Summary of Recent Inducer Testing at MSFC and Future Plans

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Agenda

• Water Flow Test History
• Water Test Facility
• Recent
  - Inducer Hydrodynamic Forces
  - RS-83 Main Lox Inducer Performance
• Current and Future
  - RS-84 Main Lox Inducer Performance and Blade Loads
  - Pump Dynamic Transfer Functions: Mass Flow Gain and Cavitation Compliance
• Test Team
Water Flow Test History

1987 to 1988: SSME Fuel Pump Inlet Tests, Passive and Active
1990: SSME Lox Pump Radial Sideloads
1992: Inducer Test Loop (ITL) Operational
1992: SSME High-Pressure Lox Inducer Synchronous Vibration
1995: Pump Test Equipment (PTE) Operational
1995 to 1998: Alternate SSME Fuel Pump Impeller (6 Designs)
1995: SSME High-Pressure Lox Inducer Blade Loads
1996: SSME High-Pressure Lox Inducer Tip Clearance Effects
1997 to 1998: 2nd Source Lox Inducer and Modified Inlet Vane

SSME High-Pressure Fuel
Pump Inlet

SSME Lox
Pump Radial
Sideloads

Instrumented SSME High-
Pressure Lox Inducer
Water Flow Test History

1999: Fastrac/MC-1 Lox Pump
2000: Simplex Lox Pump Inducer
2000 to 2001: Baseline Unshrouded Impeller Tip Clearance Effects
2001: Advanced Unshrouded Impeller Tip Clearance Effects
2001: Cavitation-Induced Hydrodynamic Forces
2002: Inducer Test Loop Upgraded
2002: RS-83 Main Lox Pump Inducer
2003: COBRA Low Pressure Lox Pump
2003: RS-84 Main Lox Pump Inducer
2004: RS-84 Main Lox Inducer Blade Loads

SSME High-Pressure Lox Inducer
Fastrac/MC-1 Lox Pump
Water Test Facility
**Facility Operating Conditions**

- Shaft Speed: up to 6000 rpm
- Shaft Torque: up to 100 ft-lbf
- Flow Rate: up to 2900 gpm
- Inlet Pressure: 3 to 50 psia
- Discharge Pressure: up to 375 psia
- Water Temperature: 60 to 120 deg F

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**Water Test Facility**

[Diagram of the Water Test Facility showing components such as Slave Pump, Drive Motor Stand, Flow Control Valve, Reservoir, Test Article Exit, and Test Article Inlet.]
Water Test Facility

Test Article Discharge

6-inch Turbine Flow Meter

FLOW

50 hp Boost Pump

Test Article Inlet
Water Test Facility

Suction Specific Speed, \( N_{ss} = \frac{NQ^{\frac{3}{2}}}{NPSH^{\frac{3}{4}}} \)

\( NPSH = \) Net Positive Suction Head

Flow Coefficient, \( \phi = \frac{Q}{ND^3} \)

\( Q = \) Volumetric Flow Rate

\( N = \) Speed

\( D = \) Inducer Tip Diameter
Inducer Hydrodynamic Forces

- 6-component force and moment measurement device ("Rotating Balance") validated in water at engine-equivalent operating conditions with the SSME high-pressure Lox inducer.
Inducer Hydrodynamic Forces

Inlet guide vane assembly used to simulate volute exit condition (proper radial velocity gradient and incidence) in axial configuration.
Inducer Hydrodynamic Forces

- Sensitivity confirmed by directly measuring imbalance in air and buoyancy in water.

**Computed Maximum Imbalance***

<table>
<thead>
<tr>
<th>Imbalance (oz-in)</th>
<th>1.0</th>
<th>0.9</th>
<th>0.8</th>
<th>0.7</th>
<th>0.6</th>
<th>0.5</th>
<th>0.4</th>
<th>0.3</th>
<th>0.2</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (rpm)</td>
<td>0</td>
<td>500</td>
<td>1000</td>
<td>1500</td>
<td>2000</td>
<td>2500</td>
<td>3000</td>
<td>3500</td>
<td>4000</td>
<td>4500</td>
</tr>
</tbody>
</table>

With Added Mass

Measured Imbalance

Clean Assembly

**Measured Imbalance** = 0.058 ± 0.015 oz-in

**Difference (Added Mass - Clean)** = 0.596 ± 0.023 oz-in

**Expected Difference** = 0.596 ± 0.022 oz-in

*Includes piece-part allowable imbalance, assembly misalignment, etc.

**Measured buoyancy** = 1.12 ± 0.26 lbf

**Computed buoyancy** = 1.27 lbf

![Diagram of forces and measurements]
Inducer Hydrodynamic Forces

- Inducer steady and unsteady performance consistent with previous experimental tests.

- Observed cavitation modes for the 4-bladed inducer: symmetric tip vortex, alternate blade, and indications of "higher-order" cavitation.

\[ \text{Head Coefficient} = \frac{\text{Total Pressure Rise}}{\rho U_{\text{tip}}^2} \]

\[ \text{Normalized Flow Coefficient} = \frac{\phi}{\phi_{\text{Design Point}}} \]

Slight difference on onset of alternate blade cavitation and slope attributed to inlet condition - guide vane simulator versus "baby pants" inlet volute.
Inducer Hydrodynamic Forces

- Cavitation modes captured on strobed SVHS and high-speed video tape.

Direction of Rotation

FLOW

Frame Rate = 30 fps
Speed = 4200 rpm
Inducer Hydrodynamic Forces

- Radial force magnitude and angle relative to inducer sensitive to cavitation mode.
- Radial force magnitude comparable to similar experimental investigations of 3 and 4-bladed inducers.
- Shifting pitch and yaw moment consistent with leading edges "unloading" and center of pressure moving axially with increasing cavitation intensity.
Inducer Hydrodynamic Forces

Simultaneous Single-Cell Rotating Disturbances at 8.7N and 10.2N Moving in Opposing Directions "Higher-Order Cavitation"

Structural Bending Mode "Split" with Forward and Backward Propagation

4 x Blade Pass (4N) in Stationary Frame

7 x Blade Pass (7N) in Rotating Frame
RS-83 Main Lox Inducer
RS-83 Main Lox Inducer


Rotating cavitation appeared as a 5% drop in inducer steady-state head rise.

\[
\text{Normalized Suction Specific Speed} = \frac{N_{ss}}{N_{ss, \text{Design Point}}}
\]

\[
\text{Head Coefficient} = \frac{\text{Total Pressure Rise}}{\rho U_{\text{Tip}}^2}
\]

\[
\text{Normalized Flow Coefficient} = \frac{\phi}{\phi_{\text{Design Point}}}
\]
RS-83 Main Lox Inducer

- Small measured deviation with exit flow closely following blade at and near design flow coefficient.

At Inducer Exit:

- Approaching hub separation with decreasing flow rate.

- Decreasing Flow Rate
RS-83 Main Lox Inducer

- Suction capability trend consistent with predicted although peak performance shifted to lower flow coefficient.
- Measured efficiency relatively uniform with flow coefficient and equal to predicted at design point.

NPSH margin = 23% at design flow coefficient
RS-83 Main Lox Inducer

- Single-cell rotating disturbance observed at 70% of design flow moving in direction of inducer rotation (1.3 x N).
RS-83 Main Lox Inducer

- Inlet backflow and swirl captured on high-speed digital video.

Tufts on near pipe wall aligned with swirling backflow.

~ 1.8 x Dia Upstream of Leading Edge

FLOW

~ 4.1 x Dia Upstream of Leading Edge

Frame Rate = 7000 fps
Speed = 4200 rpm
**Future**

- **Objective:** Directly measure inducer blade loads by miniature pressure transducers embedded in blades.
- Technology demonstrated in air turbine applications.
- Water demonstration partially successful - performance matched reference device but life limited by sealant failure.
Future

- Objective: Revive Cal Tech's dynamic pump test facility, replicate data, and establish institutional capability to measure pump dynamics - mass flow gain and cavitation compliance.

Video courtesy of Dr. Christopher Brennen, California Institute of Technology
Test Team Members

- Unsteady Data Analysis: Thomas Zoladz, Andrew Mulder
- Facility Operation: James Aaron, Bo Jones, Doug McBride
- Data Acquisition System Development: Joey Kirkpatrick, Richard Norman, David Goodwin
- Test Article Design: Dwight Goodman, John Forbes, Phyllis Rabun, John Farrow