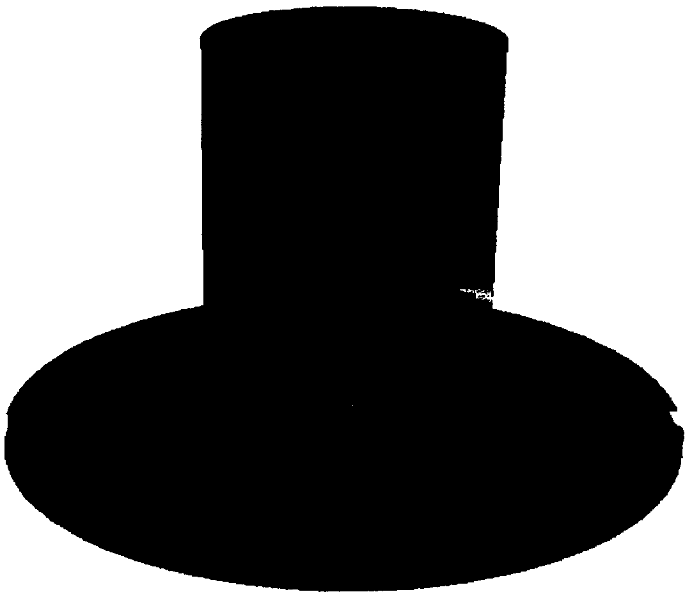

Figure 1. Geometry of a SSME pump including inlet guide vanes, impeller and diffuser blades.

NUMERICAL METHOD

The present computations are performed utilizing the INS3D computer code, which solves the incompressible Navier-Stokes equations for both steady-state and unsteady flows. The numerical solution of the incompressible Navier-Stokes equations requires special attention in order to satisfy the divergence-free constraint on the velocity field because the incompressible formulation does not yield the pressure field explicitly from the equation of state or through the continuity equation. One way to avoid the numerical difficulty originated by the elliptic nature of the problem is to use an artificial compressibility method, developed by Chorin[3]. The artificial compressibility algorithm, which introduces a time-derivative of the pressure term into the continuity equation; the elliptic-parabolic type partial differential equations are transformed into the hyperbolic-parabolic type. An incompressible flow solver, INS3D, has been developed [4] based on this algorithm. Since the convective terms of the resulting equations are hyperbolic, upwind differencing can be applied to these terms. The current version uses Roe's flux-difference splitting[5]. The third and fifth-order upwind differencing used here is an implementation of a class of high-accuracy flux-differencing schemes for the compressible flow equations. To obtain time-accurate solutions, the equations are iterated to convergence in pseudo-time for each physical time step until the divergence of the velocity field has been reduced below a specified tolerance value. The total number of sub-iteration required varies depending on the problem, time step size and the artificial compressibility parameter used, and typically ranges from 10 to 30 sub-iterations. The matrix equation is solved iteratively by using a non-factored Gauss-Seidel type line-relaxation scheme[6], which maintains stability and allows a large pseudo-time step to be taken. Details of the numerical method can be found in [4]. The GMRES scheme has also been utilized for the solution of the resulting matrix equation[7]. Computer memory requirement for the flow solver INS3D with line-relaxation is 35 times the number of grid points in words, and with GMRES-ILU(0) scheme is 220 times the number of grid points in words. When a fast converging scheme, such as a GMRES-ILU(0) solver, was implemented into the artificial compressibility method, previous computations showed that reasonable agreement was obtained between computed results and experimental data[8].

TURBOPUMP SCRIPTS

For each component of a turbopump (inlet guide vanes, impeller and diffuser), a script was developed to rapidly perform the various steps of the simulation process prior to the flow solver call. The starting point is the geometry definition of a component which consists of the hub and shroud profile curves and the surface panels of each distinct blade. Functions provided by the script include overset surface and volume grid generation, creation of object X-ray maps for hole-cutting [9], and creation of overset domain connectivity inputs. After running the domain connectivity program OVERFLOW-

D/DCF [10] with the script-created input file, the resulting grids and iblank connectivity information are used as input for the INS3D flow solver. Figure 2 illustrates the procedures automatically handled by the scripts. Important attributes of each component are parameterized in the scripts. For example, parameterized geometric attributes include the number of blades for the inlet guide vanes and the diffuser; and the number of distinct blades per section and the number of sections for the impeller. Parameterized grid attributes include hub and shroud surface grid spacings, leading and trailing edge spacings, viscous wall spacing for the volume grids, stretching ratios and marching distances for the hyperbolic surface and volume grids. All parameters are controlled via an input file and the script can be rapidly re-run to generate different configurations. For example, the user can input different geometry definitions for the hub, shroud and blades, try different number of blades and grid resolutions.

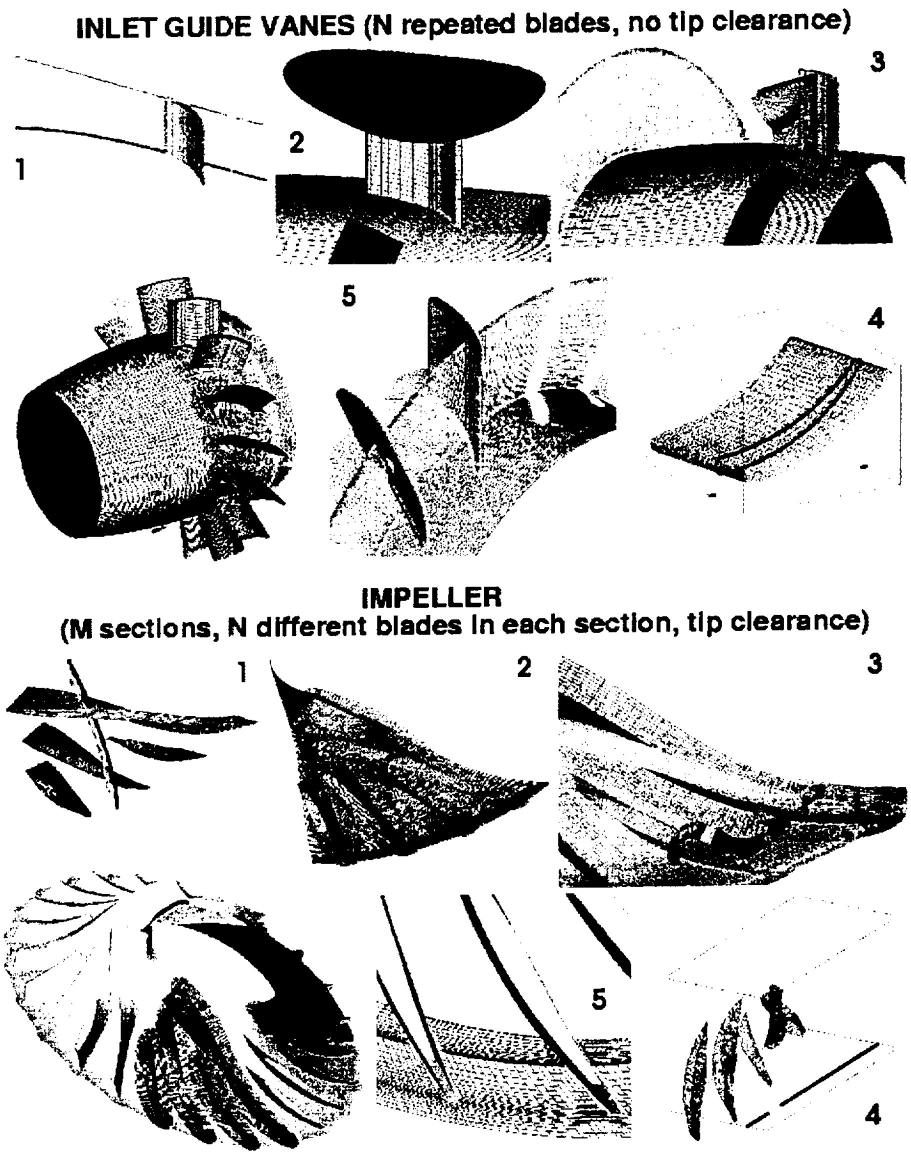

Figure 2. Illustration of turbopump scripts for inlet guide vanes and impeller sections.

A high level scripting language Tcl [11] is utilized which provides modularity as well as floating point arithmetic capability (unlike basic shell languages such as C-shell). Although extra time and expertise are needed to construct the scripts, the pay-off is well worth the effort. The advantages include the ability to rapidly re-run the entire process in just a few minutes versus one or more days of manual effort. Tedious repetitive error-prone inputs are avoided with the scripts while they also provide a documentation of the entire grid generation procedure. Grid refinement and parameter studies can also be easily and efficiently performed. Table 1 shows a comparison of the process time from geometry definition to domain connectivity inputs for the various turbopump components. Significant time savings is accomplished for generating a large number of different parameter studies as is frequently practiced in a design environment.

Inlet Guide Vanes	Manual	Script (coarse)	Script (fine)
No. of points (millions)	7.1	5.8	1.1
User time	1 day	43 sec.	20 sec.
Impeller	**Manual**	**Script (coarse)**	**Script (fine)**
No. of points (millions)	19.2	15.2	8.8
User time	2 weeks	319 sec.	234 sec.
Diffuser	**Manual**	**Script (coarse)**	**Script (fine)**
No. of points (millions)	8.0	6.4	1.6
User time	1 day	37 sec.	22 sec.

Table 1. Comparison of process time from geoemtry definition to domain connectivity inputs. User time for the manual process is the total wall clock time for working through the different parts of the process. User time for the scripts is the wall clock time to run the scripts on an R12000 300MHz Silicon Graphics workstation.

PARALLEL COMPUTATIONS

Parallel computing strategies vary depending on computer architecture such as memory arrangement relative to processing units. Two approaches have been implemented in the present study: the first approach is hybrid MPI/OpenMP and the second one is Multi Level Parallelism (MLP) developed at NASA-Ames Research Center. The first approach is obtained by using massage-passing interface (MPI) for inter-zone parallelism[12], and by using OpenMP directives for intra-zone parallelism[13]. INS3D-MPI[12] is based on the explicit massage-passing interface across MPI groups and is designed for coarse grain parallelism. The primary strategy is to distribute the zones across a set of processors. During the iteration, all the processors would exchange boundary condition data between processors whose zones shared interfaces with zones on other processors. A simple master-worker architecture was selected because it is relatively simple to implement and it is a common architecture for parallel CFD applications. All I/O was performed by master MPI process and data was distributed to the workers. After the initialization phase is complete, the program begins its main iteration loop. Figure 3 shows the MPI/OpenMP scalability for SSME impeller computations using 19.2 Million grid points.

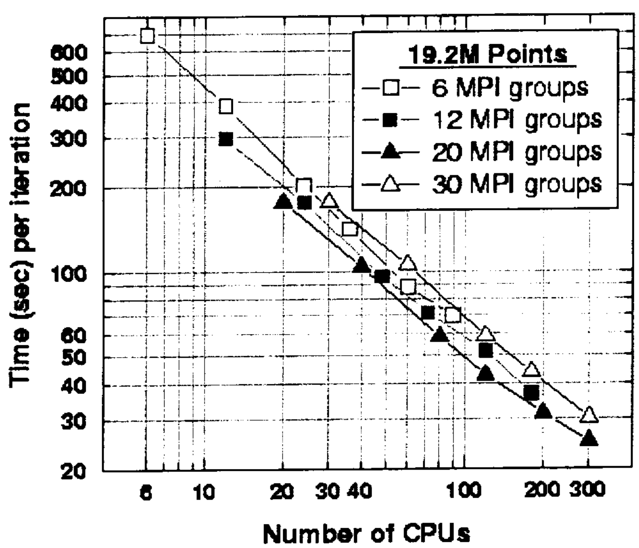

Figure 3. INS3D-MPI/OpenMP performance versus CPU counts on SGI Origin platform.

The second approach in Multi-Level Parallelism (MLP) is obtained by using NAS-MLP[14] routines. The shared memory MLP technique developed at NASA Ames Research Center has been incorporated into the INS3D code. This approach differs from the MPI/OpenMP approach in a fundamental way in that it does not use messaging at all. All data communication at the coarsest and finest level is accomplished via direct memory referencing instructions. This approach also provides a simpler mechanism for converting legacy code, such as INS3D, then MPI. For shared memory MLP, the coarsest level parallelism is supplied by spawning of independent processes via the standard UNIX fork. The advantage of the UNIX fork over MPI procedure is that the user does not have to change the initialization section of the large production code. Library of routines are used to initiate forks, to establish shared memory arenas, and to provide synchronization primitives. The shared memory organization for INS3D is shown in figure 4. The boundary data for the overset grid system is archived in the shared memory arena by each process. Other processes access the data from the arena as needed. Figure 5 shows the MLP scalability for SSME impeller computations using 19.2 Million grid points.

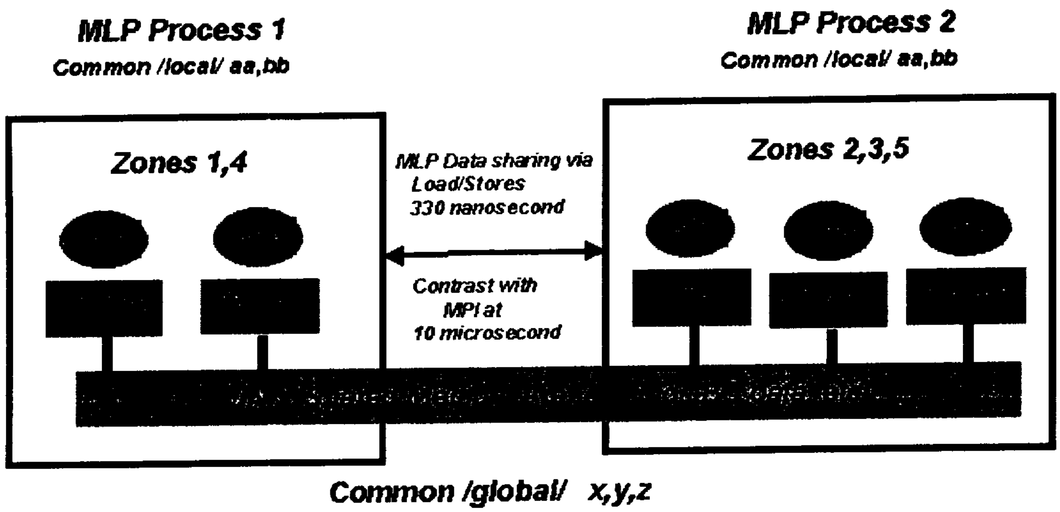

Figure 4. Shared memory MLP organization for INS3D-MLP.

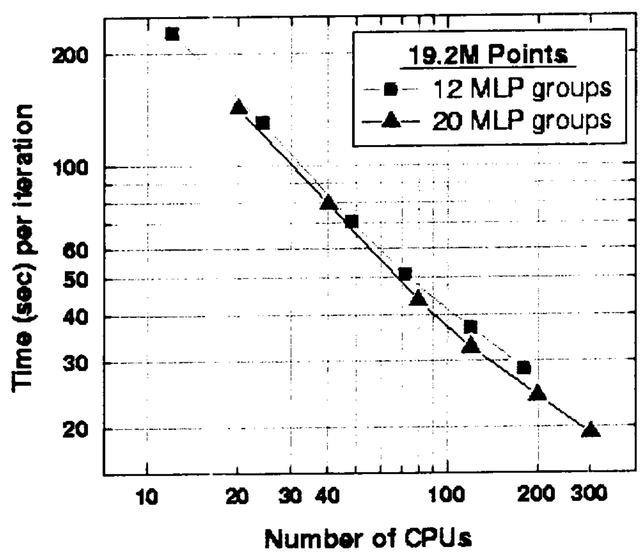

Figure 5. Time (sec) per iteration for, SSME impeller computations using INS3D-MLP on SGI Origin platforms.

Using INS3D-MLP parallel implementation, time-accurate computations for SSME-rig1 configuration have been carried out on SGI Origin 2000 and 3000 platforms. Instantaneous snapshots of particle traces and pressure surfaces from these computations are shown in Figure 6. This procedure provides flow-field details not readily available from experiments. The initial conditions for these simulations were the flow was at rest and the impeller started to rotate impulsively. Three full impeller rotations were completed in the simulations using 34.3 Million grid points. Using 128 SGI Origin 3000 CPU's, one impeller rotation was competed in less then 3.5 days. When 480 processors were used, one impeller rotation was completed in less than 1.5 days. One impeller rotation could be completed in 42 days in 1999. More than 30 times speed-up has been obtained over 1999 capabilities.

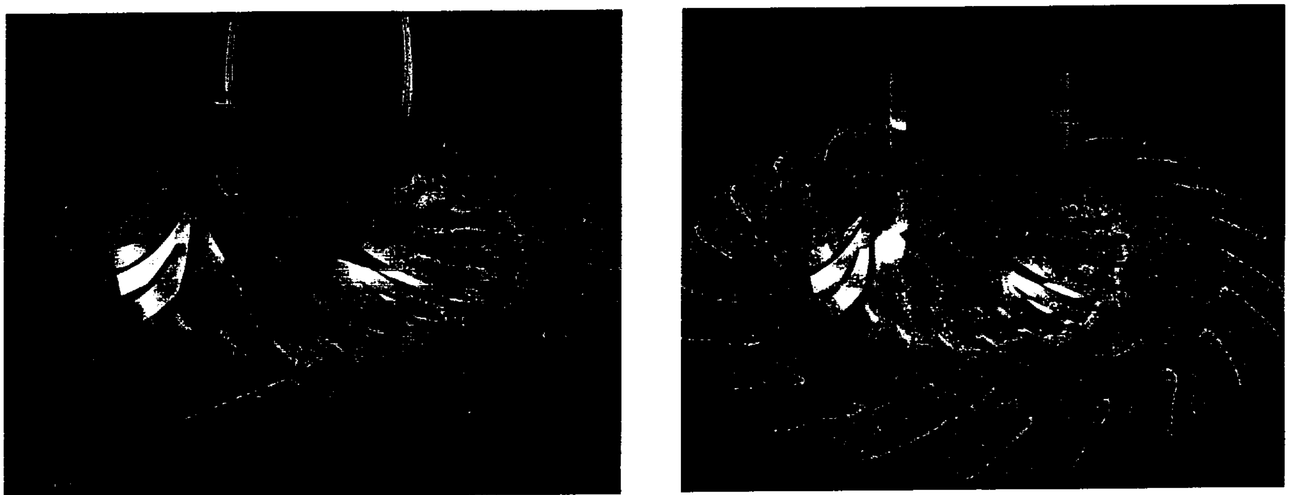

Figure 6. Snapshots of particle traces and pressure surfaces from unsteady turbopump computations.

SUMMARY

An incompressible flow solver in steady and time-accurate formulations has been utilized for parallel turbo-pump computations. Numerical procedures and turbopump scripts for rapid grid system generation and for overset connectivity input generation are outlined. Performance of the INS3D-MPI/OpenMP and INS3D-MLP versions of the flow solver for SSME impeller model are presented. Using INS3D-MLP parallel implementation, time-accurate computations for SSME-rig1 model, which includes 114 zones with 34.5 Million grid points, have been carried out on SGI Origin platforms. More than 30 times speed-up has been obtained over 1999 capability for these computations.

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A Three-Dimensional Parallel Time-Accurate Turbopump Simulation Procedure Using Overset Grid Systems

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Outline

- Introduction
- Scope of Present Work
- Computational Challenges
- Computational Technology for Rocket Pump
  - Flow Solver
  - Flow Simulation Procedure for Rocket Pump
- A Case Study
  - CFD Applications to Consortium Impeller
- Summary and Discussion

Introduction

Ames Research Center

- Turbopump
  - Liquid rocket engine is likely to be used for the next generation reusable launch vehicle
  - Efficient, reliable and cost-effective turbopump is a crucial element of the new propulsion system

    i.e. $10,000/lb ⇒ $1,000/lb payload

    Crew loss down to 1/10,000 mission
- Current Design Procedure
  - Existing method is semi-empirical, and no more technologically advanced than those for the Space Shuttle Main Engine (SSME)
  - During the past 30 years a vast amount of experimental and operational has been accumulated

Turbopump for Liquid Propulsion System: Space Shuttle Main Engine / Advanced Engine

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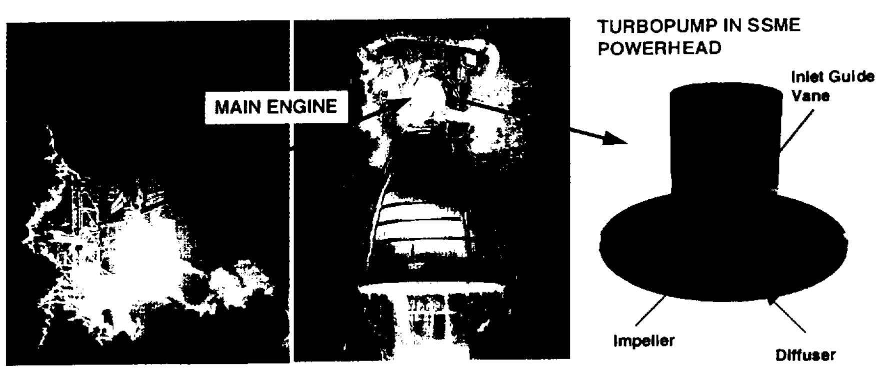

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Scope of Present Work

- Computational Approach
  - There are many important flow features not fully accounted for in earlier design processes
  - During the same period, huge strides have been made in computers, numerical methods/codes, and physical modeling

- Flow Simulation Challenges
  - Geometry is complex, including full and partial blades, tip clearance, high-speed impeller and stationary diffuser
  - Variety of flow phenomena are encountered such as boundary layer separation, transition, tip vortex, wake and cavitation

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Scope of Present Work

- Existing CFD Tools
  - There exist CFD tools for design and analysis primarily based on rotational-steady formulation

- Scope of Current Work
  - Current effort is focused on developing an unsteady, 3-D viscous flow analysis tool
  - Stationary and rotational components are included for simulating the entire turbopump assembly
  - Simulation time from a given geometry to solution is the main metrics
  - SSME turbopump is used for test

Computational Challenges

- Validation
  - Experimental data for time-dependant flow are rare
- Computational challenges
  - Time-integration scheme, convergence
  - Moving grid system, zonal connectivity
- Computer science

  As the computing resources are changed to parallel and distributed platforms, computer science aspects become important, such as
  - Parallel coding and 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

Flow Solver - INS3D

- 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.

Validation- Impulsively Started Flat Plate at 90°

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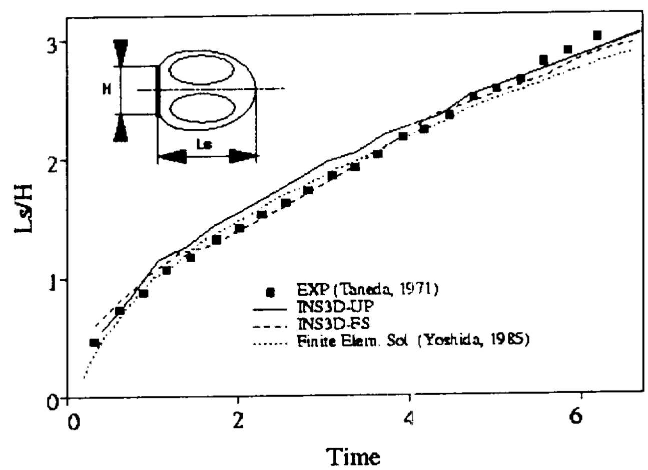
- Time History of Stagnation Point



Validation-SSME Turbopump Flow Analysis

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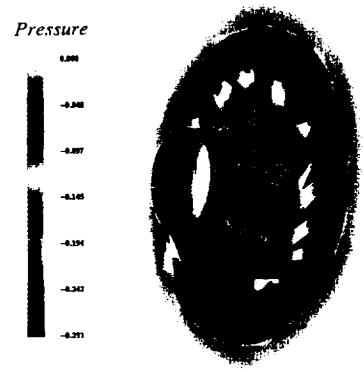
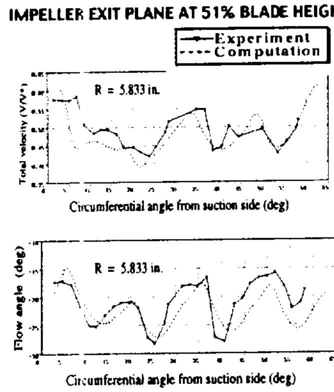
- SSME HPFTP 11' Impeller
  Shrouded impeller: 6 full blades, 6 long partials, 12 short partials 6322 rpm, Re=1.81x10^5 per inch

HUB SURFACE COLORED BY STATIC PRESSURE



COMPARISON WITH EXPERIMENTAL DATA

IMPELLER EXIT PLANE AT 51% BLADE HEIGHT



Parallel Implementation of INS3D

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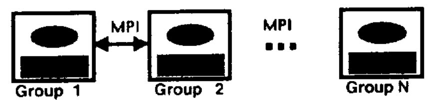
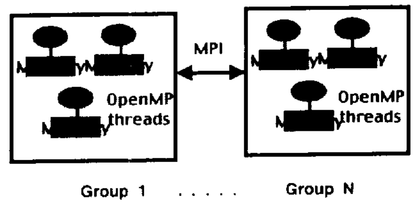
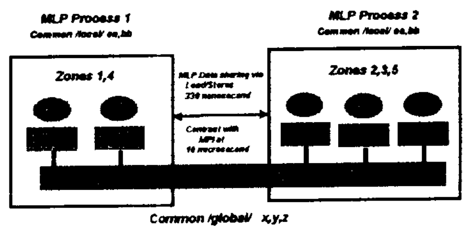
- INS3D-MPI
  (coarse grain)
  T. Faulkner & J. Dacles



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



- INS3D-MLP
  C. Kiris



Parallel Implementation of INS3D

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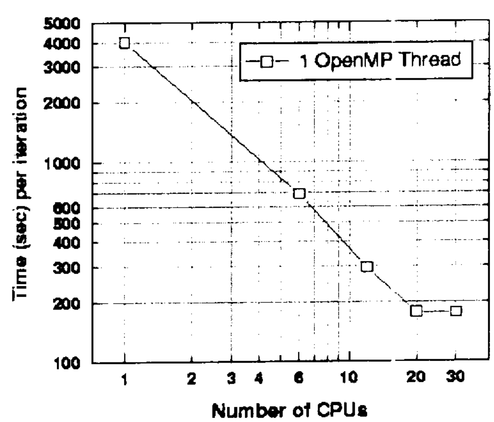
MPI coarse grain + OpenMP fine grain

TEST CASE : SSME Impeller
60 zones / 19.2 Million points



Parallel Implementation of INS3D

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MPI coarse grain + OpenMP fine grain

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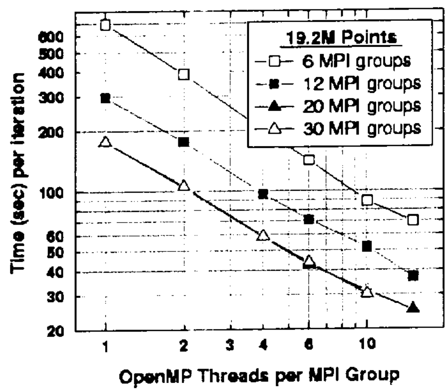

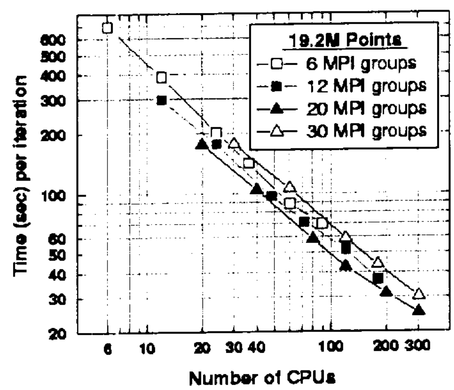

Parallel Implementation of INS3D

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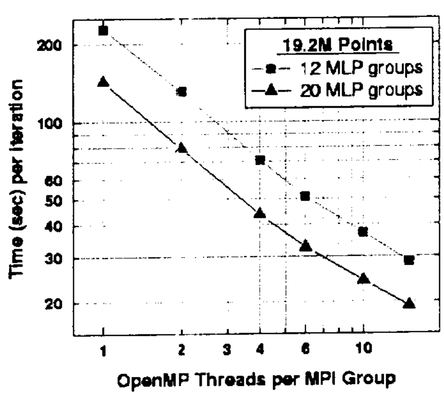
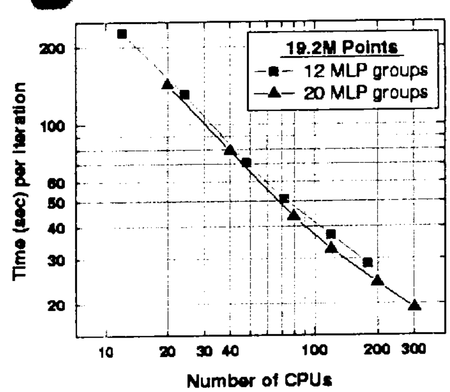
INS3D-MLP (NAS MLP no pin-to-node) / OpenMP

TEST CASE : SSME Impeller

60 zones / 19.2 Million points

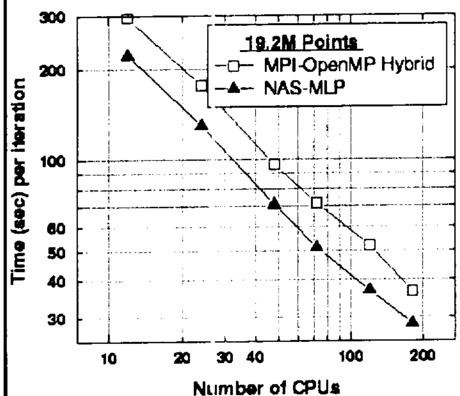


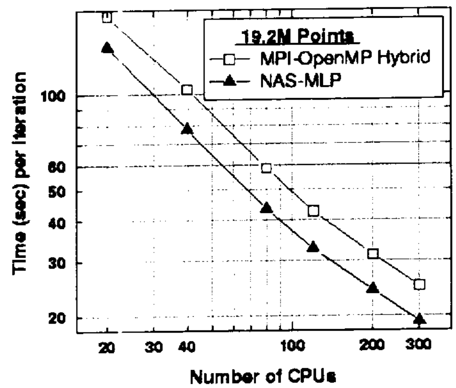


Parallel Implementation of INS3D

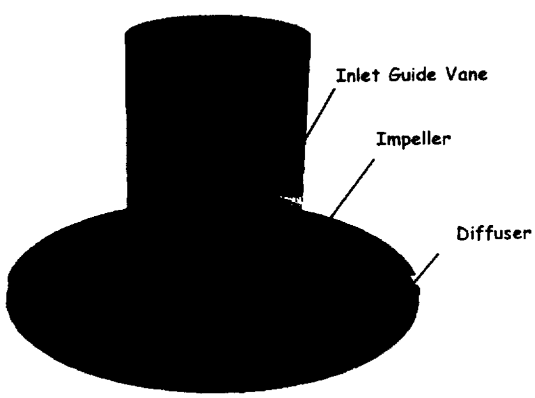
INS3D-MLP (NAS MLP no pin-to-node) / OpenMP

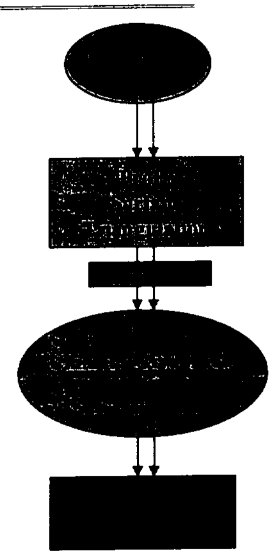
TEST CASE : SSME Impeller
60 zones / 19.2 Million points



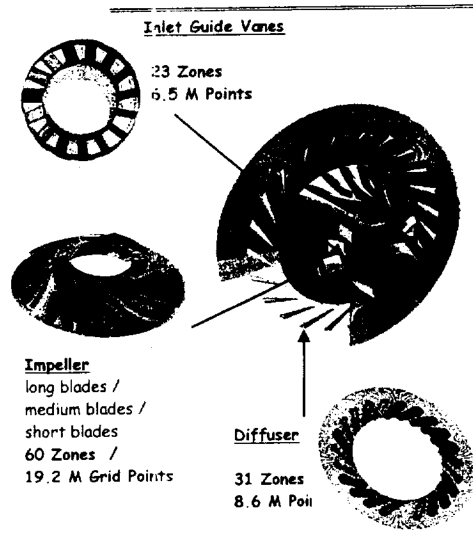


Space Shuttle Main Engine Turbopump





High-fidelity Simulation of 2nd Gen RLV Turbopump

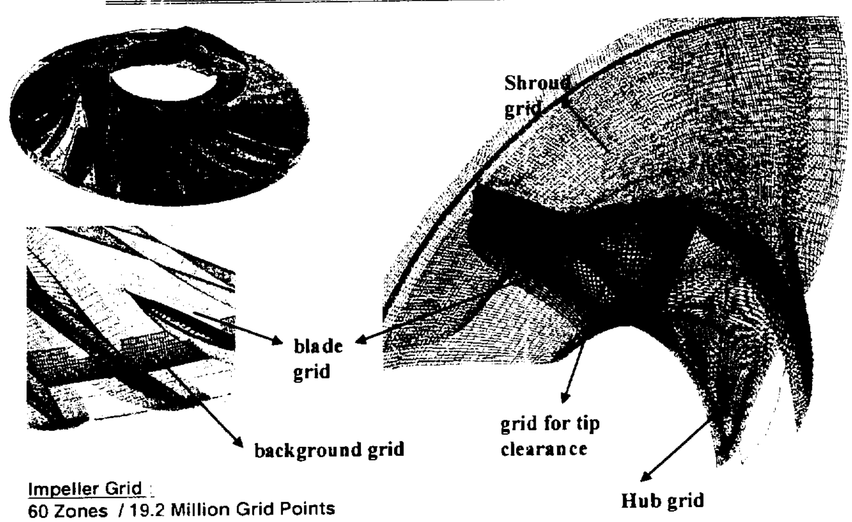


- Major Technical Issues
  - Pump codes exist, mostly in rotational frame of reference, for quick design analysis
  - Fully 3-D, transient capability is needed to advance pump technology

  To make a timely impact on turbopump systems development, wall-clock time from CAD to solution has to be short enough for design evaluation

⇒ CFD Need
- Rapid grid generation
- Accelerated solution time (parallel implementation)
- Large data set management in multiple sites (transmission and storage)
- Feature extraction tool

Shuttle Upgrade SSME-rig1



Impeller Grid :
60 Zones / 19.2 Million Grid Points
Smallest zone : 75K /Largest zone : 996K
Less than 156 orphan points.

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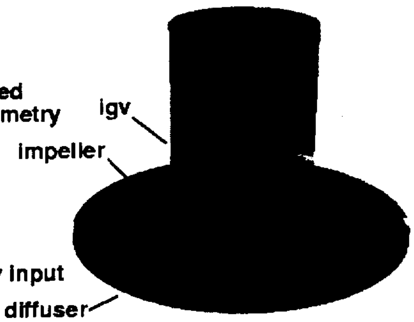
Scripting for Acceleration of Grid Generation

Motivation

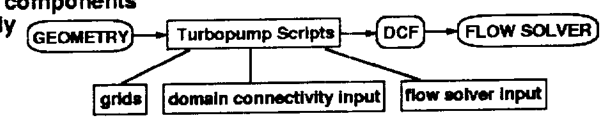
Significant user's effort needed in complex process from geometry to flow solver



Objective

Develop script system to
- generate grids
- create domain connectivity input
- create flow solver input

for different components automatically



Approach

Develop one script for each component with ring interface between components => easy plug in for different designs and combinations of components

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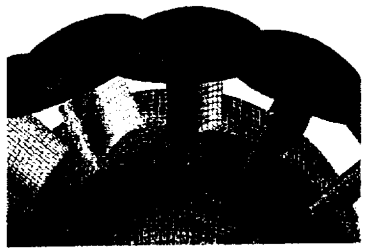
Scripting for Acceleration of Grid Generation

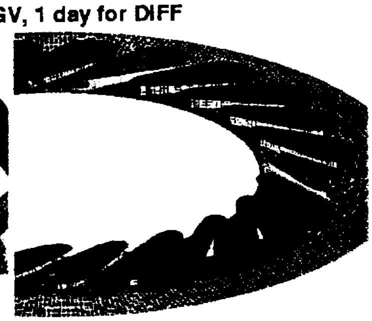
INLET GUIDE VANES AND DIFFUSER

	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

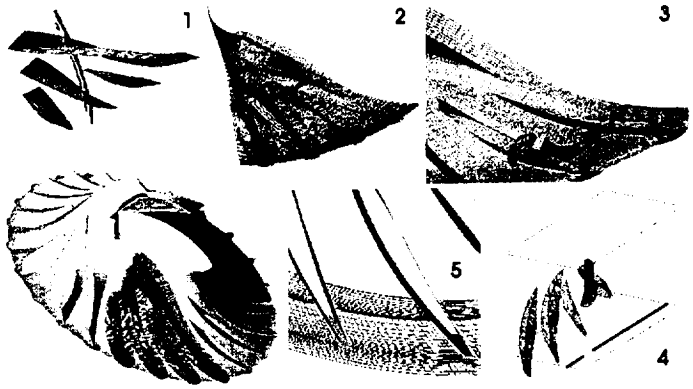
Time to build script = 1 day for IGV, 1 day for DIFF





Scripting for Acceleration of Grid Generation

IMPELLER
(M sections, N different blades in each section, tip clearance)

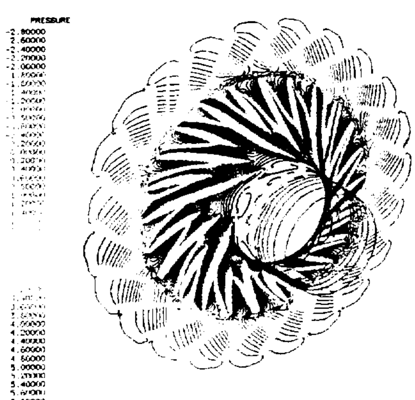


	Manual	Script (fine)	Script (coarse)
No. of pts (million)	19.2	15.2	8.8
User time *	~ 2 weeks	319 sec.	234 sec.

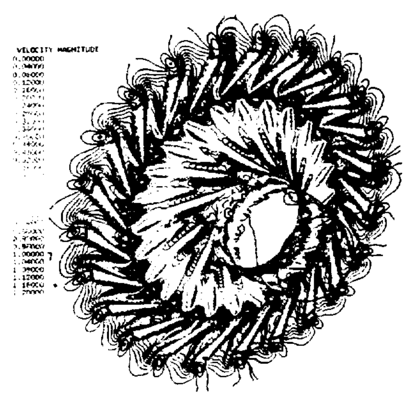
(* from geometry def. to DCF input with SGI R12k 300MHz CPU)

SSME-rig1 / Initial start

Time Step 13: Impeller rotated 8-degrees at 100% of design speed



PRESSURE



VELOCITY MAGNITUDE

SSME-rig1 / Initial start

After 2 1/2 rotation:

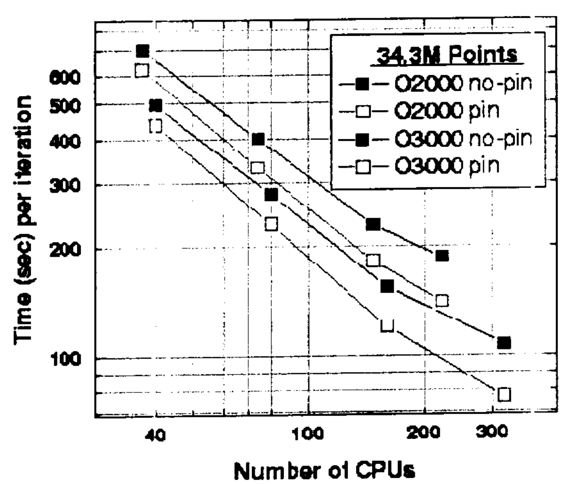
Particle Traces and Pressure

- Status
  - 34.3 Million Points
  - 400 physical time steps in one rotation.
  - One physical time-step requires less then 12 minutes wall time with 128 CPU's on Origin platforms. One complete rotation requires 3.5-days wall-clock time with 128 processors dedicated to the task.
  - I/O and memory management are critical for wall-clock time reduction
- Issues / Needs
  - In reality, more than 10% of the supercomputing facility to one task is not always practical.
  - Need 100x bigger supernode or use lower-fidelity method
  - Commun cation to/from designers and experimental group is a part of critical technologies (in Grid computing)

Parallel Implementation of INS3D

INS3D-MLP / 40 Groups

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



**Per processor Mflop is between 60-70.
Code optimization for cache based platforms is currently underway.
Target Mflops is to reach 120 per processor.
Increasing number of OpenMP threads is also the main objective for this effort.**

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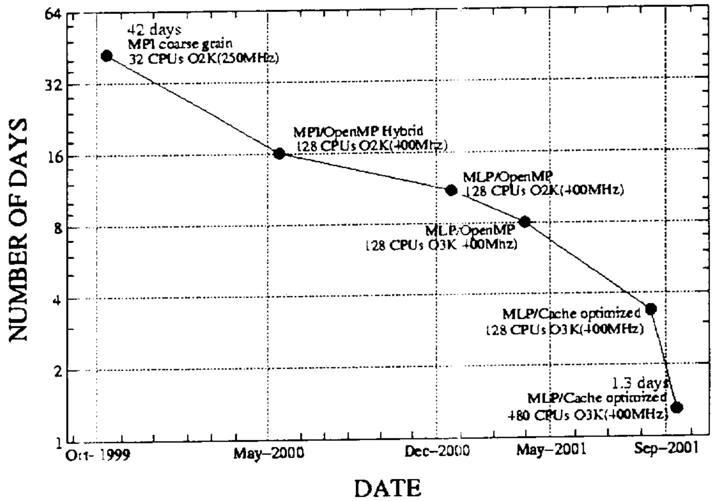
RLV Turbopump

34.3 Million Grid points RLV Turbopump one impeller rotation



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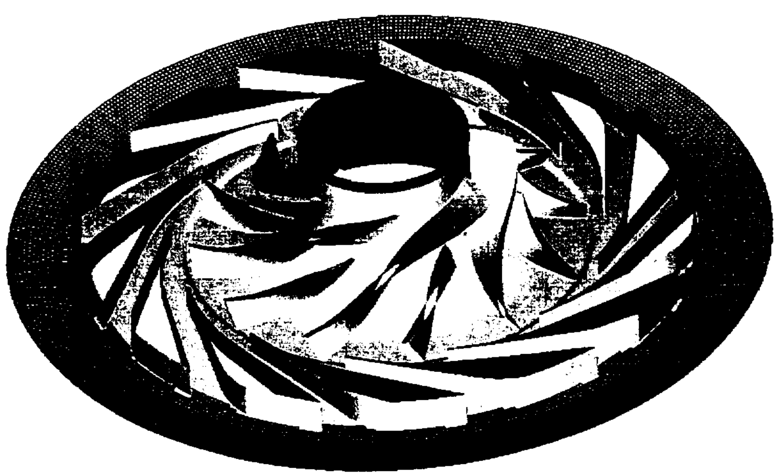
Test Case 1 : Consortium Impeller-Diffuser

-Geometry and operating conditions obtained on January 24, 2002

-Impeller : long blades and short blades, + Diffuser



Test Case 1 : Consortium Impeller-Diffuser

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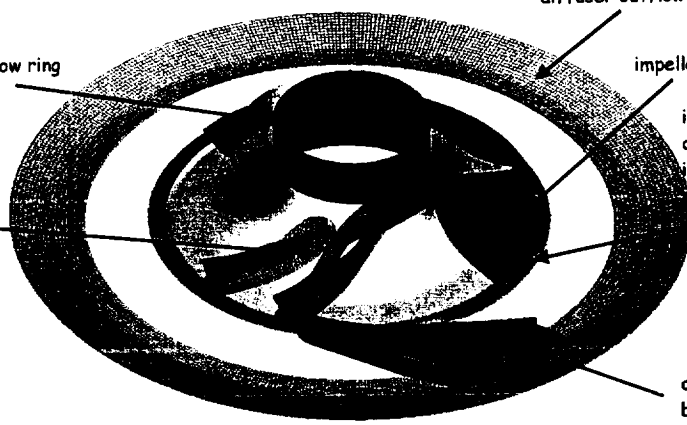
-Rotational speed :6322 RPM / Mass Flow Rate : 1210 gallons/min.
-Re : 1.37×10^7 / L_{ref} = 4.5225 inches, $V_{ref} = V_{tip}$ = 249.5 ft/sec
-39 Million grid points / 41 zones in overset grid systems



Test Case 1 : Consortium Impeller-Diffuser

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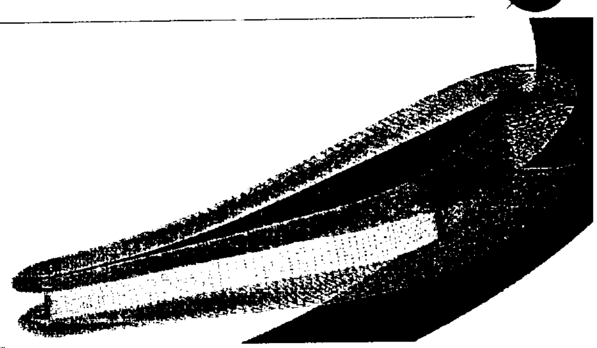

diffuser blade collar grids

impeller blades collar grids

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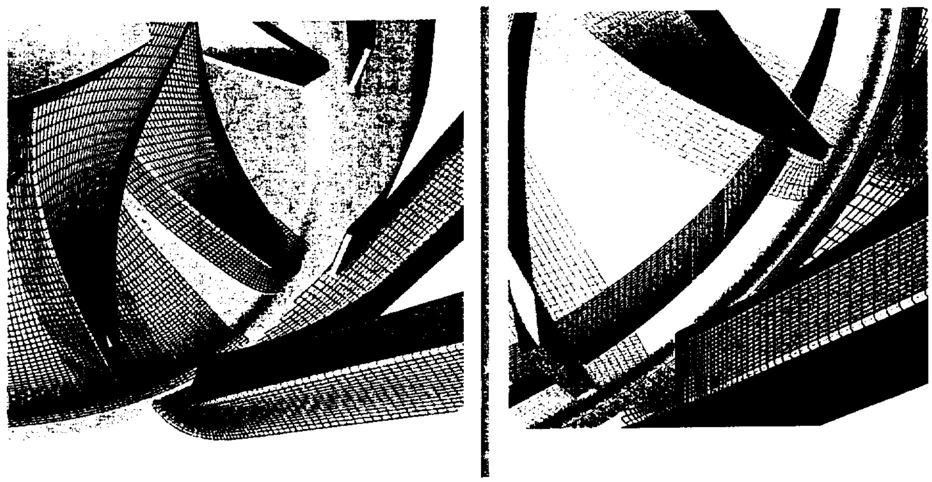
Test Case 1 : Consortium Impeller-Diffuser



Impeller - diffuser interaction

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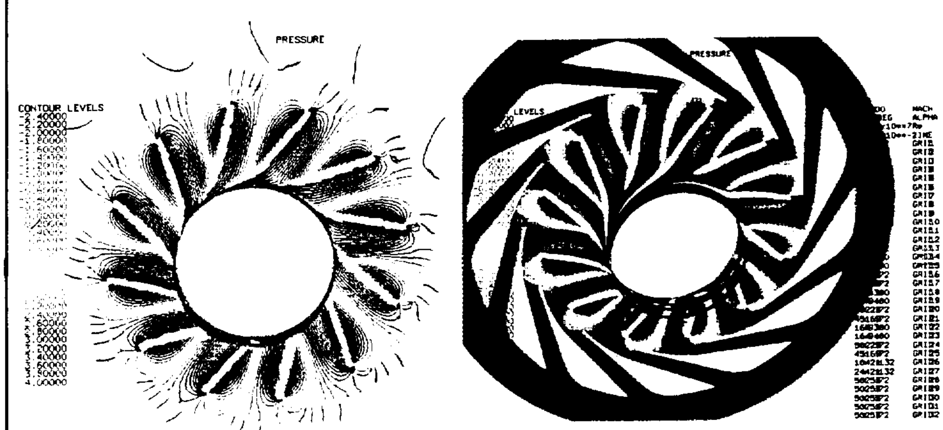
Test Case 1 : Consortium Impeller-Diffuser

INITIAL START / Impeller started rotating at design speed

pressure contours and surfaces



Test Case 1 : Consortium Impeller-Diffuser

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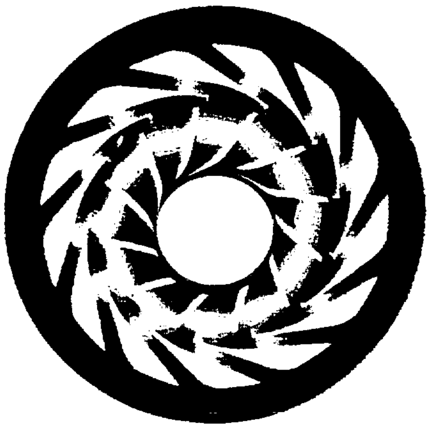
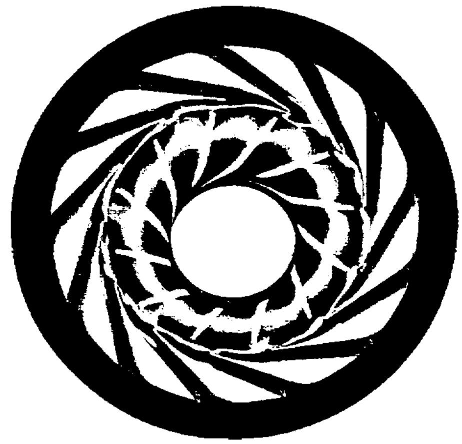
First Rotation : Impeller rotated 90 degrees.

pressure surfaces



total velocity surfaces



Test Case 1 : Consortium Impeller-Diffuser

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First Rotation : Impeller rotated 360 degrees.

pressure surfaces

total velocity surfaces

Test Case 1 : Consortium Impeller-Diffuser

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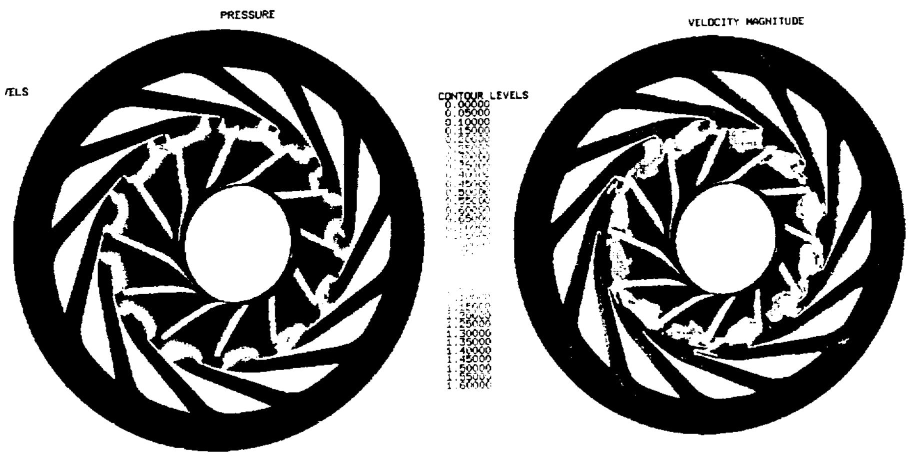
Second Rotation : t/T = 1.2

pressure surfaces

total velocity surfaces



Summary

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- Three-dimensional unsteady flow simulation procedure has been developed for turbopump in liquid propulsion system
  - MPI/OpenMP hybrid parallelism, and MLP shared memory parallelism has been implemented in incompressible flow solver, INS3D
  - Scripting capability from CAD geometry to solution has been developed and evaluated for two different configurations
  - Unsteady flow computations for RLV 2nd Gen baseline turbopump are performed by using 34.3 Million grid points model
    ⇒ more than 30 times speed-up has been obtained over 1999 baseline
- Future work
  - Unsteady validation and design applications are in progress