Measurements of Rotordynamic Response in a High temperature Rotor Supported on Two Metal Mesh Foil Bearings

TRC-BC001-12

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Mast-Childs Professor

May 2012

TRC Project 32513/1519FB
Metal Mesh Foil Bearing (MMFB)

MMFB COMPONENTS: bearing cartridge, metal mesh ring and top foil

Hydrodynamic air film develops between rotating shaft and top foil.

WHY METAL MESH?

- Large hysteresis damping.
- Wide temperature range
- Damping unaffected by soaking in oil
- Empirical model available (Vance et al., 2000-2005)
- Hybrid gas bearings with metal mesh improves overall performance.
- Enhanced damping without compromising stiffness.
- Static load does not affect damping
- Shape memory alloys (expensive) gives + damping as excitation amplitude grows (Ertas et al., 2008-2010)

Potential applications: ACMs, micro gas turbines, turbo expanders, turbo compressors, turbo blowers, automotive turbochargers, APUs
Objective: Demonstrate high temperature reliable operation of MMFB with adequate thermal management.

a) Construct two MMFBs fitting test rig.
b) Measure rotor response for temperatures to 200 ºC & speed to 50 krpm
c) Compare thermal performance: MMFB vs. bump-foil bearing
TRC Budget  Metal Mesh Foil Bearings

Support for graduate student (20 h/week) x $ 1,700 x 12 months  $ 21,600
Fringe benefits (0.6%) and medical insurance ($191/month)  $ 2,419
Travel to (US) technical conference  $ 1,200
Tuition three semesters ($3,488 x 3)  $ 10,138
Supplies for test rig and construction of test bearings  $

$ 38,557

Research will characterize, qualitatively and quantitatively, MMFBs of low cost, simple in construction, and suited for high temperature operation. The work is important for turbochargers, turboexpanders and microgas turbines.
Test rig for high temperature tests

Max. rotor speed 50 krpm
Coil heater warms hollow rotor from inside (max 300 C).
Imbalance masses added at two ends of rotor (in phase & out of phase)
Top Foil
0.12 mm top foil
Chrome-Nickel alloy
Rockwell 40/45
Heat treated at
~ 450 °C for 4 hours
and allowed to cool.
Foil retains arc shape
after heat treatment
Sprayed with MoS₂
sacrificial coating

Metal mesh pads
Compressed weave of
copper wires
Compactness
(density)=20%

Bearing cartridge
(+top foil+ metal mesh)
Metal mesh pads and
top foil inserted inside
bearing cartridge.
Top foil firmly affixed
in a thin slot made
with wire-EDM
machining

Stiffness and
damping of MMFB
depend on metal
mesh compactness
### Dimensions: rotor and bearings

<table>
<thead>
<tr>
<th>Rotor</th>
<th>Inconel 718</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, $M$</td>
<td>1.36 kg</td>
</tr>
<tr>
<td>Length</td>
<td>200.7 mm</td>
</tr>
<tr>
<td>Inner diameter, $D_i$</td>
<td>17.90 mm</td>
</tr>
<tr>
<td>Outer diameter, $D_o$</td>
<td>36.51 mm</td>
</tr>
<tr>
<td>Rotor diameter at bearings</td>
<td>36.51 mm</td>
</tr>
<tr>
<td>Bearing span</td>
<td>103 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bearings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartridge outer diameter</td>
</tr>
<tr>
<td>Cartridge inner diameter</td>
</tr>
<tr>
<td>Inner diameter, $D$</td>
</tr>
<tr>
<td>Axial length, $L$</td>
</tr>
<tr>
<td><strong>Copper</strong> mesh pad thickness</td>
</tr>
<tr>
<td>mesh density (compactness)</td>
</tr>
<tr>
<td>Wire diameter (mm)</td>
</tr>
<tr>
<td>Number of metal mesh pads</td>
</tr>
<tr>
<td>Top foil thickness</td>
</tr>
<tr>
<td>Top foil (Chrome Nickel steel alloy)</td>
</tr>
<tr>
<td>Radial clearance based on geometry</td>
</tr>
</tbody>
</table>

Cooling air flow rate 160 LPM
Predicted MMFB force coefficients

Predictive (in-house) tool models metal mesh pad as a uniform stiffness layer beneath the elastic top foil

Drive end bearing

Direct stiffness increases 80% with speed. Damping drops!
Small cross-$K$’s
Critical speeds and damping ratios

Critical speeds < 10 krpm b/c bearings are soft. Rigid rotor modes: conical and cylindrical.

Model rotor-bearing system

Damping decreases with speed. Typical of system with material damping.
Rotordynamic tests at room temperature

In-phase imbalances

Out of phase imbalances

240 mg \((u = 15 \, \mu\text{m})\) and 360 mg \((u = 22.6 \, \mu\text{m})\).
Normalized rotor responses show the system behaves linearly up to a maximum speed of 50 krpm.

Rotor response normalized with respect to the smaller imbalance mass (240 mg). Out of Phase (180°) imbalance masses.

Room temperature tests:

- Critical speed: ~15 μm

Axes:
- Rotor speed [rpm]
- Amplitude 0-pk [μm]
- Phase lag [deg]

Legend:
- 240 mg
- 360 mg

Diagram:
- T_Fe
- T_S
- T_DE
- FE rotor
- DE rotor
Predictions and test results

Predictions and measurements in good agreement

Drive end Horizontal

240 mg out-of-phase

360 mg out-of-phase
Tests with increasing heater temperature

Graph does not show axial thermal gradient)

**Rotor and bearings heat unevenly.**
## Test cases

<table>
<thead>
<tr>
<th></th>
<th>Heater set Temperature, $T_s$ [ºC]</th>
<th>Rotor speed [krpm]</th>
<th>Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>~ 22 (Heater off) $\rightarrow$ 100$\rightarrow$ 150$\rightarrow$ 200</td>
<td>0</td>
<td>135</td>
</tr>
<tr>
<td>2</td>
<td>~ 22 (Heater off) $\rightarrow$ 100$\rightarrow$ 150$\rightarrow$ 200</td>
<td>30</td>
<td>145</td>
</tr>
<tr>
<td>3</td>
<td>~ 22 (Heater off) $\rightarrow$ 100$\rightarrow$ 150$\rightarrow$ 200</td>
<td>40</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td>~ 22 (Heater off) $\rightarrow$ 100$\rightarrow$ 150$\rightarrow$ 200</td>
<td>50</td>
<td>230</td>
</tr>
</tbody>
</table>

Cooling flow rate: 160 LPM

In-phase imbalances

Out of phase imbalances

240 mg ($u = 15$ um) and 360 mg ($u = 22.6$ um).
Thermocouples location

Heater reference temperature, $T_s$

Rotor free end

$T_{FE}$

Air inlet (160 LPM)

$T_{DE}$

Rotor drive end

Free end bearing

$T_1$, $T_2$, $T_3$, $T_4$

$T_{duct}$

Duct temperature

Drive end bearing

$T_5$, $T_6$, $T_7$, $T_8$
Rotor and duct temperatures increase with heater temperature. Large axial thermal gradient, DE to FE.
Bearings show similar temperatures. The cooling air supply (~160 L/min) maintains low bearing temperatures.
At any fixed heater temperature, the rotor temperature increases with time (until thermal equilibrium).
Due to the heater thermal gradient, rotor free end is hotter than drive end.

**Rotor OD temperature rises**

**Heater temperature:** 22-200 °C

**Rotor speeds:** 0-50 krpm

**Heater off**

- $T_S = 100 °C$
- $T_S = 150 °C$
- $T_S = 200 °C$

**Heater temperature:** 22-200 °C

- $T_{FE}$: Rotor FE temperature
- $T_{DE}$: Rotor DE temperature

**Graphs:**

- Rotor FE temperature ($T_{FE}$)
- Rotor DE temperature ($T_{DE}$)

**Temperature rise [°C]**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Rotor speed [krpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 °C</td>
<td>0 10 20 30 40 50</td>
</tr>
<tr>
<td>150 °C</td>
<td></td>
</tr>
<tr>
<td>100 °C</td>
<td></td>
</tr>
<tr>
<td>Heater off</td>
<td></td>
</tr>
</tbody>
</table>

**Rotor speed [krpm]**

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<td>0 10 20 30 40 50</td>
</tr>
</tbody>
</table>
Bearing OD temperature rises

Rotor speeds: 0-50 krpm

Heater temperature: 22-200 °C

Bearing temperatures increase with rotor speed and are impervious to rotor thermal gradient. Supply air flow at ~ 160 L/min cools the bearings.
Rotor response at increasing temperatures

Out of Phase imbalance masses = 240 mg. Large remnant rotor imbalance.

Rotor free end horizontal response. Runout at ~2.3 krpm

<table>
<thead>
<tr>
<th>Heater set $T_s$ ($^\circ$C)</th>
<th>22</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor FE $T_{FE}$ ($^\circ$C)</td>
<td>26</td>
<td>47</td>
<td>63</td>
<td>82</td>
</tr>
</tbody>
</table>
Out of Phase imbalance masses = 240 mg. Large remnant rotor imbalance.

Rotor drive end horizontal response. Runout at ~2.3 krpm

<table>
<thead>
<tr>
<th>Heater set $T_s$ (°C)</th>
<th>22</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor DE $T_{DE}$ (°C)</td>
<td>26</td>
<td>36</td>
<td>46</td>
<td>54</td>
</tr>
</tbody>
</table>

Idem
Large amplitude peaks at critical speed. Not affected by rotor temperature.

Out of Phase Imbalance masses = 240 mg. Large remnant rotor imbalance.

Rotor drive end vertical response. Runout at ~2.3 krpm

<table>
<thead>
<tr>
<th>Heater set $T_s$ (°C)</th>
<th>22</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor DE $T_{DE}$ (°C)</td>
<td>26</td>
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</table>

Large amplitude peaks at critical speed. Not affected by rotor temperature.
Evidence of small amplitude sub synchronous whirl with hottest rotor (Rotor DE temp increases from 24°C to 62°C)

Synchrous response is dominant.
Conclusions

a) At room temperature, rotor response predictions and measurements are in agreement. Measurements show bearings have low damping.

b) Rotor-bearing system behaves linearly up to 50 krpm.

c) Most rotor responses do not show significant different between cold (room) and high temperature.

d) With sufficient cooling air ~ 160 L/min, the bearings’ performance is not affected by rotor temperature.

f) Prior TAMU work showed the importance of cooling air flow. The current tests reinforced need of air supply for adequate thermal management.
Questions?

For more information

http://rotorlab.tamu.edu