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
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
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
Water Test Facility

Suction Specific Speed, \( N_{ss} = \frac{NQ^{\frac{1}{2}}}{NPSH^{\frac{3}{4}}} \)

\( NPSH = \text{Net Positive Suction Head} \)

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

\( Q = \text{Volumetric Flow Rate} \)

\( N = \text{Speed} \)

\( D = \text{Inducer Tip Diameter} \)
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

Inducer Diameter = 5.160 inch (Full Scale)

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**

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**With Added Mass**

**Measured Imbalance**

- **Clean Assembly**
- **With Added Mass**

**Speed (rpm)**

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

**Difference** = Buoyancy

- **Measured buoyancy** = 1.12 ± 0.26 lbf
- **Computed buoyancy** = 1.27 lbf

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

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.

Normalized Suction Specific Speed = \( \frac{N_{ss}}{N_{ss \text{ Design Point}}} \)

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

Normalized Flow Coefficient = \( \frac{\phi}{\phi_{\text{Design Point}}} \)

Hub separation with strong radial velocity gradient.
RS-83 Main Lox Inducer

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

At Inducer Exit:

\[ C \theta \]

\[ \frac{Cm}{U} \]

\[ \beta \]

Decreasing Flow Rate

Approaching hub separation with 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

Peak suction capability at approximately 80% - 85% of design flow coefficient.
RS-83 Main Lox Inducer

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

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

~ 1.8 x Dia Upstream of Leading Edge

Tufts on near pipe wall aligned with swirling backflow.

~ 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