MSFC Turbomachinery Fluid Dynamics Roadmap

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To expand the knowledge and understanding of the fluid dynamics of turbomachinery and to use that knowledge and understanding to improve the performance, reliability, and robustness of turbomachinery hardware
Approach

- Develop and enhance aerodynamic and hydrodynamic design tools and CFD analysis tools
- Apply these tools to the development of hardware technology and concepts
- Define judicious, relevant cold flow experiments to provide tool validation, technology and concept verification, and to further expand fluid dynamics knowledge and understanding
- Apply the technical knowledge, design and analysis tools, experimental data, and hardware concepts to support the development and anomaly investigation of flight hardware
For the purposes of the TD64, turbomachinery fluid dynamics includes the following hardware elements

- **Turbine primary flowpath**
  - Blading (vanes, blades, struts, guide vanes)
  - Manifolds (toruses, volutes)
  - Pipes and ducts (including diffusers)

- **Pump primary flowpath**
  - Blading (inducer, impeller, diffuser vanes)
  - Manifolds (toruses, volutes)
  - Pipes and ducts (including crossovers)

- **Turbomachinery cavities**

- **Elements with a prescribed motion**
  - Valves
  - Bearings
MSFC is an applications center with no research and technology programs
- With the demise of the ETO program in the mid-1990s, all technology paid for through projects
- Projects come and go with an ever-increasing frequency, rarely providing long-term, continuous funding for technology
- Projects interested in funding their problem of the moment

Although in the Turbomachinery Fluids Team we try to dedicate some of our time to technology development that has general applicability, our project work load has us stretched very thin
- Dates on our technology roadmaps have little meaning because
  - We work the technology when we have time
  - The technology has suddenly become urgent to a project, and the well-thought out plan goes out the window

Technology tasks are generally funding because of some urgency, not because some well-thought out, well-blessed plan says its time to work them
Good Reasons for the Roadmap Process

 Within the Turbomachinery Fluids Team
  • Forces us to step back and define the whole problem
     What is turbomachinery fluid design and analysis and what should it be?
  • Provides us with a view of our current level of proficiency and where we need to be in order to work areas in the whole problem
  • Identifies the areas where we are deficient
  • Defines the process by which to improve our proficiency
  • Helps us to identify items of improvement that are necessary for multiple areas of the whole problem

 For Team Leader/Group Leader
  • Identifies items that will achieve the most bang for the buck when we get funding, piecemeal or otherwise, for technology improvements
  • Provides a good visual aid for project managers to show what areas have to be worked for their projects and how it fits into the overall plan

The Roadmap Works for the Turbomachinery Fluids Team In the Context of a Highly Flexible Plan that Helps Us Define Our CurrentCapabilities, Our Required Capabilities, and the Process to Get from One to the Other
Roadmap development is a work in progress
- Map itself not completed
- Input needed to develop the map contained in this presentation

The roadmap represents our capabilities in TD64

As a work in progress, the roadmap has deficiencies and omissions
- Bearings, valves, seals currently not considered

Roadmap will provide industry and academia insight into MSFC's plans for turbomachinery fluid dynamics

We are soliciting feed-back from the turbomachinery and fluid dynamics community
- Identify deficiencies and omissions in the roadmap
- Identify areas of where improvements are needed by the entire community
- Identify areas where TD64 seems to lag the turbomachinery community
- Identify ways to improve proficiency levels, TD64 and industry-wide
♦ Our roadmap considers the next 5 years
♦ Before we begin a roadmap, a few items had to be considered
  • Define the whole turbomachinery fluid dynamics problem
  • What will our project requirements be in the next 5 years based on what we know today?
  • Are there general problems that we can’t tackle in 5 years, but need to start the ground work for now to meet space transportation goals?
  • What are our current capabilities in fluid design and analysis as applied to areas of the whole problem?

This Presentation Discusses the Items that Must be Defined to Develop the Roadmap
Particular concepts to meet project goals present challenges for turbomachinery

- Full-flow staged combustion cycle engines are experiencing weight, turbine blade stress, and turbine performance issues
  - Require turbine manifold and blading (axial, subsonic) design and analysis
- Turbine-based combined cycle rocket and upper-stage engine turbomachinery require deep-throttle capability
  - Require turbine manifold design and analysis capability and hardware concept development
  - Require pump diffuser design and analysis capability and hardware concept development
  - Compact radial turbine concepts should be investigated

All turbomachinery concepts will have to deal with high and low cycle fatigue to address reliability goals

- Unsteady CFD analysis for turbines and pumps required
- Efficient methods of providing unsteady fluids loads to structural models needed
- CFD analysis of turbomachinery during start and shutdown transients necessary
Project Requirements

- Inducer cavitation must be addressed for pump performance and reliability goals
  - Cavitation modeling/prediction required
  - Concepts to reduce inducer cavitation needed
- Hydraulic turbines used low pressure turbomachinery
  - Design and analysis capability needed
The whole problem was broken into categories
- Turbine blading design and analysis
- Pump blading design and analysis
- Inlet and exit design and analysis
- Flange-to-flange analysis
- Turbopump analysis

Readiness levels were developed
- Design and analysis capability
- Validation data availability
- Turn around time required

Current capabilities were assigned a readiness level along with issues needing to be worked

5 year required capabilities were assigned based on discipline and project needs
<table>
<thead>
<tr>
<th>Level</th>
<th>Design and Analysis</th>
<th>Validations Data</th>
<th>Turn Around Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not attempted with current tools</td>
<td>No data in house; little data in literature</td>
<td>Requires more than 6 months</td>
</tr>
<tr>
<td>1</td>
<td>Have conducted preliminary work</td>
<td>Experimental result shown in literature but little geometric or BC detail to enable problem simulation</td>
<td>Requires more than 3 months but less than 6 months</td>
</tr>
<tr>
<td>2</td>
<td>Have applied to a simplified problem</td>
<td>Steady or time-averaged overall or ‘flange-to-flange’ pressures and temperatures available; flows and torque available for pumps</td>
<td>Requires more than 1 month but less than 3 months</td>
</tr>
<tr>
<td>3</td>
<td>Have applied to a relevant problem, issues to be worked</td>
<td>Steady or time-averaged overall pressures and temperatures and detailed flow path and/or row information; Flow vis. may be available; Fluctuating pressures on walls may be available</td>
<td>Requires more than 1 week but less than 1 month</td>
</tr>
<tr>
<td>4</td>
<td>Routinely apply to relevant problems, issues to be worked</td>
<td>Time-averaged temperatures and unsteady and time-averaged pressures in flow path and on blading</td>
<td>Requires more than 1 day but less than 1 week</td>
</tr>
<tr>
<td>5</td>
<td>Routinely applied to relevant problems, currently no issues to be worked</td>
<td>Multiple datasets with time-averaged temperatures and unsteady and time-averaged pressures; details like boundary measurements and all velocity components resolved</td>
<td>Requires 1 day or less</td>
</tr>
</tbody>
</table>
Turbine Blading

- Turbine blading categories divided by turbine type; these categories represent types we have used for rocket engines in the past or considering in the future
  - Axial
  - Radial/mix flow
  - Hydraulic
  - Counterrotating

- Required readiness levels are set for a 5 year time frame
- Required readiness levels chosen based on current and projected project needs

ADVANCED LIQUID-HYDROGEN TURBOPUMP
Turbine Velocity Vectors - 6% Span

SSME LPOTP Turbine
Turbine Blading Aerodynamic Design and Analysis

Requirements → Meanline Design and Analysis
Output: Flow Path Dimensions, Efficiency, Gas Conditions, Velocity Triangles

→ Geometry Generation
Output: Detailed Airfoil Shapes

→ Radial Fairing
Output: 3D Blades

→ Detailed CFD
Output: 3D Unsteady Fluid Environment, Aero, Loads, Performance, Ballpark stress

To Inlet and Exit Design and Analysis

Preliminary CFD
Output: Pressure Distributions

Fluid/Structure
Output: Preliminary Stress

→ To Systems, Stress, Dynamics, Thermal

→ To Flange-to Flange Analysis
Meanline Tools
- MLFPDesign - Meanline design
- MLOD - Meanline analysis

Geometry Generation
- Airfoil

Radial Fairing
- Fairing

CFD Grid Generation
- Wildgrd - 2D grid generator for Wildcat
- Corgrd - 3D grid generator for Corsair

CFD Analysis
- Wildcat - 2D unsteady compressible CFD
- Corsair - 3D unsteady compressible CFD

CFD Post-Processing
- Postflt - Corsair post-processor
- Fieldview - general fluid post-processor
## Turbine Blading Readiness Matrix

<table>
<thead>
<tr>
<th>Element</th>
<th>Design and Analysis</th>
<th>Validation Data</th>
<th>Turn Around Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Readiness Level</td>
<td>Required Readiness Level</td>
<td>Issues</td>
</tr>
<tr>
<td>Blading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subsonic</td>
<td>4</td>
<td>4</td>
<td>K,L</td>
</tr>
<tr>
<td>Transonic</td>
<td>4</td>
<td>4</td>
<td>K,L</td>
</tr>
<tr>
<td>Supersonic</td>
<td>3</td>
<td>4</td>
<td>F,G,K,L</td>
</tr>
<tr>
<td>Partial Admission</td>
<td>3</td>
<td>4</td>
<td>G,K,L</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>2+</td>
<td>4</td>
<td>G,H,J,K,L</td>
</tr>
<tr>
<td>Counterrotating</td>
<td>3</td>
<td>3</td>
<td>G,K,L</td>
</tr>
</tbody>
</table>

Assume 1-2 Stages, Periodic Solutions (except for Partial Admission), and 32 CPUs available for periodic solutions (96 CPUs for partial admission)
<table>
<thead>
<tr>
<th></th>
<th>Issue</th>
<th></th>
<th>Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Upgrade algorithms for speed needed</td>
<td>I</td>
<td>Geometry generation code development work required</td>
</tr>
<tr>
<td>B</td>
<td>Generalization of domain decomposition for memory and parallel</td>
<td>J</td>
<td>General fluid properties implementation/validation required</td>
</tr>
<tr>
<td></td>
<td>processing efficiency needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Automation/Template Development of grid generation tools for</td>
<td>K</td>
<td>Methodology to pass fluids loads/frequencies to structural models</td>
</tr>
<tr>
<td></td>
<td>turbomachinery needed</td>
<td></td>
<td>required</td>
</tr>
<tr>
<td>D</td>
<td>Generalization/automation of Turbomachinery CFD pre- and post-</td>
<td>L</td>
<td>Improvements to turbulence models for off-design conditions needed</td>
</tr>
<tr>
<td></td>
<td>processing tools needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Design and analysis tool integration required</td>
<td>M</td>
<td>Radial blade geometry generator needed</td>
</tr>
<tr>
<td>F</td>
<td>Meanline loss model improvement required</td>
<td>N</td>
<td>Hydrodynamamic design system selection/development needed</td>
</tr>
<tr>
<td>G</td>
<td>Further code validation needed</td>
<td>O</td>
<td>Two-phase flow modeling needed</td>
</tr>
<tr>
<td>H</td>
<td>Meanline module development and implementation required</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:** This key is used throughout the presentation
Pump hydrodynamic design and analysis capabilities lag the turbine aerodynamic design and analysis capabilities in TD64.

Pump blading categories divided by element:
- Inducer
- Impeller
- Vaned Diffusers

Final blading category includes the coupled inducer/impeller/diffuser.
Pump Blading Hydrodynamics
Design and Analysis

Requirements

Meanline Design and Analysis
Output: Flow Path Dimensions, Performance, Fluid Conditions, Velocity Triangles

Geometry Generation
Output: Detailed Blade Shapes

Detailed CFD (Single Element)
Output: 3D Fluid Environment, Hydro. Loads, Performance, Ballpark stress

Detailed CFD (Coupled) Elements
Output: 3D Unsteady Fluid Environment, Hydro. Loads, Performance, Ballpark stress

To Inlet and Exit Design and Analysis

Preliminary CFD
Output: Pressure and Velocity Distributions

Fluid/Structure
Output: Preliminary Stress

Fluid/Structure
Output: Preliminary Stress

To Systems, Stress, Dynamics
To Flange-to-Flange Analysis
Meanline Tools
- Under evaluation - Meanline design
- Under evaluation - Meanline analysis

Geometry Generation
- Under evaluation

CFD Grid Generation
- Corgrd - 3D grid generator for Corsair

CFD Analysis
- Corsair - 3D unsteady compressible CFD

CFD Post-Processing
- Postfltl - Corsair post-processor
- Fieldview - general fluid post-processor
# Pump Blading Readiness Matrix

## Design and Analysis

<table>
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<tr>
<td></td>
<td>Current Readiness Level</td>
<td>Required Readiness Level</td>
<td>Issues</td>
</tr>
<tr>
<td>Blading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inducers</td>
<td>2</td>
<td>4</td>
<td>G,I,J,K,L,M,N</td>
</tr>
<tr>
<td>Impellers</td>
<td>3</td>
<td>4</td>
<td>G,I,J,K,L,M,O</td>
</tr>
<tr>
<td>Vaned Diffusers</td>
<td>3</td>
<td>4</td>
<td>G,I,J,K,L,M,O</td>
</tr>
<tr>
<td>Coupled Elements (inducer + Impeller + Diffuser)</td>
<td>1</td>
<td>4</td>
<td>G,I,J,K,L,M,N,O</td>
</tr>
</tbody>
</table>

Assume 1 Stage Impeller, Full Annulus, and 32 CPUs available for non-coupled Elements, 96 CPUs for coupled elements solution
Pipe and duct analyses are routinely conducted

Manifold design and analysis capabilities lag the blading design and analysis capabilities in TD64

Volute Flow Path Design - VolGen
Pump Stage Design & Analysis Tools
Used at MSFC

♦ Meanline Tools
  • VolGen - Meanline design and analysis

♦ Geometry Generation
  • VolGen

♦ CFD Grid Generation
  • Gridgen

♦ CFD Analysis
  • Corsair - 3D unsteady compressible CFD

♦ CFD Post-Processing
  • Postfit - Corsair post-processor
  • Fieldview - general fluid post-processor

Moving to Phantom
## Inlet and Exits Readiness Matrix

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Readiness Level</td>
<td>Required Readiness Level</td>
<td>Issues</td>
</tr>
<tr>
<td>Inlet/Exits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe and Ducts</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Manifolds</td>
<td>2</td>
<td>4</td>
<td>G,H,I,J,K,L,O</td>
</tr>
</tbody>
</table>

Assumes there may be struts or vanes in the inlet and exits
Flange-to-Flange Analysis

- Flange-to-flange analysis currently not conducted at MSFC
  - Necessary to achieve correct boundary conditions and interactions
- Begin to integrate multiple domain analysis (turbine/pump + cavities)
- Flange-to-flange analysis includes
  - Primary flowpath only at Engine Steady State conditions
  - Primary flowpath + Cavities at Engine Steady State conditions
  - Primary flowpath + Cavities at Engine Transient conditions w/ simplified models for preburner/GG, seals, bearings, and turbine or pump
- Engine transient analysis is needed ASAP; however, we will not be ready for such an analysis within 5 years
  - Readiness levels will still be low in 5 years, but ground work will be laid for the transient analysis
From Detailed Turbine CFD

Detailed CFD Flange-to-Flange-Engine Steady-State

Output: Fluid Environment w/interactions between elements, Aero. Loads, Performance

To Systems, Stress, Dynamics, Thermal

Detailed CFD Flange-to-Flange w/ Cavities-Engine Steady-State

Output: Fluid Environment w/interactions between elements, Aero. Loads, Performance

To Systems, Stress, Dynamics, Thermal

Detailed CFD Flange-to-Flange w/ Pump, Preburner/GG, Seals, Bearings, etc. Simplified Models - Engine Transient

Output: Fluid Environment w/interactions between elements, Aero. Loads, Performance During Start-up and Shut-down

To Systems, Stress, Dynamics, Thermal

To Turbopump Analysis
## Flange-to-Flange Readiness Matrix

<table>
<thead>
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<tr>
<td></td>
<td>Current Readiness Level</td>
<td>Required Readiness Level</td>
<td>Issues</td>
</tr>
<tr>
<td>Flange-to-Flange</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary Flow Path, Engine Steady State</td>
<td>0</td>
<td>3</td>
<td>G,H,I,J,K,L,M,N,P,Q</td>
</tr>
<tr>
<td>Primary Flow Path + Cavities, Engine Steady State</td>
<td>0</td>
<td>3</td>
<td>G,H,I,J,K,L,M,N,P,Q</td>
</tr>
<tr>
<td>Primary Flow Path + Cavities, Engine Transient</td>
<td>0</td>
<td>1</td>
<td>G,H,I,J,K,L,M,N,P,Q</td>
</tr>
</tbody>
</table>
For a turbopump analysis, further integration of multiple domain analysis is necessary (preburner/gg + turbine + pump + cavities + bearings + seals)

- Multidisciplinary Analysis should be incorporated at some point to include rotordynamics, stress, and thermal analysis in addition to fluids

- Turbopump analysis includes
  - Engine steady state conditions
  - Engine transient conditions

- Because so many steps must be completed before we are ready for a turbopump analysis, readiness levels will remain low in 5 years
Turbopump Fluid Dynamics Analysis

Detailed Turbopump CFD Analysis - Engine Steady State

To Systems, Stress, Dynamics, Thermal

Detailed Turbopump CFD Analysis - Engine Transient

To Systems, Stress, Dynamics, Thermal
## Turbopump Readiness Matrix

<table>
<thead>
<tr>
<th>Element</th>
<th>Design and Analysis</th>
<th>Validation Data</th>
<th>Turn Around Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current Readiness Level</td>
<td>Required Readiness Level</td>
<td>Issues</td>
</tr>
<tr>
<td>Turbopump</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Steady State</td>
<td>0</td>
<td>1</td>
<td>G,H,I,J,K,L,M,N,P,Q,R</td>
</tr>
<tr>
<td>Engine Transient</td>
<td>0</td>
<td>1</td>
<td>G,H,I,J,K,L,M,N,P,Q,R</td>
</tr>
</tbody>
</table>
Manifold flow path design and analysis
- Initial meanline and geometry generation tools developed - Frank Huber

Unsteady, generalized fluids CFD codes are being developed - Dan Dorney (TD64) and Doug Sondak (Boston University)
- Aarvark (2D) and Phantom (3D) will be used to analyze gas and hydraulic turbines and pumps

Cavitation modeling is being developed and validated - (Ashvin Hosangadi CRAFT Tech.)
- Models will be implemented into Aardvark and Phantom

Wide flow diffuser concepts will be developed using Phantom and the Rocketdyne code, Enigma - TD64 and Rocketdyne