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Blood Pump Development Using Rocket Engine Flow Simulation Technology

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by

Robert Benkowski of MicroMed Technologies, Inc.

Outline of Talk

- Introduction / Motivation
- Mechanical Heart Assist Devices
  - Computational Issues and Requirements
  - Pulsatile Device
  - Axial Flow Pump
- Computational Technology for Rocket Pump
  - Flow Solver Development
  - Flow Simulation Procedure for Rocket Pump
- Computational Approach for VAD Development
  - CFD Applications to Blood Pump Design
- Summary and Discussion

Mechanical Assist Devices

- Motivation
  - Over 5 million Americans and 20 million people worldwide suffer from Congestive Heart Failure (CHF)
  - CHF patients are still treated with drug therapy, however, at late stage heart transplantation is traditionally the only treatment hope

Mechanical Assist Devices

- Motivation
  - Need for assist devices is very high

    Need : 25,000-60,000 / YR
    Donor hearts available : 2,000-2,500 / YR
    (e.g. more than 4,000 patients were on the waiting list in 1999)
  - Need to find right match
  - Heart pump or VAD, for ventricular assist device, is being used as a temporary support to sick ventricle

    "BRIDGE-TO-TRANSPLANT"

Mechanical Assist Devices

- Motivation
  - VAD vs Drug treatment,

    recent study suggests that
    - Survival rate for VAD patients vs for patients receiving drug treatment

      After 1 year 52 % vs 24.7% (it also depends on the methods and drugs used)

      After 2 years 22.9 % vs 8.1 %
    - Some patients who stayed in ICU because of short of breath can walk a block after 1 year assisted by VAD

Mechanical Assist Devices

- Motivation
  - VAD vs Drug treatment
    - However, complication rate for VAD is 2.35 times higher than that for drugs

      Complications include infections, bleeding, and mechanical malfunctions like motor failure, deformed tube and worn bearings

      ⇒ Design improvements are needed to lower the risk, and possibly to use it as a permanent therapy (long-term device)

      "BRIDGE-TO-RECOVERY"

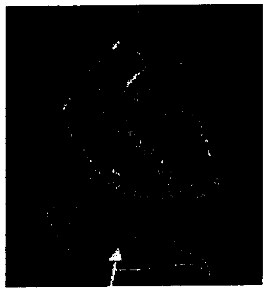
Mechanical Heart-Assist Devices

- Heart Valves
- Ventricular Assist Device (VAD)

  <u>Pulsatile Pump</u>
  - Piston Driven : Low speed, Bulky
  - Pneumatically Driven : Need external support equipment

  <u>Rotary Pump</u>
  - Axial Flow Pump : High speed, Small

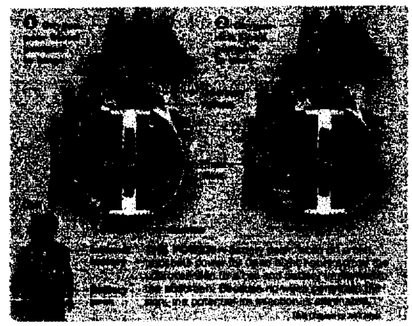
  ⇒ DeBakey VAD is based on this concept
- Total Artificial Heart



DeBakey VAD

Jarvik 2000

ABIOMED Artificial Heart



Ventricular Assist Device

- Requirements
  - Simplicity and Reliability
  - Small size for ease of implantation
  - Supply 5 liter/min of blood against 100 mmHg pressure
  - High pumping efficiency to minimize power requirements
  - Minimum Hemolysis and Thrombus Formation

Computational Issues

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- Geometry / grid definition
  Moving boundary
- Solver
  Time accurate solver
- Physical modeling
  Newtonian vs non-Newtonian
  Turbulence
- Experimental & clinical data

Solver: Viscous Incompressible Flow

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- Formulation
  Can be viewed as a limiting case of compressible flow where the flow speed is insignificant compared to the speed of sound (Preconditioned compressible N-S eq.)
  ⇒ Artificial compressibility approach
  - Artificial Compressibility Method (Chorin, 1967)
    INS3D family of codes
    Merkle et. al
    ..... many more

  Or truly incompressible
  ⇒ Pressure projection approach
    - MAC (Harlow and Welch, 1965)
    - Fractional Step Method (Chorin, 1968; Yanencko, 1971; Marchuck, 1975.....)
    - SIMPLE type Pressure Iteration (Caretto et al., 1972; Patanka & spalding, 1972...)

  ⇒ Use derived variables
    - Vorticity-Velocity (Fasel, 1976; Dennis et al., 1979; Hafez et al., 1988
    - Stream function-vorticity

Artificial Compressibility Method

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- Formulation

$$\frac{1}{\beta}\frac{\partial p}{\partial t}+\frac{\partial u_i}{\partial x_i}=0$$

  - Introduces hyperbolic behavior into pressure field.
    Speed of pressure wave depends on the artificial compressibility parameter, β.
  - The equations are to be marched in a time like fashion until the divergence of velocity converges to zero.
    $\Rightarrow$ Relaxes incompressibility requirement.
    Time variable during this process does not represent physical time step.

  For time-accurate solutions
  - Iterate the equations in pseudo-time level for each time step until incompressibility condition is satisfied.
    $\Rightarrow$ Efficient sub-iteration is the key for success

Artificial Compressibility Method (INS3D-UP)

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- Time accuracy is achieved by subiteration
  - Discretize the time term in momentum equations using second-order three-point backward-difference formula

$$\frac{3q^{n+1}-4q^{n}+q^{n-1}}{2\Delta t}=-(rhs)^{n+1}$$

  - Introduce a pseudo-time level and artificial compressibility,
  - Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

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

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

- Code performance
  - Computing time : 50-120 ms/grid point/iteration (on C90 single cpu)
  - Memory usage: **Line-relaxation** 45 words/grid point
    GMRES-ILU(0) 220 words/grid point

Pressure Projection Method(INS3D-FS)

- Approach in generalized coordinates
  - Finite volume discretization
  - Accurate treatment of geometric quantities
  - Dependent variables - pressure and volume fluxes
  - Implicit time integration
  - Fractional step procedure
    Solve auxiliary velocity field first,
    then enforce incompressibility condition by solving a Poisson equation for pressure.
- Code performance
  - Computing time : 80 ms/grid point/iteration (on C90 single cpu)
  - Memory usage: 70 words/grid point

Pressure Projection Method

- Fractional-step
  - Solve for the auxiliary velocity field, using implicit predictor step:

$$\frac{1}{\Delta t}(u_i^* - u_i^n) = -\nabla p^n + h(u_i^*)$$

  - The velocity field at time level (n+1) is obtained by using a correction step:

$$\frac{2}{\Delta t}(u_i^{n+1} - u_i^*) = -\nabla p^{n+1} + h(u_i^{n+1}) - \nabla p^* + h(u_i^*)$$

  - The incompressibility condition is enforced by using a Poisson equation for pressure ($p' = p^{n+1} - p^*$)

$$\nabla^2 p' = \frac{2}{\Delta t}\nabla \cdot u^*$$

History of INS3D Development

● Code

1982-1987 Original version
(Kwak, Chang)

1988-1997 INS3D-UP
(Rogers, Kiris, Kwak)
INS3D-LU
(Yoon, Kwak)
INS3D-FS
(Rosenfeld, Kiris, Kwak)

1998-Parallel version
(Kiris, Kwak)

● Applications

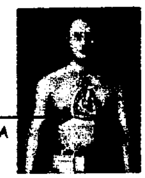
SSME Phase II+
HGM Redesign

Flight engines
1995

Inducer

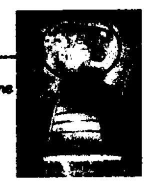
Impeller

DeBakey/NASA
VAD, 1998



Turbopump

Advanced engine



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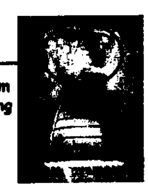
Inducer

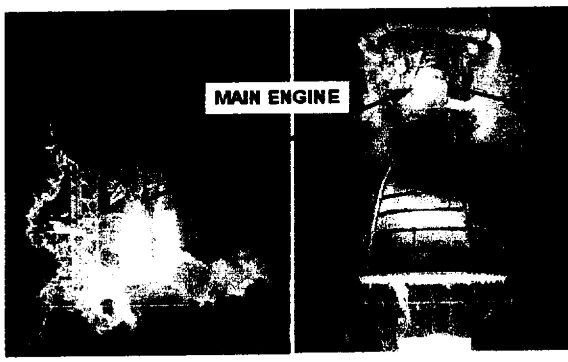
Impeller

Liquid Sub-system
Analysis Tool using
IPG

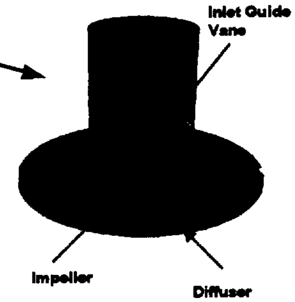


Advanced pump

Computational Methods Developed for Space Shuttle Main Engine Redesign / Advanced Engine



TURBOPUMP IN SSME POWERHEAD



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

Parallel Implementation of INS3D

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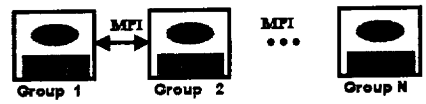
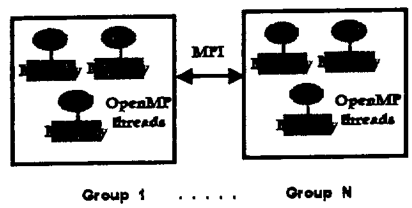
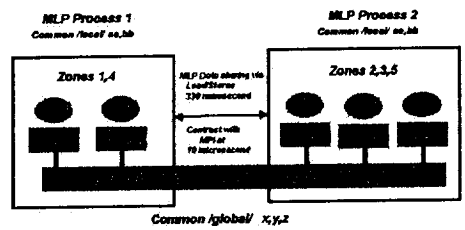
- INS3D-MPI
  (coarse grain)
  T. Faulkner & J. Dacles



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



- INS3D-MLP
  C. Kiris



Validation-SSME Turbopump Flow Analysis

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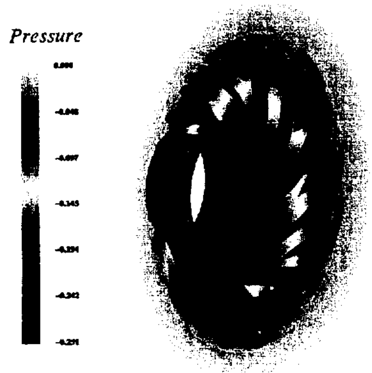
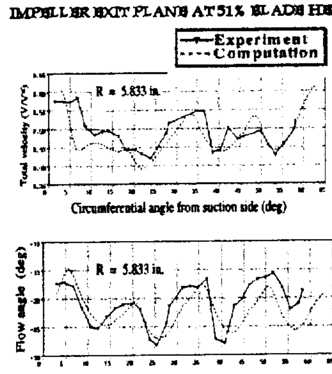
- SSME HPFTP 11' Impeller
  Shrouded impeller: 6 full blades, 6 long partials, 12 short partials 6322 rpm, Re=1.81x10⁶ per inch

HUB SURFACE COLORED BY STATIC PRESSURE



COMPARISON WITH EXPERIMENTAL DATA

IMPELLER EXIT PLANE AT 51% BLADE HEIGHT



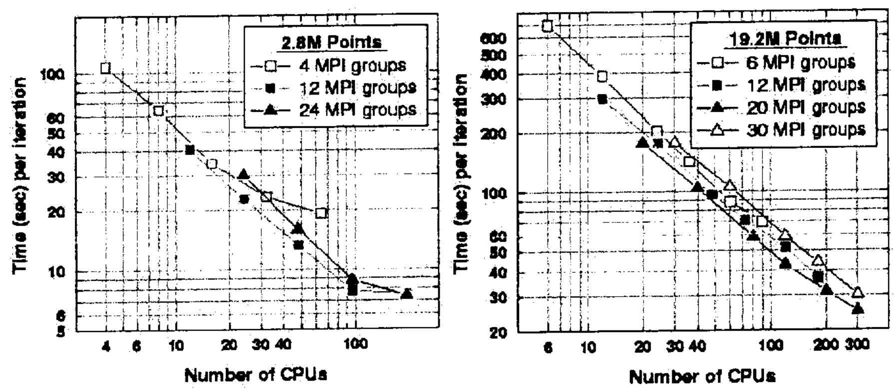
Parallel Implementation of INS3D

MPI coarse grain + OpenMP fine grain

TEST CASE : SSME Impeller

24 zones / 2.8 Million points

60 zones / 19.2 Million points

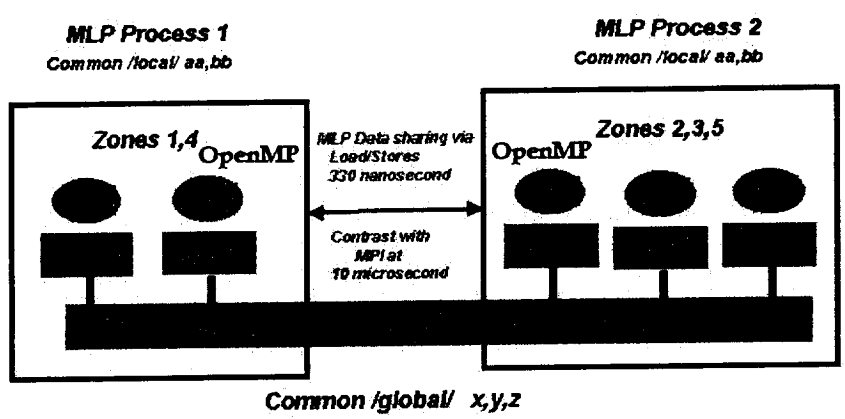


Parallel Implementation of INS3D

Multi-Level Parallelism (MLP)

INS3D-MLP : MLP routines + OpenMP

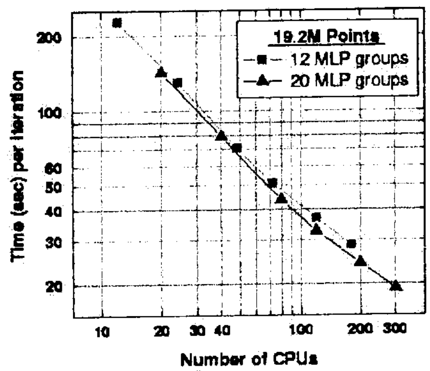
Shared Memory MLP Organization for Origin 2000

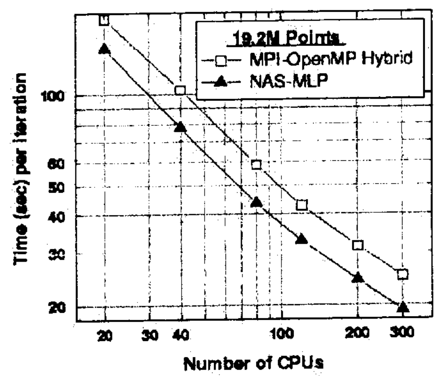


Parallel Implementation of INS3D

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

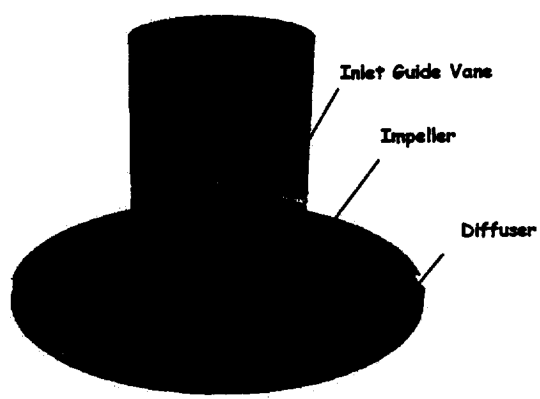
TEST CASE : SSME Impeller
60 zones / 19.2 Million points

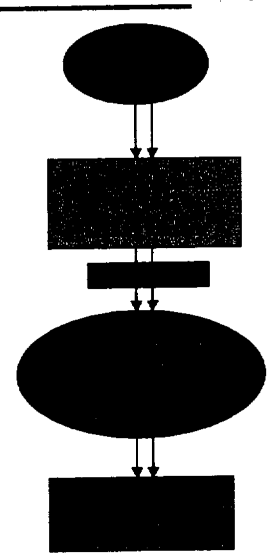




Space Shuttle Main Engine Turbopump

Impeller Technology Water Rig
Baseline SSME/ATD HPFTP Class Impeller





High-fidelity Simulation of 2nd Gen RLV Turbopump

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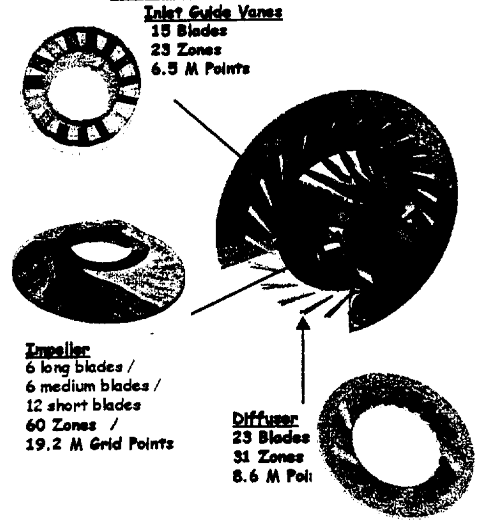

- Major Technical Issues
  - Pump codes exist, mostly in rotational frame of reference, for quick design analysis
  - Fully 3-D, transient capability is needed to advance pump technology

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

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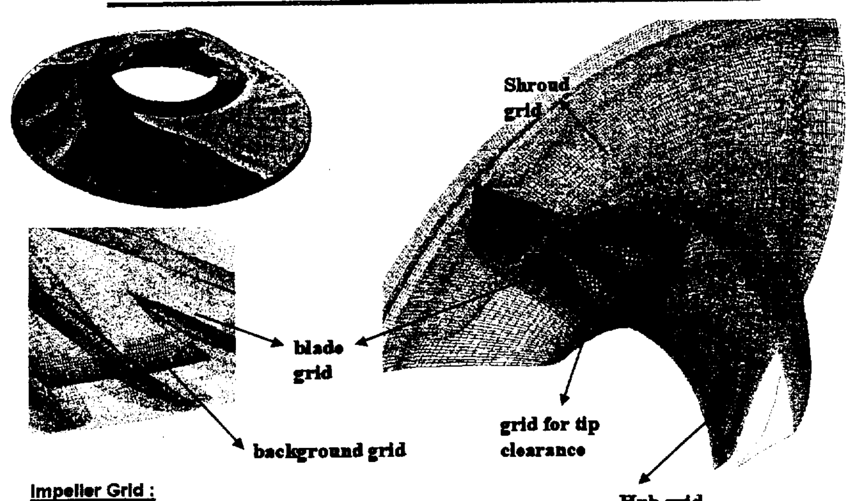


Impeller Grid :
60 Zones / 19.2 Million Grid Points
Smallest zone : 75K /Largest zone : 996K
Less than 192 orphan points.

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.

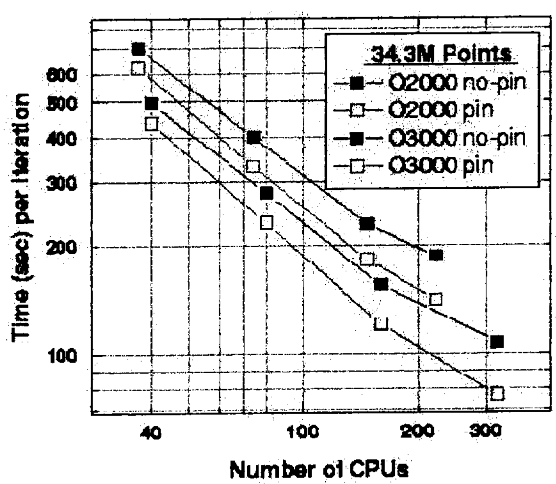
Script timings on new grids based on SGI R12k 300MHz processor

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

Parallel Implementation of INS3D

INS3D-MLP / 40 Groups

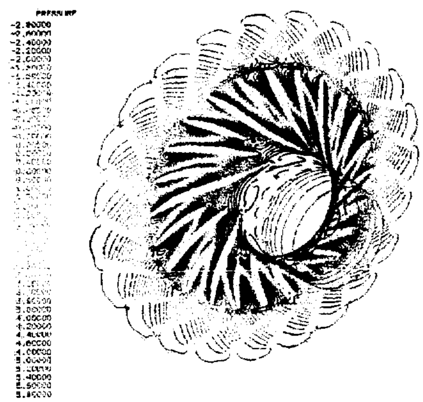
RLV 2nd Gen Turbo pump
114 Zones / 34.3 M grid points



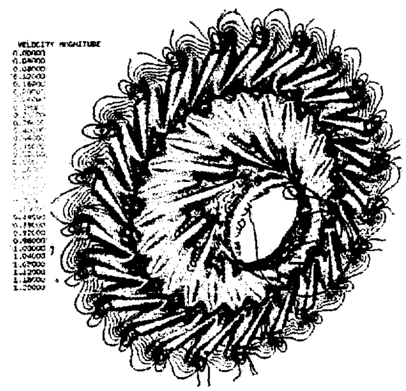
Per processor Mflop is between 60-70. Code optimization for cache based platforms is currently underway. Target Mflops is to reach 120 per processor. Increasing number of OpenMP threads is also the main objective for this effort.

SSME-rig1 / Initial start

Time Step 18: 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
  - Communication to/from designers and experimental group is a part of critical technologies (in Grid computing)

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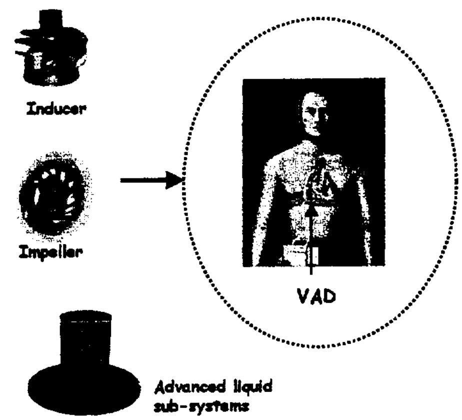

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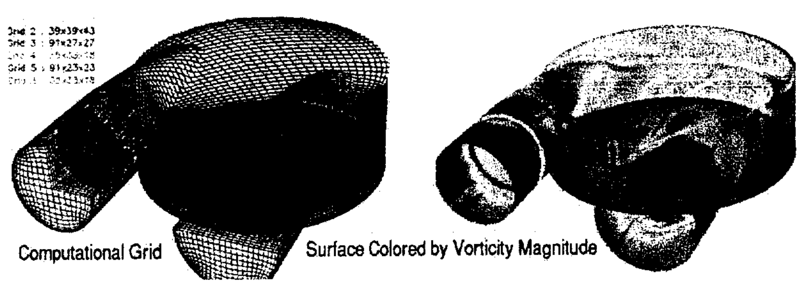
Example of Pulsatile Pump

- Penn-State Artificial Heart
  - **Chimera Grid for moving components**



This and other results were first reported by Kiris et. al in 1991: "Computation of Incompressible Viscous Flows through Artificial Heart Devices with Moving boundaries," Proc. American Mathematical Society Summer Research on Biofluid Dynamics Conference, July 6-12, 1991, Seattle, WA

Example of Pulsatile Pump

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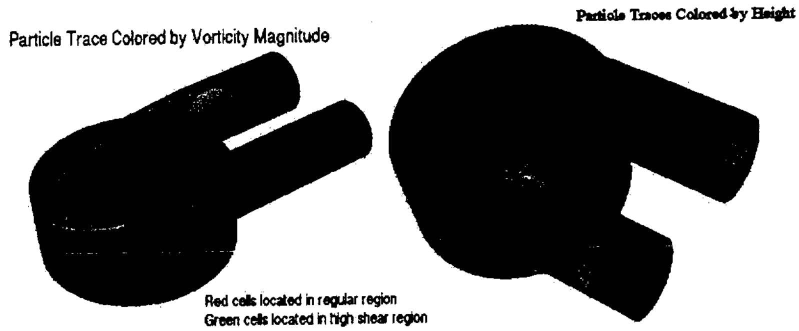
- Penn-State Artificial Heart
  Analysis of time dependant data was an issue



Schematic of DeBakey VAD™

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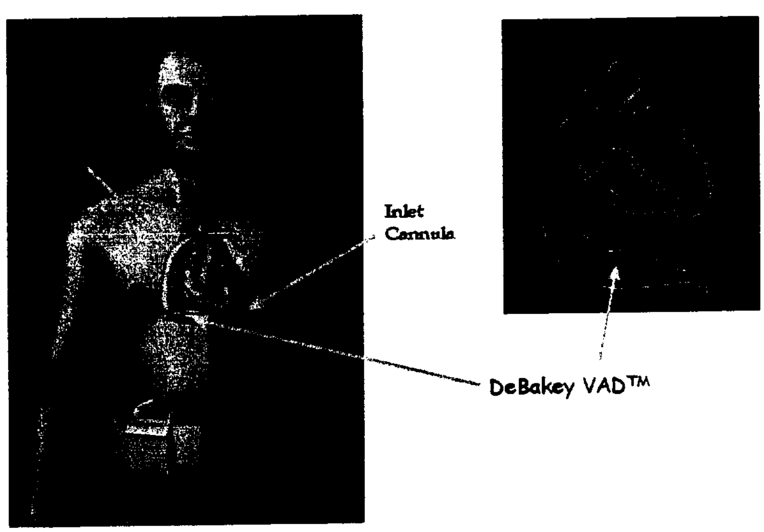
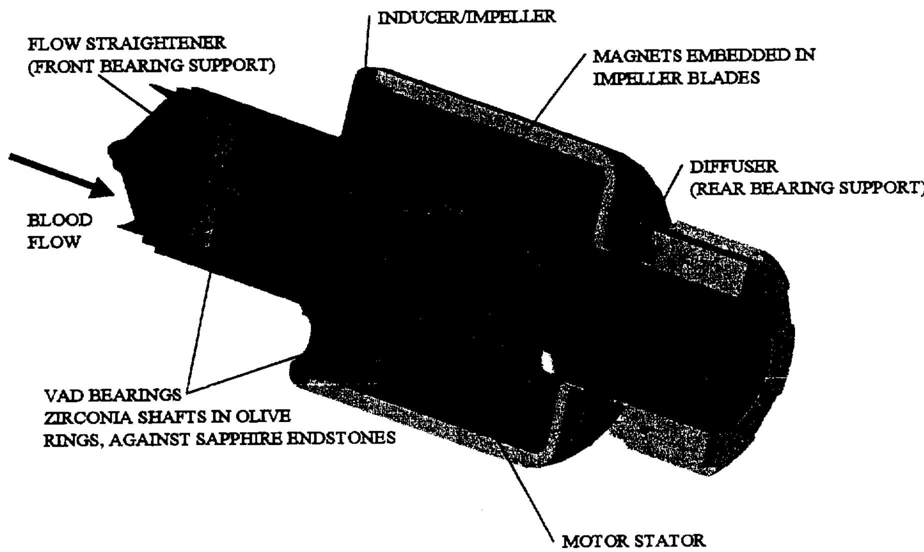


DeBakey VAD™ Pump Schematic



Issues in Axial flow VAD

- Problems Related to Fluid Dynamics
  - Small size requires high rotational speed
    Highly efficient pump design required
  - High shear regions in the pump may cause excessive blood cell damage
    Minimize high shear regions
  - Local regions of recirculation may cause blood clotting
    Good wall washing necessary

⇒Small size and delicate operating conditions make it difficult to quantify the flow characteristics experimentally

DeBakey VAD Development Timeline

- Baseline Design

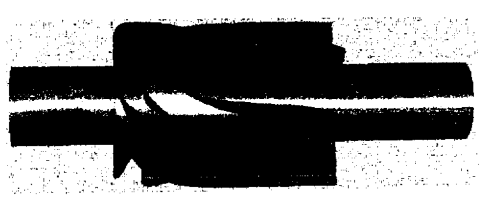
1984 - NASA Johnson Space Center's David Saucier begins initial design work on axial pump VAD with Dr. DeBakey

1988 - NASA/JSC and Baylor College of Medicine signs Memorandum of Understanding to develop the DeBakey VAD

1992 - NASA/JSC begins funding the project

NASA/DeBakey VAD (Baseline Design)

NASA / DeBakey Axial Flow VAD Impeller



Zone 1 :101 x 39 x 33

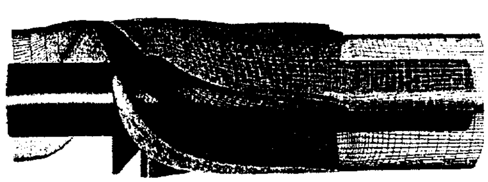
Zone 2 :101 x 39 x 33

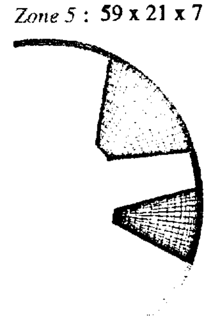
Zone 3 : 59 x 21 x 7

Zone 4 : 47 x 21 x 7

Zone 5 : 59 x 21 x 7

Geometry





Computational Grid

Rotational Speed : 12,600RPM

Flow Rate : 5 lit/min

NASA/DeBakey VAD (Baseline Design)

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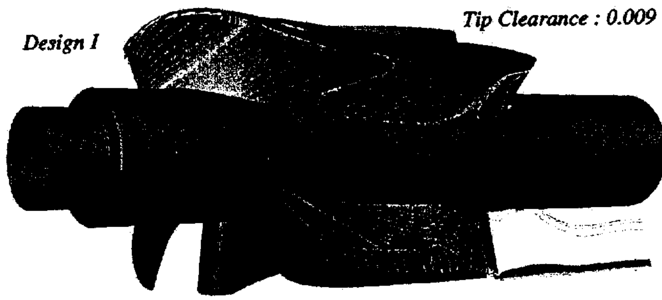
Flow Pattern Near Suction and Pressure Sides of Full Blade

Design I *Tip Clearance : 0.009 in.*



Traces Colored by Axial Velocity Magnitude

−0.690 −0.365 −0.040 0.285 0.610

Rotational Speed :12,600RPM *Flow Rate : 5 lit/min*

DeBakey VAD Development Timeline

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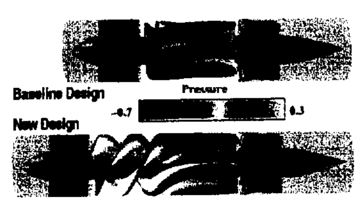
- CFD Assisted Design

1993 - NASA/ARC is asked to develop CFD procedure to improve design and performance. D. Kwak and C. Kiris visit JSC to study the device
The technology developed for rocket engine such as the Space Shuttle main engine was to be extended to blood flow simulation

1994 - Kiris and Kwak begin work on design analysis using NAS supercomputers

⇒ NEW DESIGN WAS PROPOSED TO INCLUDE AN INDUCER BETWEEN THE FLOW STRAIGHTNER AND THE IMPELLER



Particle Traces Colored by Velocity Magnitude

DeBakey VAD Development Timeline

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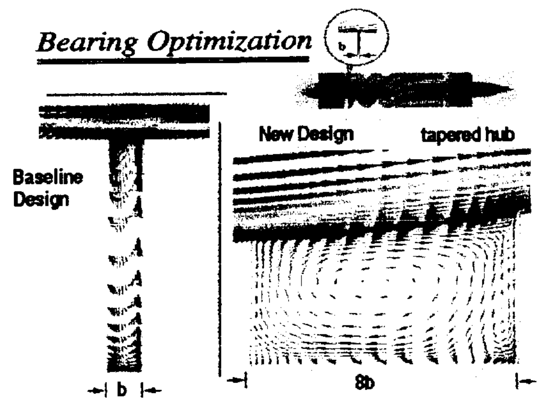
- CFD Assisted Design

  1994 -Kiris and Kwak continued design changes

  ⇒ IMPROVE BEARING, HUB AND HUB EXTENSION DESIGN TO REDUCE BLOOD CLOTTING



DeBakey VAD Development Timeline

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- Animal Tests

  1995 - Animal implantation: passed two-week requirements

  1996 - Fulll design rights are granted to MicroMed, Inc. to produce the pump
  Began using bio-compatible titanium replacing polycarbonate

  1997 - Configuration design finalized

CFD Contributions to VAD Design

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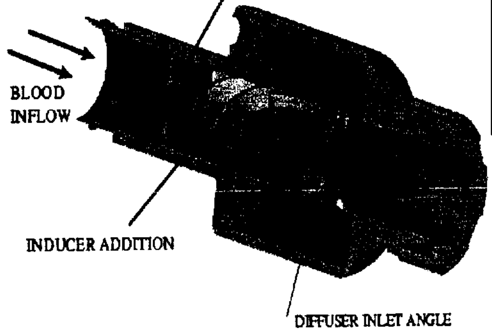
CFD Contributions To Design



	Baseline Design	New Design
Hemolysis Index	0.02	0.002
Thrombus Formation	Yes	no
Test Run Time	2 days	30+ days
Human Implantation		~ 1 year*

* As of July 2001

- *Inducer addition*
- *Bearing cavity design*
- *Change diffuser inlet angle*

Inlet Cannula Study

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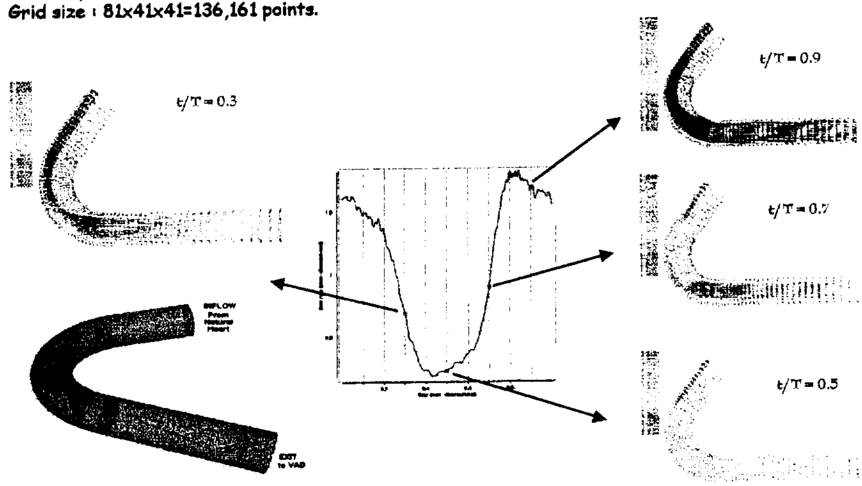
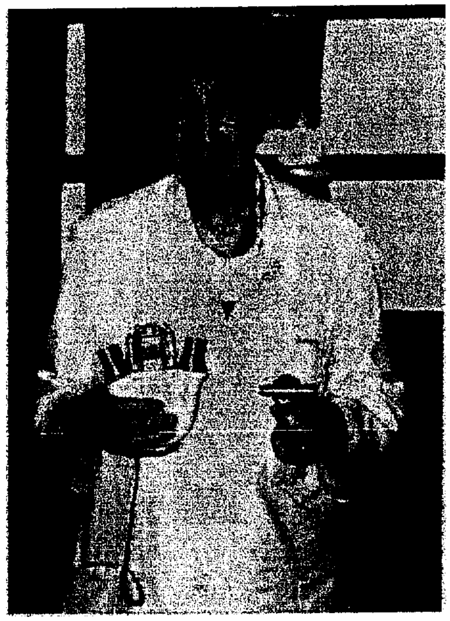
Time-dependent inflow flow rate is used in the elbow parametric study
Grid size : 81x41x41=136,161 points.





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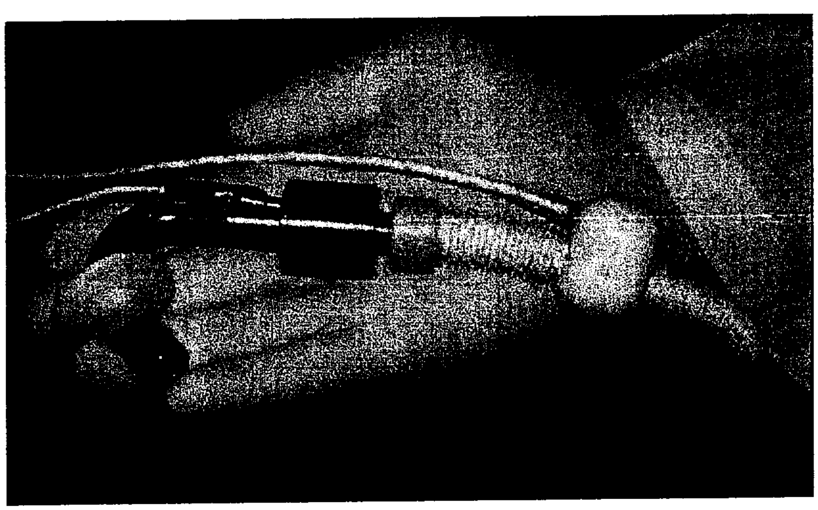
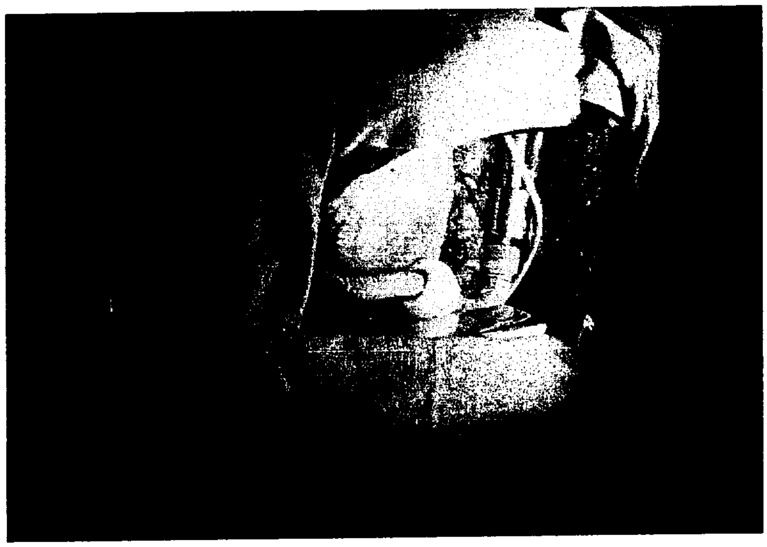
DeBakey VAD



DeBakey VAD - In situ



DeBakey VAD Development Timeline

- Human Implantation in Europe

1998 - On November 13, 1998, the first six DeBakey VADs are implanted in European patients by Roland Hetzer and DeBakey at the German Heart Institute of Berlin. One of the patients, fifty six year old Josef Pristov, is able to return home and spend Christmas with his wife after a month's stay for recovery and monitoring at the clinic

NASA/DeBakey VAD- Patient Pictures

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A patient in Munich fully mobile and discharged awaiting transplant

The first patient in Houston with Drs. DeBakey and Noon on her discharge day after transplant

NASA/DeBakey VAD- Patient Pictures

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A patient in Berlin, on his discharge day with the device

A patient in a regular ward before discharge

NASA/DeBakey VAD
Accomplishments to date (7/1/01)

- 120+ patients implanted
- Number of patients currently ongoing with device
- US trial
  Approved for 20 patients (14 male, 6 female) in a multi-center trial
- European trial
  Received "CE mark" (the EU equivalent to FDA approval)
- Results to date
  Favorable compared to existing VADs

  Small incidence of thrombus is being investigated
  ⇒ Further computational support is essential

Summary and Discussion-1

- Computational approach provides
  - **a possibility of quantifying the flow characteristics: especially valuable for analyzing compact design with highly sensitive operating conditions**
  - **a tool for conceptual design and for design optimization**
- CFD + rocket engine technology has been applied
  - **to modify the design of NASA/DeBakey VAD which enabled human implantation**
- Computing requirement is still large
  - **Unsteady analysis of the entire system from natural heart to aorta involves several hundred revolutions of the impeller**
  - **During on heart beat, impeller has 125 revolutions**
  - **With 1024 processors of Origin, one simulation (with several heart beat) from heart to aorta can be completed in months**

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Summary and Discussion-2

- Further study is needed
  - **to assess long term impact of mechanical VAD on human body, which requires modeling flexible wall and non-Newtonian effect and better downstream boundary conditions**
- There exist some gaps between
  - **CFD (assuming IT is a part of CFD applications) and biomedical expertise**