MSFC Turbine Performance Optimization (TPO) Technology Verification Status

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**Introduction**

- **Turbine performance optimization** → Increased reliability
  - Higher Isp
  - Higher thrust-to-weight

Turbine temperature
Engine Isp
Thrust-to-weight

- **Unsteady aero loads impact efficiency and life**

**Capability to optimize for turbine performance and accurately predict unsteady loads will allow for increased reliability, Isp, and thrust-to-weight. The development of a fast, accurate, validated aerodynamic design, analysis, and optimization system is required.**
Goal: Develop and demonstrate advanced design and analysis tools for optimized turbine performance

- Develop advanced turbine aerodynamic design procedure
- Apply advanced design procedure to an RLV fuel turbine to improve efficiency

Baseline $\eta_{t-t}$ $\rightarrow$ + 8 points (goal)

- Verify design and analysis with testing in air at MSFC
Both preliminary and detailed design were considered
  - Preliminary design - diameter, speed, number of stages, areas, chords, reaction, work split
  - Detailed design - vane and blade contours

Task Status
  - Preliminary design completed
  - Detailed aerodynamic design completed
  - Mechanical design of test rig completed
  - Test rig currently in manufacture

For this presentation, the Verification Status will be the primary focus of discussion
Team Members

♦ MSFC
  • Meanline and CFD analysis
  • CFD code enhancement
  • Rig design and testing
  • Task management

♦ Rocketdyne
  • Aerodynamic design
  • Systems analysis
  • Test support

♦ Riverbend Design Services (Frank Huber)
  • Design code development
  • Design consultant

♦ University of Florida
  • Optimization methodology development
  • Optimization application
Background - Baseline Turbine Description

♦ Design features
  • Supersonic turbine
  • 2 stages, full admission
  • First stage
    — 21 converging-diverging, straight centerline nozzles with rectangular cross sections
    — 52 impulse, unshrouded blades
  • Second stage
    — 49 vanes
    — 42 unshrouded blades
  • Mean Diameter = 10.16 in
  • Speed = 31,396 rpm

♦ Flow conditions
  • Gaseous hydrogen/oxygen mixture, $\gamma = 1.354$
  • $P_T = 2235$, $T_o = 2235^\circ R$, $\dot{m} = 62.04 \text{ lbm/s}$
  • $Pr_{t-s} = 8.71$
Background - Approach

- Preliminary design
  - Overall sizing (diameter, chords, etc.) and performance variables (speed, reaction, etc.)

- Design process - systematic application of RSM computationally coupled to a meanline analysis
  - Meanline Analysis
    - Predicts performance
    - Calculates gas conditions and velocity triangles
    - Generates flowpath elevation
    - Estimate of turbopump weight
    - Provides initial spanwise distribution of row exit angle
  - Meanline results used to populate the design space
  - Second order polynomials used to approximate response surface
  - Equation describing the surface interrogated to find maximum or minimum of chosen variable

Flowpath Elevations
Design features

- Supersonic turbine
- 2 stages, full admission
- First stage
  - 12 airfoil-type vanes
  - 30 impulse, unshrouded blades
- Second stage
  - 73 vanes
  - 56 unshrouded blades
- Mean Diameter = 11.4 in
- Speed = 32,084 rpm

Flow conditions same as baseline

Meanline predicted $\eta_{t-s}$ +9 higher than baseline

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Mean Diameter</td>
<td>1.12</td>
</tr>
<tr>
<td>Speed</td>
<td>1.02</td>
</tr>
<tr>
<td>Exit Annulus Area</td>
<td>1.08</td>
</tr>
<tr>
<td>1st Blade Height</td>
<td>1.50</td>
</tr>
<tr>
<td>1st Vane Axial Chord</td>
<td>1.30</td>
</tr>
<tr>
<td>2nd Vane Axial Chord</td>
<td>0.79</td>
</tr>
<tr>
<td>1st Blade Axial Chord</td>
<td>0.71</td>
</tr>
<tr>
<td>2nd Blade Axial Chord</td>
<td>0.62</td>
</tr>
<tr>
<td>Reaction (1st Stg)</td>
<td>0.10</td>
</tr>
<tr>
<td>Reaction (2nd Stg)</td>
<td>0.50</td>
</tr>
<tr>
<td>Work Fraction (1st Stg)</td>
<td>0.90</td>
</tr>
</tbody>
</table>
A detailed design was generated for the optimized preliminary design using current design practices → INTERIM DESIGN

Large number of variables made optimizing all rows simultaneously unfeasible

Design process broken into two steps

- STEP 1: Generate and optimize the mean airfoil contours
- STEP 2: Generate the 3D vanes and blades (schedule constraints precluded performing design optimization for the 3D vanes and blades)
Background - Airfoil Contour Design Process

♦ **STEP 1**: Choose design variables
  • Design variables chosen as those having the most effect of the airfoil contour

♦ **STEP 2**: Select combinations of variables to be analyzed to populate design space
  • DOE technique, orthogonal arrays, employed

♦ **STEP 3**: Analyze design points using quasi-3D, unsteady CFD for each stage
  • Parametrics were performed for the vane first with the baseline blade
  • Parametrics were then performed for the first blade with the optimized blade

♦ **STEP 4**: Train neural nets with CFD results to augment number of design points

♦ **STEP 5**: Approximate the design space using polynomial-based RSM

♦ **STEP 6**: Find the maximum $\eta_{t-t}$ using a generalized reduced gradient method
Background - 3D Design Process

- STEP 1: Stack the vanes and blades on their CGs with constant sections from hub to tip
- STEP 2: Twist blades according to free vortex distribution
- STEP 3: Perform 3D, unsteady, multistage CFD analysis of the turbine design
- STEP 4: Adjust angle distribution, sections, and stacking for improved aerodynamics
Aerodynamic Design Results - Final

**Baseline CFD Analysis**

**Optimized CFD Analysis**

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**Optimized Blade Rows**

Current improvement in turbine efficiency is 11 points. This could be traded for approximately 230° R in turbine inlet temperature or ~2.25 seconds of Isp, or a combination of the two.
Test Program Objectives

♦ **Verify TPO turbine design**
  - Map design and off-design performance (efficiency, flow capacity, and reaction)
  - Measure aerodynamic loads at design and off-design points (steady vane pressures, time-averaged and unsteady 1st blade pressures)

♦ **Verify design and analysis tools**
  - Map design and off-design efficiency
  - Measure row pressure drop
  - Measure circumferential and radial distributions of pressure, temperature, and flow angle at turbine exit
  - Measure detailed vane pressure distributions
  - Measure time-averaged and time-varying pressures on first stage blades

♦ **Produce detailed dataset for supersonic turbine**

♦ **Produce unique unsteady dataset for supersonic turbines**
  - Enhance understanding of dynamic environment in supersonic turbine
  - Provide CFD analysis validation

♦ **Demonstrate extended capabilities of Turbine Airflow Facility**
  - Addition of ejector for high pressure ratios
- **TPO turbine test article was designed in-house**
  - 70% scale model of the TPO to fit in the facility

- **Planned to use as much existing hardware as possible from SSME turbine rigs to reduce cost**
  - Unfortunately, rig requirements did not allow use of many existing parts
    - Bearings, slip ring, exhaust collector

- **Instituted drawingless design and manufacturing process**
  - Desire to reduce design cycle/iteration time and cost
  - First project to implement this process at MSFC
♦ Data management and flow
  • VISION: All design information stored in a database accessible by team
  • IMPLEMENTATION: EDS iMAN database was used for the management of the Computer Aid Design files providing team access to the design files
  • RESULTS: After passing the learning curve, team members had instant access to current design files for review or for use in analysis

♦ Data visualization
  • VISION: Team members will be able to access the database from their desktop computers and view all information (requirements, solid models, assembly procedures, etc.)
  • IMPLEMENTATION: EDS ProductVision used to view and mark-up files
  • RESULTS: Promising, put not trouble-free
    — After passing the learning curve, some team members used ProductVision quite successfully.
    — Because of cultural change, design reviews were not as thorough as they should have been allowing errors to persist longer than they should have
    — Unable to get ProductVision to perform fully as advertised. For example, annotations could not be viewed on the models necessitating separate note files
Manufacturing

- **VISION**: Fabrication of the test article would be conducted from solid models reducing programming and inspection time and cost
- **IMPLEMENTATION**: Provided Unigraphics 3D solid models to fabrication vendors
- **RESULTS**: All results are not in yet, but results are promising
  - Vendors for the instrumented first stage rotor and for the rest of the test article were able to provide good bids
  - Manufacturing from models currently going smoothly
  - Instrumented rotor vendor reduced schedule by one month due to success with working with the models
  - At the vendor's discretion, some drawings can be made for parts that are better/more cheaply obtained
The TPO turbine test article is highly instrumented to achieve the objectives of the test:

- **Performance**
  - Total pressures and temperatures at 5 radial locations on 4 inlet struts
  - Total pressures and total temperatures on exit rotating ring, 5 radial positions at 8 circumferential locations
- **Static pressure**
  - Static pressure taps from upstream of strut to EGV exit at ID and OD at 8 circumferential locations
  - 1st vane pressures at 5 axial locations (pressure and suction sides) at 50% span
  - 2nd vane pressures at 5 axial locations (pressure and suction sides) at 10%, 50%, and 90% span
- **Exit flow angles**
  - Probes measuring angles at locations corresponding to rake locations

### Instrumentation

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<tr>
<th>Type</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Steady-state pressure</td>
<td>267</td>
</tr>
<tr>
<td>Temperature</td>
<td>71</td>
</tr>
<tr>
<td>Fluctuating pressures:</td>
<td></td>
</tr>
<tr>
<td>1st stage blade</td>
<td>30</td>
</tr>
<tr>
<td>Casing</td>
<td>6</td>
</tr>
<tr>
<td>Accelerometers</td>
<td>4</td>
</tr>
<tr>
<td>Speed</td>
<td>2</td>
</tr>
</tbody>
</table>

**Flow Path Instrumentation Planes**

**1st Vane Pressure Taps @ 50% Span**
1st stage blades of test article instrumented with 30 Kulite semiconductor type miniature fluctuating pressure transducers

- Installed frequency response over 100 kHz (max 1st vane passing frequency ~ 2496 Hz)
- Flush-mounted and epoxied into pockets on the blade surface
- Most instrumentation concentrated at midspan with 8 transducers total at 10% and 90% span (2 axial locations each on suction and pressure surfaces)
- Sensors distributed over 6 blades
- Oxford University will perform extensive calibration of all surface mount pressure channels
  - Each of 6 blades placed in pressure chamber, outputs mapped over P-T
  - Span and offset sensitivity to temperature determined
  - Blade temperature via “sense voltage” mapped for determining blade temperatures in TPO testing
  - RPM and base strain sensitivities will be evaluated via a test coupon with 2 surface mount pressures
- Calibration information improves manufacture-quoted accuracy of 3% full-scale range to ~0.3% full-scale range
  - This level of accuracy is CRUCIAL to effectively mapping the blade surface pressure

*CFD Predicted 1st Blade Pressure Envelope at 50% Span.*
*Blue bars represent manufacture-quoted 3% full-scale range accuracy as an error band centered on the predicted mean pressure at 70% axial chord. Pink bars at 30% span represent expected improvement attained through calibration*
MSFC Turbine AirFlow Test Facility

- Blowdown facility using air (run times depend on inlet pressure and ejector)
- Regenerative thermal matrix heater
- Herschel venturi (large and small)
- Torquemeter (30, 500, and 1000 ft-lbf shafts)
- Gearbox (2:1, 1:1, and 1:2 ratios)
- Dynamometer (600 HP continuous)
- Axial or radial inflow and outflow
- Control parameters -- $P_0, T_0, N$, and $Pr$
- Exhaust to atmosphere or ejector can be used to pull vacuum pressures
  - Ejector is a new feature added to the facility
  - Checkout tests conducted November 01
♦ **Series A -- In-situ tare and calibration test**
  - Measurement of torque tare due to bearing and seal losses
  - Verification of on-blade pressure transducer calibration in rotating and non-rotating environment

♦ **Series B -- 1st blade unsteady pressure data acquisition**
  - Performed early to reduce risk of transducer failures

♦ **Series C -- Steady-state performance data testing**
  - **C1**: Preheat evaluation
    - Determination of preheat temperature to minimize time required for temperature stabilization during critical portions of performance testing
  - **C2**: Exit flow angle mapping
    - Angles obtained with probes will be used to set approximate rake angles for C3
  - **C3**: Performance data acquisition
# Test Operating Conditions and Envelope

## Control Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Point</th>
<th>Operating Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Fluid</td>
<td>air</td>
<td>air</td>
</tr>
<tr>
<td>Scale</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>Pressure Ratio (Total to Static)</td>
<td>8.71</td>
<td>4 to 12</td>
</tr>
<tr>
<td>Inlet Total Temperature</td>
<td>300 deg F</td>
<td>300 deg F</td>
</tr>
<tr>
<td>Inlet Total Pressure</td>
<td>70 psia</td>
<td>70 psia</td>
</tr>
<tr>
<td>Speed</td>
<td>10,413 rpm</td>
<td>4950 to 12,500 rpm</td>
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</tbody>
</table>

## Measured Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Point</th>
<th>Operating Range</th>
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</thead>
<tbody>
<tr>
<td>Mass Flow Rate</td>
<td>4.2 lbm/sec</td>
<td>4.2 lbm/sec</td>
</tr>
<tr>
<td>Exhaust Pressure (Total and Static)</td>
<td>8 psia</td>
<td>2 to 17.5 psia</td>
</tr>
<tr>
<td>Exhaust Temperature (Total)</td>
<td>62 deg F</td>
<td>35 to 185 deg F</td>
</tr>
<tr>
<td>Power</td>
<td>335 hp</td>
<td>160 to 420 hp</td>
</tr>
<tr>
<td>Torque</td>
<td>169 ft-lbf</td>
<td>100 to 220 ft-lbf</td>
</tr>
</tbody>
</table>

## Overview of Operating Conditions

The image shows a graph titled "Test Envelope" with the following data points:

- Pressure Ratio (PR) vs. U/Co
- Test envelope
- Test points
- Design point

The graph illustrates the envelope and data points for the test conditions.
♦ Meanline calculations were performed for the entire test matrix
  • Efficiency, torque, and exit flow angle plots were provided to the test engineer
♦ Unsteady CFD calculations were performed for select points in the matrix
♦ Comparisons made between meanline and CFD results
  • Velocity triangles are similar
  • Qualitatively, the efficiency trends are similar (except at PR = 4)
  • Efficiencies are consistently predicted higher by the meanline code
  • TPO supersonic test data and CFD to be used to calibrate meanline loss model
Meanline and CFD Prediction Comparisons

**Eta ts vs U/C isen**

- Pt/Ps = 8.71
- Pt/Ps = 4.0
- Pt/Ps = 12.0
- Pt/Ps = 8.71, CFD
- Pt/Ps = 12.0, CFD
- Pt/Ps = 4.0, CFD

**Eta ts vs RPM**

- Pt/Ps = 8.71
- Pt/Ps = 4.0
- Pt/Ps = 12.0
- Pt/Ps = 8.71, CFD
- Pt/Ps = 12.0, CFD
- Pt/Ps = 4.0, CFD

**Eta t-s Predictions CFD vs Meanline**

- Meanline Prediction
- CFD Prediction

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CFD Pretest Predictions

Unsteady Pressure Envelopes

Unsteady Pressure Trace - LE

Fourier Decomposition - LE
Successfully completed aerodynamic design and analysis phases of TPO project

Implemented "drawingless" mechanical design process
- First implementation at MSFC
- Implemented with varying degrees of success, but overall has been successful

Test article currently in fabrication

Testing in air to occur in August
- Highly instrumented test article for detailed performance maps and code validation data
- Fluctuating pressures on the 1st stage blades will be obtained. Extensively calibrated transducers ensure the required high degree of accuracy
- Pretest predictions complete. Comparisons between meanline and CFD predictions are qualitatively very good and quantitatively reasonable. Meanline-predicted efficiencies consistently higher than CFD predictions
- Unique supersonic turbine dataset will be used for design verification, code validation, and to provide insight into the flow phenomena of supersonic turbines