MEASUREMENT OF STATIC LOAD PERFORMANCE IN A WATER LUBRICATED HYBRID THRUST BEARING

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• Compressors, turbochargers, turbo expanders, blowers, etc., rely on thrust bearings as they are the primary means of axial load support and rotor position.

• Axial loads in turbomachinery are speed and pressure dependent, their prediction is largely empirical.

• Thrust bearing design relies on validated models, experimental results will benchmark predictive tools for thrust bearings.
Cross Section of Thrust Bearing Test Rig

- Dynamic Load Mechanism
- Thrust Load Mechanism
- Aerostatic Bearings
- Test Thrust Bearing
- Air Buffer Seals
- Rotor Assembly
- Radial Hydrostatic Bearings
- Slave Thrust Bearing
Exploded View of Thrust Bearing Test Rig
Schematic Thrust Bearing Test Rig

TB load shaft + housing

Axial Force

Radial (air) Bearings: $K_{xx}, K_{yy}, C_{xx}, C_{yy}$

Radial (water) Bearings: $K_{xx}, K_{xy}, K_{yx}, K_{yy}, C_{xx}, C_{yy}, C_{xy}, C_{yx}$

Thrust Bearings (Test & Slave): $K_z, C_z$

Rotor (8.5 lb)

Test Thrust Bearing
Summary of Work

• Measurement of static load performance of a thrust bearing for operation with water at various bearing supply pressure and low shaft rotational speed.
  ✓ Axial Clearance vs. Load
  ✓ Flow Rate vs. Clearance
  ✓ Recess Pressure Ratio vs. Clearance
  ✓ Comparison to Predictions
  ✓ Derived Axial Stiffness
Closed Loop Water Supply System

Max Thrust Bearing Operating Conditions:
- Supply Pressure: **150 psi**
- Flow Rate: **25 GPM**

<table>
<thead>
<tr>
<th>Components</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main pump</td>
<td>$1,975</td>
</tr>
<tr>
<td>Return pump</td>
<td>$596</td>
</tr>
<tr>
<td>Reservoir tank</td>
<td>$475</td>
</tr>
<tr>
<td>Heat exchanger (in-house)</td>
<td>-</td>
</tr>
<tr>
<td>Deionizing plant &amp; filters</td>
<td>$494</td>
</tr>
<tr>
<td>Electrical wiring</td>
<td>$3,271</td>
</tr>
<tr>
<td>Piping and fittings</td>
<td>$1,765</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>$363</td>
</tr>
<tr>
<td><strong>Total system cost</strong></td>
<td><strong>$8,939</strong></td>
</tr>
</tbody>
</table>

Completed: **January 2016**
(Total time to complete: **3 months**)

[Diagram of closed loop water supply system]
Closed Loop Water Supply System

The system utilizes deionized water to prevent corrosion.

Component Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main pump</td>
<td>7.5 HP, 17 stage, vertical turbine</td>
</tr>
<tr>
<td>Return pump</td>
<td>2.0 HP, centrifugal</td>
</tr>
<tr>
<td>Reservoir tank</td>
<td>500 gallon</td>
</tr>
<tr>
<td>Heat exchanger</td>
<td>Max operating conditions: 350°F, 300psig</td>
</tr>
</tbody>
</table>

Max Thrust Bearing Operating Conditions:
- Supply Pressure: 150 psi
- Flow Rate: 25 GPM
Water Lubricated Hybrid Thrust Bearings

<table>
<thead>
<tr>
<th>Nominal</th>
<th>Axial Clearance</th>
<th>76 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing</td>
<td>Inner Diameter</td>
<td>40.6 mm</td>
</tr>
<tr>
<td></td>
<td>Outer Diameter</td>
<td>76.2 mm</td>
</tr>
<tr>
<td></td>
<td>Axial Clearances</td>
<td>13 μm - 140 μm</td>
</tr>
<tr>
<td>Pockets</td>
<td>Number of Pockets</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Mean Diameter</td>
<td>54.9 mm</td>
</tr>
<tr>
<td></td>
<td>Radial Length</td>
<td>8.1 mm</td>
</tr>
<tr>
<td></td>
<td>Arc Length</td>
<td>20°</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>445/508 μm</td>
</tr>
<tr>
<td></td>
<td>Pocket/Wetted Area Ratio</td>
<td>0.19</td>
</tr>
<tr>
<td>Orifices</td>
<td>Diameter</td>
<td>1.80/1.55 mm</td>
</tr>
</tbody>
</table>

\[ C(x, y) = C_0 + \delta_x y + \delta_y x \]

- \( C_0 = \) Axial Clearance
- \( \delta_x = \) Tilt about \( x \)-axis
- \( \delta_y = \) Tilt about \( y \)-axis

\[ A = \frac{\pi}{4} (D_{out}^2 - D_{in}^2) \]

Bearing area = 32.6 cm²
## Measurements

<table>
<thead>
<tr>
<th>Controlled Inputs</th>
<th>Measured Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Speed ($\omega$)</td>
<td>Axial Clearance at Center of Thrust Bearing ($C_0$)</td>
</tr>
<tr>
<td>Water Supply Pressure ($P_S$)</td>
<td>Tilt about x-axis ($\delta_x$)</td>
</tr>
<tr>
<td>Axial Load ($W$)</td>
<td>Tilt about y-axis ($\delta_y$)</td>
</tr>
<tr>
<td></td>
<td>Supply Flow Rate ($Q_S$)</td>
</tr>
<tr>
<td></td>
<td>Flow Rate through Inner Diameter ($Q_{ID}$)</td>
</tr>
<tr>
<td></td>
<td>Recess Pressure ($P_R$)</td>
</tr>
</tbody>
</table>

![Experimental Setup Diagram]

- **Static Loader**
- **Impact Gun**
- **Load Cell**
- **Load Shaft**
### Thrust Bearing Performance at Low Rotor Speed

**Findings:** Axial clearance increases as water supply pressure increases.

Clearance decreases as applied load increases.

Slave thrust bearing operates with a larger clearance than test thrust bearing because of its larger orifice diameter.

Note: Large variation in clearance across face of thrust bearing. Variation in clearance across face increases as axial clearance increases.

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**3 krpm (surface speed = 12 m/s)**

Test Thrust Bearing

Slave Thrust Bearing

**Axial Clearance [μm]**

<table>
<thead>
<tr>
<th>Specific Axial Load [bar]</th>
<th>W/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**Axial Clearance [μm]**

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</tr>
<tr>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**Graph Details:**

- **ω** = 3 krpm
- **T** = 31 °C
- **Pa** = 0 bar(g)
**Test Thrust Bearing Flow Rate at Low Rotor Speed**

**Findings:** Supply flow rate and flow rate through inner diameter increase as axial clearance or supply pressure increases. Recess pressure decreases as axial clearance increases.

\[ \frac{P_R - P_a}{P_S - P_a} = \text{Recess Pressure Ratio} \]
Thrust Bearing Ratio of Flows at Low Rotor Speed

\[ Q_S = \text{Supply Flow Rate} \]

\[ Q_{ID} = \text{Flow Rate through Inner Diameter} \]

\[ \frac{Q_{ID}}{Q_S} = \text{Ratio of Flow through Inner Diameter to Supply Flow} \]

**Findings:** Ratio of flow through inner diameter to supply flow is fairly constant (~40%), decreasing slightly as axial load increases (clearance decreases).
Test TB Reynolds Numbers at Low Rotor Speed

Findings: $Re_{ID}$ and $Re_{OD}$ increase as the supply pressure increases due to the increase in flow rate.

Reynolds Number of Radial Flow through Outer Diameter

$Re_{OD} = \frac{\rho Q_{OD}}{\pi \mu D_{out}}$

Reynolds Number of Radial Flow through Inner Diameter

$Re_{ID} = \frac{\rho Q_{ID}}{\pi \mu D_{in}}$

<table>
<thead>
<tr>
<th>Axial Clearance</th>
<th>Inner Diameter</th>
<th>Outer Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 μm</td>
<td>160</td>
<td>300</td>
</tr>
<tr>
<td>80 μm</td>
<td>650</td>
<td>1220</td>
</tr>
</tbody>
</table>

$Pa = 0$ bar(g)
$\omega = 3$ krpm
$T = 31$ °C
Thrust Bearing Performance at Low Rotor Speed

Findings: $C_d$ reaches $\sim 0.62$ at large clearance.

\[ C_d = \frac{Q_O}{A_O \sqrt{\frac{2}{Q}(P_S - P_R)}} \]

$C_d =$ Orifice Discharge Coefficient  
$Q_O =$ Flow Rate through Orifice  
$A_O =$ Area of Orifice

<table>
<thead>
<tr>
<th>Water Supply Pressure ($P_s$)</th>
<th>Estimated Orifice Discharge Coefficient ($C_d$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.76 bar(g)</td>
<td>0.61 ± 0.07</td>
</tr>
<tr>
<td>3.45 bar(g)</td>
<td>0.62 ± 0.05</td>
</tr>
<tr>
<td>4.14 bar(g)</td>
<td>0.64 ± 0.02</td>
</tr>
</tbody>
</table>
Findings: The predicted axial clearance is larger than the estimated axial clearance, especially when operating with a high axial load (low axial clearance).
Findings: Measurements of recess pressure and flow rate correspond well to predictions at a low axial load (high axial clearance). However, measurements do not correlate well at a high axial load.
Thrust Bearing Performance at Low Rotor Speed

**Findings:**
Exp. axial stiffness is of same magnitude as predicted axial stiffness but happens at a lower clearance than the predicted axial stiffness.

**Findings:**
Measured axial load and estimated axial stiffness decay exponentially.

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**Estimated axial stiffness**

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**Load vs Clearance**

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**Findings:**
2.76 bar(g): $W = (656 \text{ N}) \exp \left( \frac{-0.027}{\mu m} \right), R^2 = 0.996$

3.45 bar(g): $W = (819 \text{ N}) \exp \left( \frac{-0.027}{\mu m} \right), R^2 = 0.999$

4.14 bar(g): $W = (1030 \text{ N}) \exp \left( \frac{-0.029}{\mu m} \right), R^2 = 0.999$

---

**Diagram:**

- $P_a = 0 \text{ bar(g)}$
- $\omega = 3 \text{ krpm}$
- $T = 31 ^\circ \text{C}$
Conclusions

Thrust Bearing:

• Axial clearance and flow rate increase as the water supply pressure increases or the axial load decreases.
• Predictions accurate on the influence of applied load and supply pressure on the thrust bearing performance.
• Discrepancies exist between the magnitudes of the measurements and predictions when operating with a high axial load (low axial clearance) because of the large thrust collar misalignment.
• A higher water supply pressure into the bearings could mitigate the misalignment of the thrust collar.
Main objectives are to automate the procedure for identification of dynamic force coefficients and to measure the performance of a water lubricated hydrodynamic TB.

The tasks to be performed are:

• Design and fabrication of a new hydrodynamic thrust bearing (eight pads).
• Troubleshooting of load mechanism for sound identification of axial force coefficients.
• Measurement of axial clearance vs. static thrust load (max. \( W=670 \) N [2.0 bar specific load]) for rotor speed to a max. 9 krpm. The water will be supplied at just above ambient pressure.
• Measurement of TB axial response from impacts and identification of axial stiffness, damping and inertia force coefficients.

The proposed work will benchmark a predictive tool for hydrodynamic thrust bearings.

Tilting pad thrust bearings have the potential to reduce the influence of misalignment.
Support for graduate student (20 h/week) x $2,200 x 12 months $26,400
Fringe benefits (2.7%) and medical insurance ($360/month) $4,995
Supplies for test rig (filters, hoses, etc.) $215
Manufacture of Dynamic Thrust Bearing $4,300
Tuition three semesters ($363 credit hour x 24 h/year) $9,090

$45,000

The products of the research are important for compressors- barrel and integrally geared, turbochargers and turbo expanders, blowers, etc.


Acknowledgments

Thanks to Turbomachinery Research Consortium and TAMU Turbomachinery Laboratory for the support and opportunity.

Learn more at http://rotorlab.tamu.edu
Other material
Findings: The clearance at the center of the thrust bearing and the axial load are constant. However, the tilt about each axis varies periodically (phase lag by 90°).
Thrust Bearing Performance at Low Rotor Speed

Findings: The thrust collar tilts about each axis with 1X frequency of 50 Hz (3,000 rpm).
Thrust Bearings Tilt Angles at Low Rotor Speed

**Findings:** Large variation in clearance across face of thrust bearing. Variation in clearance across face increases as axial clearance increases.
Structural Force Coefficient Derivation

1-DOF Model of Test TB for Parameter Identification

Stiffness: \( Re(H(\omega)) \rightarrow (K - M\omega^2)_{TTB} \)

Damping: \( Im(H(\omega)) \rightarrow C_{TTB}\omega \)

Where,

\[
H(\omega) = \frac{\overline{F_d(\omega)} - M\overline{A}(\omega)}{\overline{z_\omega(\omega)}}
\]

\[
= K_{TTB} - M_{TTB}\omega^2 + i\omega C_{TTB}
\]

EOM: Frequency Domain
Preliminary Dynamic Test Results

Typical Axial **Impact** Force and FFT Amplitude

Findings: Impact load measurement behaves as expected. Length of impact as well as the peak amplitude of force are adjustable.
Preliminary Dynamic Test Results

Typical thrust bearing **axial displacement** with respect to rotor thrust collar versus time and FFT amplitude.

Motion due to an **impact** force along the **axial direction**.

Unusual behavior at **low frequencies** (less than 200 Hz): Troubleshooting of the load mechanism is underway in order to better excite the system.
USET Thrust Bearing Test Rig

USET Research Program (2005-2008): $787,300
Test Rig: $288,500
Objective and Tasks (2005-2008)

Test rig funded by USET (AF) program

- Design and construction of thrust bearing test rig.
- Measurements of minimum film thickness, pocket pressures, and flow rates in a water hybrid thrust bearing at various speeds and loads.
- Comparison of test data to prediction of performance from XLHYDROTHRUST.