Structural and Rotordynamic Force Coefficients of a Shimmed Bump Foil Bearing: an Assessment of a Simple Engineering Practice

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Bump-Type Foil Bearings (BFBs)

A gas film in series with a top foil and an under-spring element is a proven support for microturbomachinery (<200kW). Typically the top foil and shaft are coated to minimize wear & reduce friction.

**Issues:**
- Expensive & highly engineered element
- Nonlinear substructure: prone to show rotor sub synchronous whirl motions
- Thermal management advised
- LOW load capacity (compared to oil lubricated bearings)

**Applications:** ACMs, micro gas turbines, turbo expanders, turbo compressors, turbo blowers, soon in automotive turbochargers
Example subsynchronous whirl motion


Unloaded FB: “Self-Excited” whirl motions at speed 30 krpm (500 Hz) with whirl frequency=165 Hz (WFR=0.33)
Inserting metal shims underneath bump strips introduces a preload (centering stiffness) at low cost – a typical industrial practice.
BFB supported rotors often show large amplitude sub synchronous whirl motions.

**Prior art:** A shimmed BFB increases the onset speed of rotor instability and reduces the amplitude of sub synchronous whirl motions.

Sim et al. (2012) J.Tribol., 134
Oil free turbocharger on shimmed foil bearings.

Sim et al. (2014) ASME Turbo Expo Three pad BFB.

Schiffmann & Spakovszky (2013) J. Tribol., 135
Impractical Selective Shimming Guidelines for Improved Stability.
ORIGINAL BEARING

Kim and San Andrés (2009) Trib. Trans., 52

Rotor deceleration from 50 krpm, side pressure of 0.34 bar

Original GFB

Large amplitude subsynchronous motions (27 krpm – 50 krpm)

Frequency [Hz]

Amplitude [μm]

Whirl frequency: 120 Hz - 180 Hz

2 krpm

25 krpm

50 krpm

1X

Kim and San Andrés (2009) Trib. Trans., 52
Rotor deceleration from 50 krpm, side pressure of 0.34 bar

Shimmed GFB

Amplitude [μm]
Frequency [Hz]

Whirl frequency: 140 Hz - 155 Hz
25 μm (1 mil) thick shims

Small amplitude subsynchronous motions (38 krpm – 50 krpm)

Delay ~ 11 krpm the threshold rotor speed for onset of subsynchronous whirl motions.

Kim and San Andrés (2009) Trib. Trans., 52
Objective

Experimentally characterize the effect of shimming on a bump-type foil bearing:

- frequency dependent stiffness & damping force coefficients; and
- transient rotor speed during start up events:
  - drag torque (friction coefficient),
  - peak startup
  - airborne operation
BFB and shims

Bearing dimensions
$L = 38.1 \text{ mm}, \ D = 36.5 \text{ mm} \ (L/D \sim 1.0)$

Shims with adhesive surface.
Shim pushes bumps towards rotor.

Thickness $= 30 \ \mu\text{m}, 50 \ \mu\text{m}$

Shims placed $120^\circ$ apart, stretch axially through bearing.

FB radial clearance,
$c_{\text{nom}} = \frac{1}{2} (D_1 - D_s) = 0.120 \text{ mm}$
# BFB Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing cartridge outer diameter, $D_O$</td>
<td>50.74 mm</td>
</tr>
<tr>
<td>Bearing cartridge inner diameter, $D_i$</td>
<td>37.98 mm</td>
</tr>
<tr>
<td>Bearing axial length, $L$</td>
<td>38.10 mm</td>
</tr>
<tr>
<td><strong>Top foil (Inconel X750) thickness $t_T$</strong></td>
<td>0.1 mm</td>
</tr>
<tr>
<td>foil length, $2\pi D_i$</td>
<td>110 mm</td>
</tr>
<tr>
<td>Number of bumps, $N_B$</td>
<td>26</td>
</tr>
<tr>
<td><strong>Bump foil (Inconel X750) thickness, $t$</strong></td>
<td>0.112 mm</td>
</tr>
<tr>
<td>pitch, $s_0$</td>
<td>4.3 mm</td>
</tr>
<tr>
<td>length, $l_B$</td>
<td>2.1 mm</td>
</tr>
<tr>
<td>height, $h$</td>
<td>0.50 mm</td>
</tr>
<tr>
<td><strong>Shim (AISI 4140) length</strong></td>
<td>38.1 mm</td>
</tr>
<tr>
<td>Thickness, $t_s$</td>
<td>30 &amp; 50 µm</td>
</tr>
<tr>
<td>width</td>
<td>7.87 mm</td>
</tr>
<tr>
<td>Angular extent</td>
<td>12°</td>
</tr>
<tr>
<td>Shaft diameter, $D_s$</td>
<td>36.5 mm</td>
</tr>
<tr>
<td>Measured inner diameter of FB (assembled)</td>
<td>36.74 mm</td>
</tr>
<tr>
<td>Nominal FB radial clearance, $c_{nom} = \frac{1}{2}(D_i - D_s)$</td>
<td>0.120 mm</td>
</tr>
<tr>
<td>Weight of bearing and cartridge</td>
<td>1.1 kg (10 N)</td>
</tr>
</tbody>
</table>
Clearance of shimmed BFB

The clearance of a shimmed bearing is periodic, as that of a tri-lobe or three pad bearing. The bearing clearance reduces at shim locations.

\[ c(\theta) = \left(1 - \frac{t_s}{2c_{nom}}\right)c_{nom} - \frac{1}{2} t_s \cos \left[\left(N_S \left(\theta - \theta_1 - \theta_p\right)\right)\right] \]

- \( c_{nom} \): Nominal bearing clearance
- \( t_s \): Shim thickness
- \( N_S \): Number of shims
- \( \theta \): Angular coordinate
- \( \theta_p \): Angular distance between consecutive shims
- \( \theta_1 \): Angular coordinate of the first shim
Static load vs. BFB deflection

4 cycles of push and pull

Load directed 90 degrees to top foil fixed end

A third order polynomial fits regions with bump compression

Bearing reaction force:

\[ F = K_0 + K_1 x + K_3 x^3 \]

Small BFB hysteresis loop: little mechanical energy dissipation

Regions of low load (<25 N) show diametral clearance region
Estimated BFB Structural Stiffness

BFB structural stiffness:

\[ K_{(x)} = \frac{\partial F}{\partial x} = K_1 + 3K_3x^2 \]

Bearing with 100µm shims

\( K \neq 0 \) at \( x=0 \): assembly interference fit (no clearance)

Bearing stiffness increases with bearing deflection and shim thickness.
Rotordynamic test rig

Max. operating speed: 80 krpm
Turbocharger driven rotor
Journal diameter: 36.5 mm

Model T25, donated by Honeywell Turbo Technologies
Drag Torque

Accelerate to 60 krpm, steady state operation, and deceleration to rest.

Lift off speed occurs at the lowest torque: airborne operation
Break-away drag torque (dry friction)

\[ f = \frac{\text{Torque}}{\text{RW}} \]

Drag torque and rotor lift off speed increase with specific load.

Friction factor of shimmed BFB increases with shim thickness. \( f \) decreases with specific load \((W/LD)\).
Friction factor from start up to airborne operation

\[ f = \frac{\text{Torque}}{RW} \]

\[ W/(LD) \sim 20 \text{ kPa} \]

\( f \) is low for BFB (with or w/o shims) when airborne and above >50 krpm.
Rotordynamic test rig

Dynamic load: 1000 N or 250 N

Rotor speed: up to 75 krpm

Test identification range: Up to 450 Hz
Dynamic loads: sine-sweep

Shaft speed: 50 krpm (833 Hz)
Displacement amplitude: 20 µm
Specific load \(W/(LD):14.3\) kPa

Test frequency range: 200 Hz-450 Hz
Dynamic load: up to 250 N
Starting at ambient temperature, after a 30s test, bearing cartridge temperature raised 30°C.
Parameter Identification

Apply: sine sweep load excitations (200-400 Hz), amplitude controlled (20 µm).
Measure: bearing absolute accelerations and displacements relative to journal.

System EOM:

\[
\begin{bmatrix}
K_{XX} + j \omega C_{XX} & K_{XY} + j \omega C_{XY} \\
K_{YX} + j \omega C_{YX} & K_{YY} + j \omega C_{YY}
\end{bmatrix}
\begin{bmatrix}
\bar{x}(\omega) \\
\bar{y}(\omega)
\end{bmatrix}
= \begin{bmatrix}
\bar{F}_x(\omega) \\
\bar{F}_y(\omega)
\end{bmatrix} - \begin{bmatrix}
M_{Sx} + \frac{C_{Sx}}{j\omega} - \frac{K_{Sx}}{\omega^2} \\
M_{Sy} + \frac{C_{Sy}}{j\omega} - \frac{K_{Sy}}{\omega^2}
\end{bmatrix}\begin{bmatrix}
\bar{A}_x(\omega) \\
\bar{A}_y(\omega)
\end{bmatrix}
\]

Frequency domain analysis yields stiffness and damping coefficients.

\(K_S, C_S\): soft SQ stiffness & damping
\(M_S\): effective mass

\(K_{ij}, C_{ij}\): test bearing stiffness & damping
Shaft speed 50 krpm (833 Hz)

BFB direct stiffnesses increase with excitation frequency, not affected by shims.

Uncertainty: ±0.08 MN/m
BFB Damping, C

Shaft speed 50 krpm (833 Hz)

W/(LD) = 14.3 kPa

Damping $C_{xx}$, along static load ($X$), decreases with excitation frequency. Direct damping increases a little for shimmed BFB.

Max. variability: ±100 Ns/m
Force coefficients comparison

BFB direct stiffnesses increase with excitation frequency, not affected by shims.

Damping $C_{xx}$ decreases with excitation frequency. Direct damping increases little for shimmed BFB.

Static load direction

14.3 kPa specific load

- $K_{xx}$: 0 krpm, 50 krpm
- $C_{xx}$: 0 krpm, 50 krpm

Graphs show:
- Stiffness $K_{xx}$ increases with excitation frequency and is not affected by shims.
- Damping $C_{xx}$ decreases with excitation frequency.
- Direct damping increases little for shimmed BFB.

Legend:
- Original
- 30 µm shims
- 50 µm shims

Specific load direction X Y: 14.3 kPa
**BFB loss factor, \( \gamma \)**

Proportional structural damping model

\[
C \omega = \gamma K
\]

From viscous energy dissipation \((E_v) = \text{structural material energy dissipated} \ (E_m)\)

Loss factor (frequency dependent for circular orbits) *(textbook)*

\[
\gamma = \frac{\omega (C_{XX} + C_{YY})}{K_{XX} + K_{YY}}
\]

Average loss factor

from 300 Hz \((\omega_1)\) to 400 Hz \((\omega_2)\)

\[
\overline{\gamma} = \frac{1}{\omega_2 - \omega_1} \int_{\omega_1}^{\omega_2} \gamma \, d\omega
\]
BFB loss factor, $\gamma$

$\gamma$ increases for BFB with shims. Large scatter when operating at 50 krpm.

Loss factor decreases by ~10%-20% for operation with journal speed.
### Average loss factor

#### 300 Hz ($\omega_1$) to 400 Hz ($\omega_2$) range

<table>
<thead>
<tr>
<th>Bearing Configuration</th>
<th>Loss Factor, $\bar{y}$</th>
<th>Standard deviation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0 krpm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original</td>
<td>0.61</td>
<td>0.070</td>
</tr>
<tr>
<td>30 $\mu$m shims</td>
<td>0.69</td>
<td>0.090</td>
</tr>
<tr>
<td>50 $\mu$m shims</td>
<td>0.71</td>
<td>0.056</td>
</tr>
<tr>
<td><strong>50 krpm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original</td>
<td>0.47</td>
<td>0.070</td>
</tr>
<tr>
<td>30 $\mu$m shims</td>
<td>0.58</td>
<td>0.056</td>
</tr>
<tr>
<td>50 $\mu$m shims</td>
<td>0.62</td>
<td>0.150</td>
</tr>
</tbody>
</table>

Bearing with 50 $\mu$m shims has the largest loss factor; however it also has the larger standard deviation.
TC vibration measurements

Rotor on shimmed BFB does not show sub synchronous whirl motions.
FB post test inspection

Original Condition

Bearing inner surface

~100 start stop cycles

After Testing

Bearing inner surface

Rotor surface

Rotor surface
Conclusion

• Shimmed (50 μm) BFB shows LARGEST DRY friction coefficient \( f \sim 0.80\text{-}0.40 \).
• Once airborne, drag friction factor for BFB is low \( f \sim 0.05 \).

• **Rotordynamic coefficients:** shim thickness does not affect BFB stiffnesses; however, it increases a little the damping coefficients.
• The bearing with 50 μm shims has an average loss factor \( \bar{\gamma} \sim 0.62 \), 30% higher than \( \bar{\gamma} \sim 0.47 \) with original bearing. The standard deviation is higher, however.

• Other tests demonstrate improved rotordynamic performance of a shaft supported on a shimmed BFB.
Thanks to the Turbomachinery Research Consortium for its support.

Questions(?)

Learn more at http://rotorlab.tamu.edu

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