Experimental Study of Unshrouded Impeller Pump Stage Sensitivity to Tip Clearance

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Background

- A turbopump develops required head by spinning very fast
  - The faster the pump rotates, the more head is generated
- A shroud is a heavy metal casing which covers blade passages
  - Shrouds help maintain performance and control axial thrust
- As a pump spins faster, stresses due to centrifugal force increase
  - The weight of the shroud increases the stress on the blades
  - This stress limits the speed at which a pump can operate
- A pump impeller without a shroud has less centrifugal force
  - Unshrouded Impellers operate at higher speeds with lower stress
  - Higher speeds allow Unshrouded impellers to generate more head
  - Use of unshrouded impellers allows for reduction of pump stages
- Tip clearance affects performance of unshrouded impeller
  - Experimentally quantify tip clearance effects on pump performance
Unshrouded Team Members

**MSFC Support**
- TD63 - Test Engineer, *Skelley*; Unsteady Data Reduction, *Zoladz*; Test Article Build Engineer, *Branick*
- TD64 - Impeller Design, Analysis, Test Engineer, and Mgmt, *Williams*

**Contractor Support**
- Pratt & Whitney - IGV, Baseline Impeller, and Diffuser Design, *Erler*
- Boeing, Rocketdyne - Advanced Impeller Design, Analysis, and Tool Development, *Prueger, Chen, & Williams*
- A2I2 (Micro Craft Inc.) - Rig Mechanical Design and Fabrication, *Tyler*
Objective:
- Experimentally determine unshrouded impeller performance sensitivity to tip clearance

Approach:
- Determine impeller efficiency at scaled operating conditions in water at MSFC’s Pump Test Equipment (PTE) Facility
- Test unshrouded impeller at three different tip clearances
- Test each tip clearance configuration at on- and off-design conditions
- Collect unsteady- and steady-state data in each configuration
- Determine impeller efficiency directly using drive line torquemeter and pump inlet and exit total pressure measurements
Facility Description

- Test was conducted at MSFC’s PTE Facility
  - PTE is a closed-loop water flow facility with 10,000 gallon reservoir
  - Deaeration and pressurization systems, facility flow meter, flow control valve, torquemeter, and 350 horsepower drive motor
Unshrouded Impeller Technology Water Rig
PTE Test Stand and Instrumentation Rack
Instrumentation Rack

- Housing for pressure transducers, SCXI modules, and power supplies
- Transducers selected for application, accuracy, and range
  - Honeywell
  - Validyne
  - Druck
  - Sensotec
Real Time Data Display Reduction

- **LabVIEW measurement and display system**
  - Continuously update and display the set point parameters
  - health monitoring measurements
    - Temperature
    - Leakage flow
- **LabVIEW data storage system**
  - Pressures
  - Flow rates
  - Temperatures
  - Speed
  - Torque
- **Detailed reduction and analysis**
  - Completed later by test engineer using stored data
  - Reduction performed using excel spreadsheet

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PTE Facility Operation Panel

- Control pump operation
  - Speed
  - Flow
  - Inlet pressure
- Maintain test set points
- Pump health monitoring
  - Bearing temperature

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Test Article Description

- Modular Design of the Test Article Allows for Use With a Variety of Inlet, Impeller, and Diffuser Configurations
  - Inlet Adapter
  - Inlet Guide Vane Assembly
  - 6+6 Impeller
  - Front Shroud
  - Shims
  - Diffuser
Unshrouded Impeller Test Article Cross Section

Clearance 1
- \( a = 0.3123 \) inches
- \( b = 0.7526 \) inches
- \( b_2 = b - a = 0.4393 \) inches
- \( d = 0.2591 \) inches
- \( c = a - d = 0.0532 \) inches
- \( \%b_2 = c / b_2 = 12.11\% \)

Clearance 2
- \( a = 0.3123 \) inches
- \( b = 0.7526 \) inches
- \( b_2 = b - a = 0.4393 \) inches
- \( d = 0.2358 \) inches
- \( c = a - d = 0.0765 \) inches
- \( \%b_2 = c / b_2 = 17.41\% \)

Clearance 3
- \( a = 0.3123 \) inches
- \( b = 0.7526 \) inches
- \( b_2 = b - a = 0.4393 \) inches
- \( d = 0.3003 \) inches
- \( c = a - d = 0.0120 \) inches
- \( \%b_2 = c / b_2 = 2.73\% \)
Test Measurements

- **Steady-state measurements**
  - Surface static pressure taps are grouped into 27 measurement planes
    - Static pressure taps concentrated at: front shroud, diffuser, rear shroud, and discharge housing
  - Total pressure probes are located in the facility inlet and exit spools
  - Flow direction probes are located just downstream of the inlet guide vanes and impeller discharge
  - Facility flow rate and the leakage flows in 2 external metering lines
  - Shaft speed and shaft torque measured directly
  - Water and bearing temperatures measured
  - Dissolved oxygen measured

- **Unsteady measurements**
  - High frequency pressure transducers located in facility inlet and exit spools
  - Three high frequency pressure transducers located at impeller discharge
  - Single accelerometer mounted on bearing housing
Measurement Locations

Front Shroud

Diffuser

Rear Shroud

Discharge Collector

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Test Matrix

Performance evaluated over range of scaled operating conditions at constant shaft speed of 3000 RPM

- Three test series were conducted to fully map pump performance at different clearances
- Series included definition of the basic head-flow curve at constant suction specific speed
- Suction performance mapping across a wide range of flow rates
- Unsteady pressures and accelerations were recorded during inlet pressure and speed ramps at selected flow coefficients
Stage Head Coefficient
Noncavitating Stage Head Coefficient vs Normalized Impeller Flow/Speed Ratio

Speed = 3000 rpm
Design Impeller Flow/Speed Ratio = 0.2827
Stage Head Coefficient = $32.174 \times 144 \times \text{DP}_\text{PUMP} / (\text{Density} \times U_2^2)$

Average stage head coefficient at design point
- 0.60 - 2.73%B2
- 0.58 - 12.11%B2
- 0.50 - 17.41%B2

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Impeller Head Coefficient

Noncavitating Impeller Head Coefficient vs Normalized Impeller Flow/Speed Ratio

Average impeller head coefficient at design point

- 0.67 - 2.73% B2
- 0.65 - 12.11% B2
- 0.56 - 17.41% B2

Speed = 3000 rpm
Design Impeller Flow/Speed Ratio = 0.2827
Impeller Head Coefficient = \( \frac{32.174 \times 144 \times DP_{\text{IMPELLER}}}{\text{Density} \times U_2^2} \)
Stage Efficiency
Noncavitating Stage Efficiency vs Normalized Impeller Flow/Speed Ratio

Average stage efficiency at design point
- 0.72 - 2.73%B2
- 0.70 - 12.11%B2
- 0.61 - 17.41%B2

Speed = 3000 rpm
Design Impeller Flow/Speed Ratio = 0.2827
Stage Efficiency = \( \frac{Q_{\text{FLANGE}} \times DP_{\text{PUMP}} \times 144 \times 231 \times 32.2}{(550 \times 60 \times 32.174 \times 12^3)} \) / Power_Imp
Power_Imp = \( \frac{2 \times \text{TORQUE} \times \text{SPEED}}{(550 \times 60)} \) - Power_Mech

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Impeller Efficiency
Noncavitating Impeller Efficiency vs Normalized Impeller Flow/Speed Ratio

Average impeller efficiency at design point
- 0.84 - 2.73%B2
- 0.82 - 12.11%B2
- 0.72 - 17.41%B2

Shrouded impeller efficiency from loss model - 0.88

Speed = 3000 rpm
Design Impeller Flow/Speed Ratio = 0.2827
Impeller Efficiency = \( \frac{Q_{\text{Impeller}} \times DP_{\text{IMPELLER}} \times 144 \times 231 \times 32.2}{(550 \times 60 \times 32.174 \times 12^3)} \) / Power_Imp

Q_Impeller = Q_FLANGE + Q_LEAK_152 + Q_LEAK_345
Power_Imp = \( 2 \times \pi \times \text{TORQUE} \times \text{SPEED} / (550 \times 60) \) - Power_Mech

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Unshrouded Impeller Experimental Study
Unsteady Data Overview

- determine impeller / diffuser fluctuating pressure sensitivity to tip clearance
  - over Nss
  - across Q/N
  - correlate unsteady data to stage performance
- identify / map unsteady flow features which could inhibit the development of unshrouded pump technology
  - rotating diffuser / impeller stall
  - rotating cavitation
  - rotor / stator interaction loads (synchronous - impeller wake)
Unsteady Data Overview - baseline clearance

- psi_stage_170.0
- psi_stage + disch_p' comp_170.0

*all data normalized by 2*q_tip_impeller

**unsteady composite bandwidth is 0 - 1560 Hz (2.6*discharge wake)
Unsteady Data Overview - across build (rated flow)

- psi_stage_170_0
- psi_stage + disch_p' comp_170_0

rated flow baseline clearance

decreasing clearance

(diffuser stall throughout test, frequency slightly dependent on Nsa)

rotating stall @0.138N (6.9 Hz)

*all data normalized by 2^q_tip_impeller
**unsteady composite bandwidth is 0 - 1560 Hz (2.6*discharge wake)

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Unsteady Data Overview - cavitation induced oscillations

joint time-frequency map of impeller discharge pressure in tight clearance at rated flow

increasing Nss

3N (alt. blade)

rc

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Unsteady Data Overview - flow excursion - baseline clearance

- psi_stage_174_0{}
- psi_stage + disch_p'_comp_174_0{}

flow ramp with baseline clearance

*all data normalized by 2*q_tip_impeller

**unsteady composite bandwidth is 0 - 1560 Hz (2.6*discharge wake)

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Unsteady Data Overview - flow excursion - opened clearance

*psi_stage_297_0.png*

**psi_stage + disch_p_comp_297_0.png**

flow ramp with max. clearance

*all data normalized by 2\*q_tip_impeller

**unsteady composite bandwidth is 0 - 1560 Hz (2.8*discharge wake)

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Unsteady Data Overview - rotating stall

joint time-frequency map of impeller discharge $p^*$
opened clearance during flow ramp

decreasing flow

0.14N
0.26N
3N
6N

incr. flow

Time (sec)

Frequency (Hz)

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Unsteady Data Overview - flow excursion - tight clearance

* all data normalized by $2\times q_{tip\_impeller}$

** unsteady composite bandwidth is 0 - 1560 Hz (2.6*discharge wake)

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Unsteady Data Overview - rotor_stator interaction

120% flow across locations

120% flow across builds_location C (vane l.e. suction)

- map impeller wake across diffuser channel versus Q/N and axial clearance
- use synchronous time averaging process
- build data set for time-accurate CFD

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Unsteady Data Overview - rotor_stator interaction
Unsteady Data Summary

- determine impeller / diffuser fluctuating pressure sensitivity to tip clearance
  - Nss not a major influence on overall composite unsteady pressure at impeller discharge
  - Q/N excursions identified both single and dual-cell rotating stall at impeller / diffuser interface
    - hysteresis (w/r to flow) and axial clearance dependence identified
  - unsteady data to stage performance correlation (head loss) most pronounced during rotating stall with some correlation during rotating cavitation (2-cell) and alternate blade (3N) cavitation

- identify / map unsteady flow features which could inhibit the development of unshrouded pump technology
  - rotating diffuser / impeller stall mapped
  - rotating and alternate-blade (attached) cavitation mapped
  - rotor / stator interaction loads characterized versus Q/N and axial clearance