Blood Pump Development Using Rocket Engine Flow Simulation Technology

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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"

- 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)
  - Pulsatile Pump
    - Piston Driven: Low speed, Bulky
    - Pneumatically Driven: Need external support equipment
  - Rotary Pump
    - Axial Flow Pump: High speed, Small
  - DeBakey VAD is based on this concept
- Total Artificial Heart
• 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

- Geometry / grid definition
  Moving boundary

- Solver
  Time accurate solver

- Physical modeling
  Newtonian vs non-Newtonian
  Turbulence

- Experimental & clinical data

Solver: Viscous Incompressible Flow

- 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; Yuenenko, 1971; Marchuk, 1975...)
    - SIMPLE type Pressure Iteration (Garetto 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

- Formulation
  \[
  \frac{1}{\beta} \frac{\partial p}{\partial t} + \frac{\partial u}{\partial x} = 0
  \]
  - Introduces hyperbolic behavior into pressure field.
  - Speed of pressure wave depends on the artificial compressibility parameter, \( \beta \).
  - The equations are to be marched in a time like fashion until the divergence of velocity converges to zero.
  - 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.
  - Efficient sub-iteration is the key for success

Artificial Compressibility Method (INS3D-UP)

- Time accuracy is achieved by subiteration
  - Discretize the time term in momentum equations using second-order three-point backward-difference formula
  \[
  3g^{*n} - 4q^* + q^{***} = -(rhs)^{***}
  \]
  - Introduce a pseudo-time level and artificial compressibility,
  - Iterate the equations in pseudo-time for each time step until incompressibility condition is satisfied.

\[
\frac{1}{\Delta t} (p^{*n} - p^{***}) = -\beta \rho^{***}
\]
\[
1.5 \left(q^{*n} - q^{***}\right) = -(rhs) - 3g^{***} - 4q^* + g^{**} + \frac{1}{2\Delta t}
\]

- Code performance
  - Computing time: 50-120 ms/grid point/iteration (on C90 single cpu)
  - Memory usage: Line-relaxation 48 words/grid point
  - GMRES-ILU(0) 220 words/grid point
Pressure Projection Method

- 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:
    \[
    \frac{1}{\Delta t} (u' - u^*) = -\nabla p' + h(u^*)
    \]
  - The velocity field at time level \((n+1)\) is obtained by using a correction step:
    \[
    \frac{2}{\Delta t} (u'' - u^*) = -\nabla p'' + h(u''') - \nabla p' + h(u^*)
    \]
  - The incompressibility condition is enforced by using a Poisson equation for pressure (\(p' = p''' - p'\))
    \[
    \nabla ^2 p' = \frac{2}{\Delta t} \nabla \cdot u^*
    \]
History of INS3D Development

- **Code**
  - 1982-1987: Original version (Kwak, Cheng)
  - 1988-1997: INS3D-UP (Degane, Kiris, Kwak), INS3D-LU (Yam, Kwak), INS3D-FS (Rosenfeld, Kiris, Kwak)
  - 1998-Parallel version (Kiris, Kwak)

- **Applications**
  - Flight engines: 1998
  - DeBakey/NASA VAD, 1998
  - Advanced engine

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

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 IN53D

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

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

- **INS3D-MLP**
  - C. Kiris

Validation-SSME Turbopump Flow Analysis

- **SSME HPFTP 11' Impeller**
  - Shrouded impeller: 6 full blades, 6 long partials, 12 short partials 6322 rpm, Re=1.81x10^6 per inch
  - Pressure surface colored by static pressure
  - Comparison with experimental data
  - Impeller exit plans at 51% blade height
  - Graphs comparing experimental and computational data.
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

2.8M Points
- 4 MPI groups
- 12 MPI groups
- 24 MPI groups

19.2M Points
- 6 MPI groups
- 12 MPI groups
- 20 MPI groups
- 30 MPI groups

Parallel Implementation of INS3D

Multi-Level Parallelism (MLP)
INS3D-MLP : MLP routines + OpenMP
Shared Memory MLP Organization for Origin 2000

MLP Process 1
Common /local/ ax,bb

MLP Process 2
Common /local/ ax,bb

Zones 1,4 OpenMP

MLP Data sharing via Load/Stores 200 nanosecond

OppenMP

Zones 2,3,5

Common /global/ x,y,z
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

Inlet Guide Vane
Impeller
Diffuser
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-nig1

Impeller Grid:
- 60 Zones / 19.2 Million Grid Points
- Smallest zone: 75K / Largest zone: 900K
- Less than 192 orphan points.
Scripting for Acceleration of Grid Generation

INLET GUIDE VANES AND DIFFUSER

<table>
<thead>
<tr>
<th></th>
<th>Old IGV</th>
<th>New IGV</th>
<th>Old DIFF</th>
<th>New DIFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of points (million)</td>
<td>7.1</td>
<td>1.1</td>
<td>8.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Time to build</td>
<td>1/2 day</td>
<td>10 sec.</td>
<td>1/2 day</td>
<td>8 sec.</td>
</tr>
</tbody>
</table>

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

Time (sec) per iteration

34.3M Points
- Q2000 no-pin
- Q2000 pin
- Q3000 no-pin
- Q3000 pin

Per processor Mflop is between 80-70.
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.
Time Step 18: Impeller rotated 8-degrees at 100% of design speed

- 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 CPUs 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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  - Development
  - Application to Blood Pump Design
- Summary and Discussion

Example of Pulsatile Pump

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

This and other results were first reported by Katz et. al in 1991:
"Computation of Incompressible Viscous Flows through Artificial Heart Devices with Moving boundaries."
Example of Pulsatile Pump

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

Particle Trace Colored by Vorticity Magnitude

Particle Trace Colored by Height

Red cells located in regular region
Green cells located in high shear region

Schematic of DeBakey VAD™

Inlet Cannula

DeBakey VAD™
DeBakey VAD™ Pump Schematic

FLOW STRAIGHTENER (FRONT BEARING SUPPORT)

INDUCER/IMPELLER

MAGNETS EMBEDDED IN IMPPELLER BLADES

DIFFUSER (REAR BEARING SUPPORT)

BLOOD FLOW

VAD BEARINGS ZIRCONIA SHAFTS IN OLIVE RINGS, AGAINST SAPPHIRE RENDSTONES

MOTOR STATOR

- 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

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NASA/DeBakey VAD (Baseline Design)

**NASA / DeBakey Axial Flow VAD Impeller**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>101 x 39 x 33</td>
</tr>
<tr>
<td>Zone 2</td>
<td>101 x 39 x 33</td>
</tr>
<tr>
<td>Zone 3</td>
<td>59 x 21 x 7</td>
</tr>
<tr>
<td>Zone 4</td>
<td>47 x 21 x 7</td>
</tr>
<tr>
<td>Zone 5</td>
<td>59 x 21 x 7</td>
</tr>
</tbody>
</table>

Geometry

Computational Grid

Rotational Speed: 12,600 RPM
Flow Rate: 5 l/min
NASA/DeBakey VAD (Baseline Design)

Flow Pattern Near Suction and Pressure Sides of Full Blade

Design 1
Tip Clearance: 0.009 in.

Traces Colored by Axial Velocity Magnitude

-0.690 -0.365 -0.040 0.285 0.610

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

DeBakey VAD Development Timeline

- CFD Assisted Design
  1993 - NASA/ARC is asked to develop CFD procedure to improve design and performance. D. Kwak and C. Kirle 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 - Kirle and Kwak begin work on design analysis using NASA 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

- CFD Assisted Design
  1994 - Kirke and Kwak continued design changes
  \[\Rightarrow \text{IMPROVE BEARING, HUB AND HUB EXTENSION DESIGN TO REDUCE BLOOD CLOTTING}\]

**Bearing Optimization**

![Bearing Optimization Diagram]

- Animal Tests
  1995 - Animal implantation passed two-week requirements
  1996 - Full design rights are granted to MicroMed, Inc. to produce the pump
  \[\text{Began using bio-compatible titanium replacing polycarbonate}\]
  1997 - Configuration design finalized
CFD Contributions to VAD Design

**CFD Contributions To Design**

<table>
<thead>
<tr>
<th></th>
<th>Baseline Design</th>
<th>New Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemolysis Index</td>
<td>0.02</td>
<td>0.002</td>
</tr>
<tr>
<td>Dynamic Friction</td>
<td>Yes</td>
<td>no</td>
</tr>
<tr>
<td>Test Run Time</td>
<td>2 days</td>
<td>30+ days</td>
</tr>
<tr>
<td>Human Implantation</td>
<td>~1 year</td>
<td></td>
</tr>
</tbody>
</table>

* As of July 2001

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

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**Inlet Cannula Study**

Time-dependent inflow flow rate is used in the elbow parametric study.

Grid size: 81x41x41=136,161 points.
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

A patient in Munich fully mobile and discharged awaiting transplant

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

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

A patient in a regular room 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 one heart beat, impeller has 128 revolutions
  - With 1024 processors of Origin, one simulation (with several heart beats)
    from heart to aorta can be completed in months
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