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Experimental Assessment of Drag and Rotordynamic Response for a Porous Type Gas Bearing

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Oil-Free Bearings for Turbomachinery

Justification

Current advancements in vehicle turbochargers and midsize gas turbines need of <u>proven</u> gas bearing technology to procure compact units with improved efficiency in an oil-free environment.

DOE, DARPA, NASA interests range from applications as portable fuel cells (< 60 kW) in microengines to midsize gas turbines (< 250 kW) for distributed power and hybrid vehicles.

2025 mandate on + efficiency for IC engines: materials and oil-free bearing systems will enable 55 mpg.

Gas Bearings

Ideal gas bearings for micro turbomachinery (< 0.5 MW) must be:

Simple – low cost, small geometry, low part count, constructed from common materials, manufactured with elementary methods.

Load Tolerant – capable of handling both normal and extreme bearing loads without compromising the integrity of the rotor system.

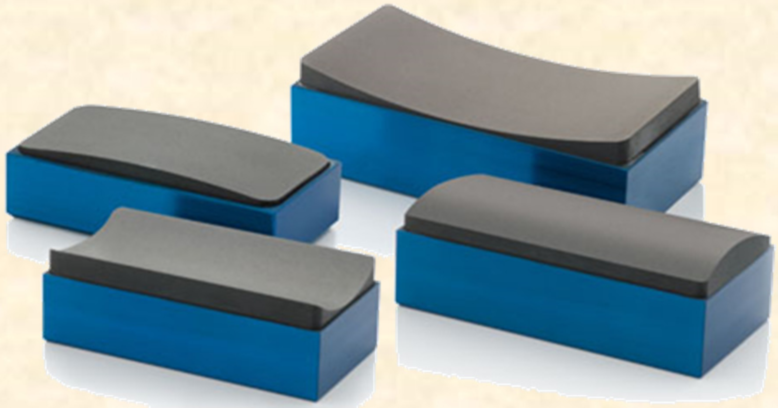
High Rotor Speeds – no specific speed limit (such as DN) restricting shaft sizes. Small Power losses.

Good Dynamic Properties – predictable and repeatable stiffness and damping over a wide temperature range.

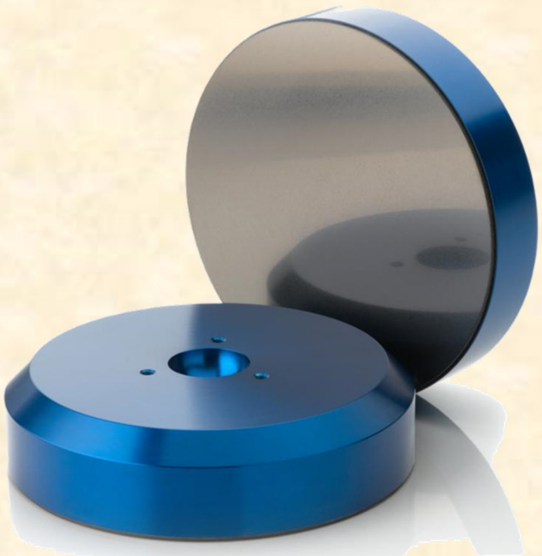
Reliable – capable of operation without significant wear or required maintenance, able to tolerate extended storage and handling without performance degradation.

+++ Modeling/Analysis (anchored to test data) readily available

Porous Type Gas Bearings



Porous type gas bushing pads



Porous type thrust bearings

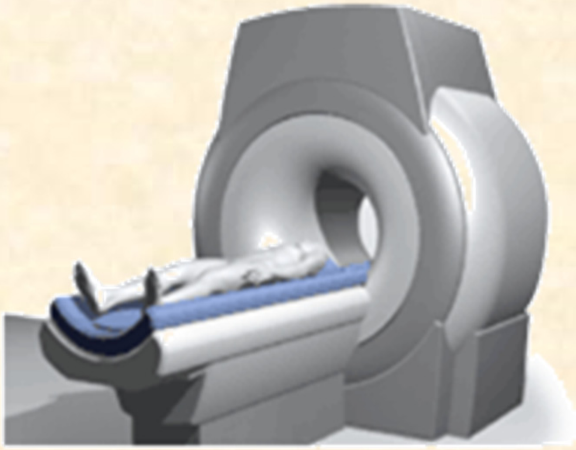
http://www.newwayairbearings.com/catalog/components

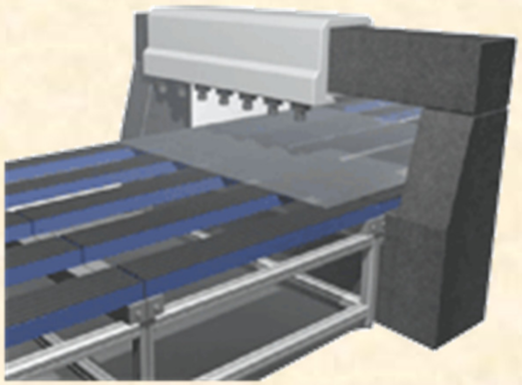
Porous type gas bearings (PTGB) make use of sub-micron sized holes distributed in their matrix material, allowing for an even distribution of gas flow over the entire bearing surface.

When compared to orifice restricted hydrostatic gas bearings, PTGBs have higher stiffness & damping coefficients.

Applications of porous gas bearings

- Coordinate measuring machines.
- Precision machine tools & spindles.
- Semiconductor manufacturing industry.
- Computed tomography imaging machines (CAT scan).
- Flat panel display (FPD) manufacturing industry.





http://www.newwayairbearings.com/solutions/markets/computed-tomography
http://www.newwayairbearings.com/solutions/markets/flat-panel-display

Brief Literature Review

Heller, Shapiro and Decker (1971) **ASLE Transactions, 14**

Design of a tilting porous pad bearing to increase stability and with reduced power loss.

Su, You and Lai (2003) **Industrial Lubrication and Technology, 55**

Show lower permeability and a thicker wall produce higher load capacity. Higher permeability and thicker wall give a higher stiffness.

Lee and You (2009) **Tribology Transactions, 52**

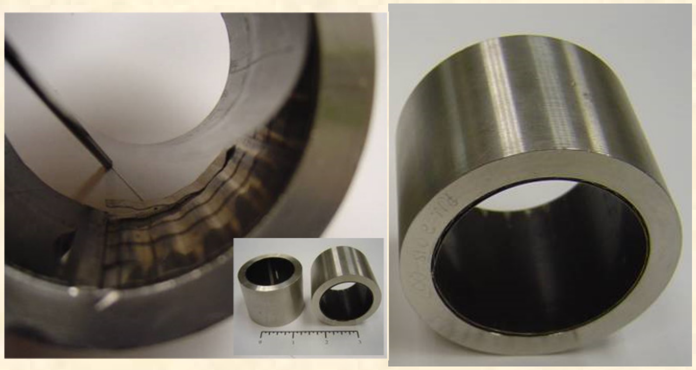
Porous bearings with a large feed parameter ($\Lambda_P = 12kR^2 / (C^3 H)$) operate with a hydrostatic effect, while a bearings with a small feed parameter operates as hydrodynamic and have higher risk of rubbing.

Lee and You (2010) **Tribology Transactions, 53**

Optimization of bearing aspect ratio, clearance ratio, and porous matrix thickness to maximize load capacity and minimize whirl instability.

Gas bearings at TAMU

Develop experimentally validated computational tools for predicting the performance of radial and thrust gas bearings (GFB, MMFB etc)



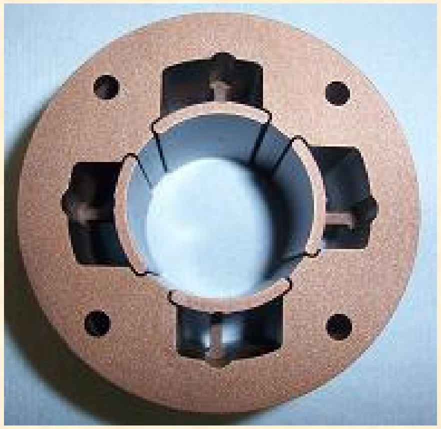
Bump type foil bearing

Performance Characteristics:

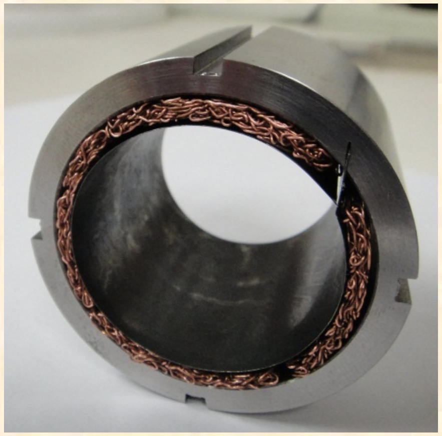
- Structural mechanics
- Drag torque, power loss
- Dynamic force coefficients
- High temperature performance

Aid to system development:

- **Oil-free turbocharger**
- **Water aeration systems**
- **CO2 turbo expanders**



Tilting pad bearing



Metal mesh foil bearing

Since 2003 supported by NSF, NASA, Capstone, Borg-Warner and TRC

Objective

Thrust of research program:

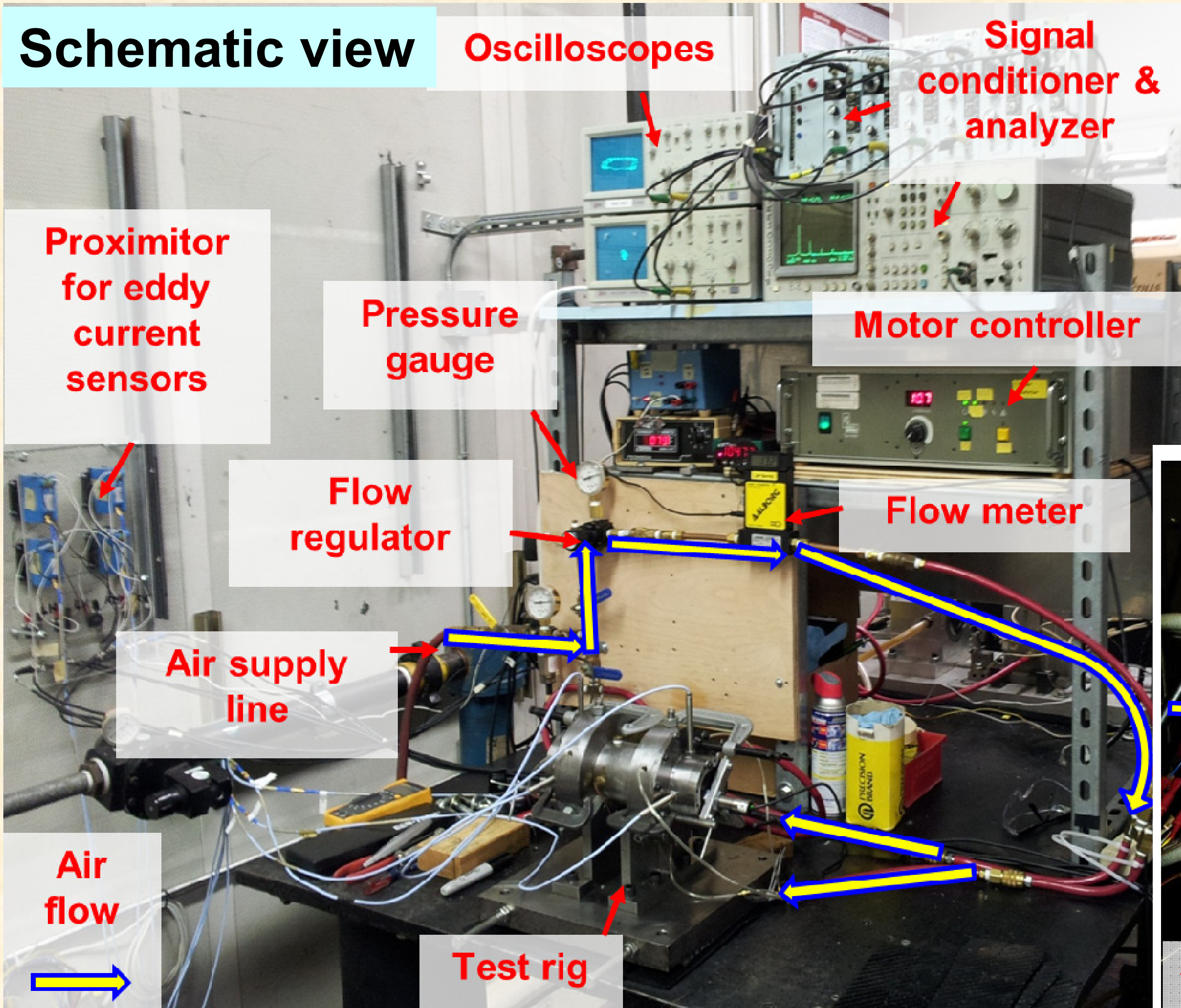
Investigate **novel porous gas bearings of low cost and easy to install. Externally pressurized bearings allow for rub-free operation at start up & shut down.**

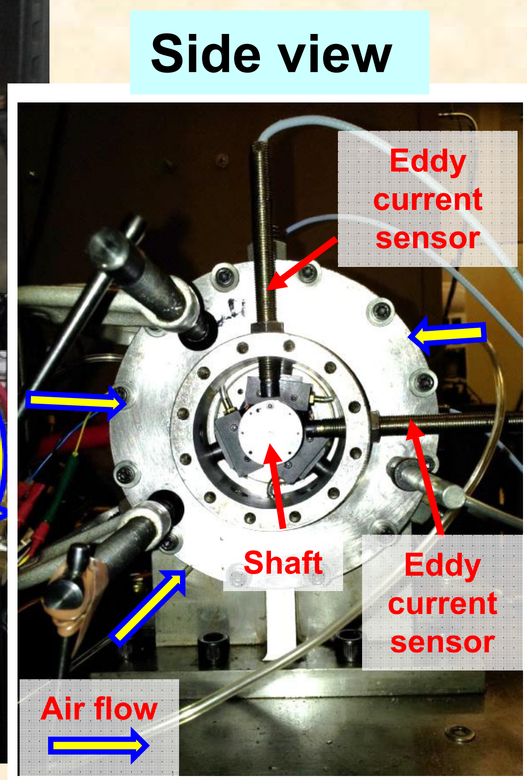
Major issues:

Little damping, Instability (whirl & hammer), & reliability under shock operation

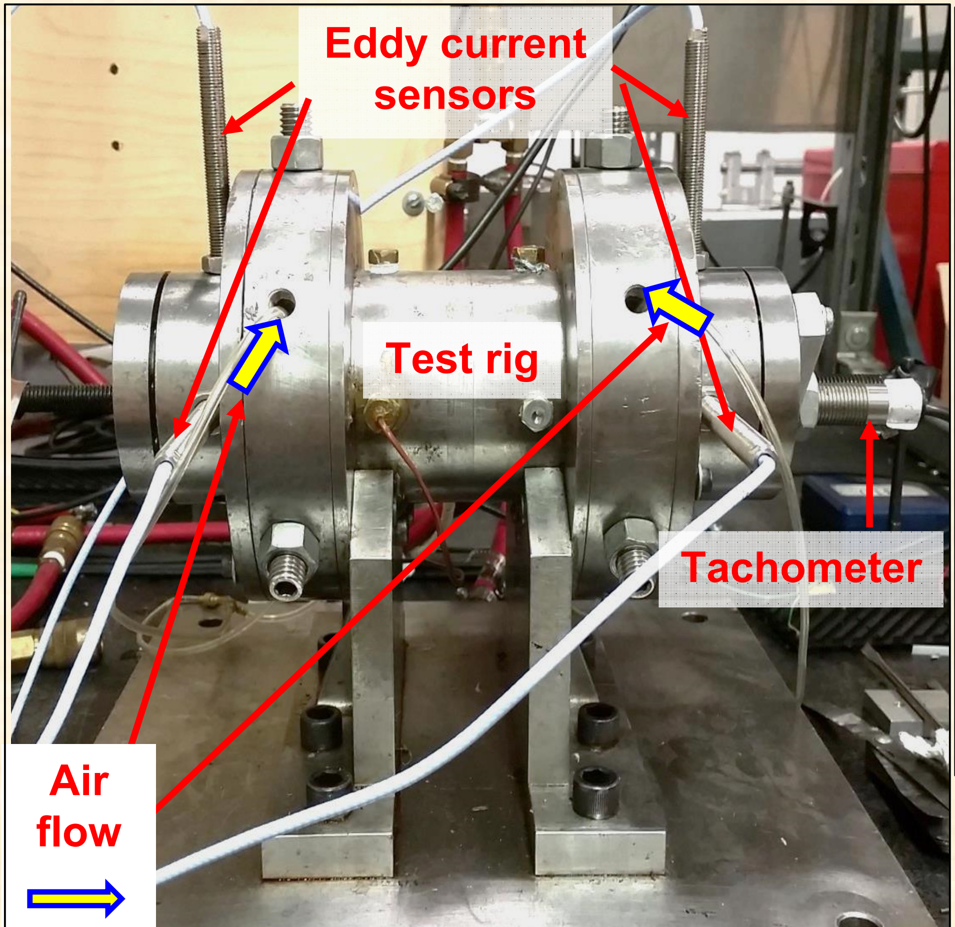
Evaluate the performance of novel porous carbon-graphite tilting pad gas bearings engineered for high speed rotating machinery: determine drag coefficient and measure rotordynamic response.

Test Rig and Instrumentation

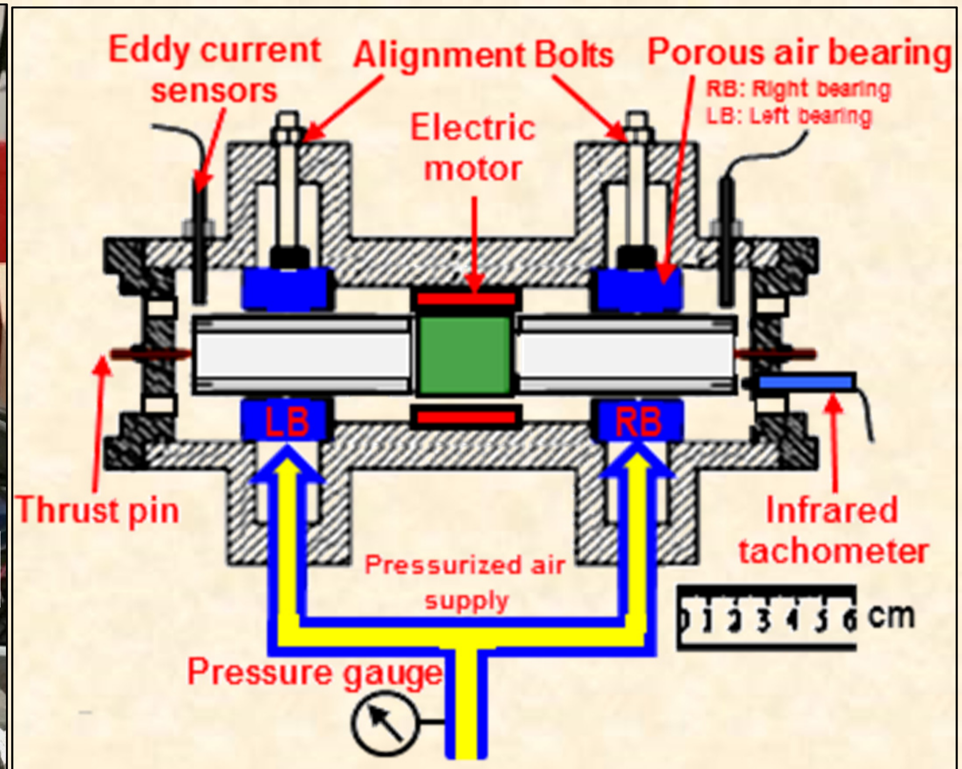


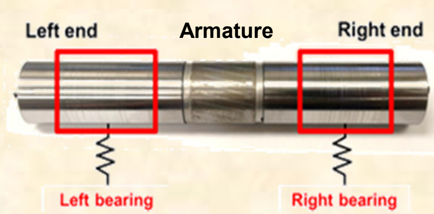


Gas Bearing Test Rig



Max. operating speed: 100 kpm
3.5 kW (5 Hp) AC integral motor





Rotor mass, *M*	0.89 kg
Rotor diameter, *D*	28.5 mm
Rotor length, *l*	190 mm
Polar moment of inertia	0.91 kg-cm^2

Past work with same test rig

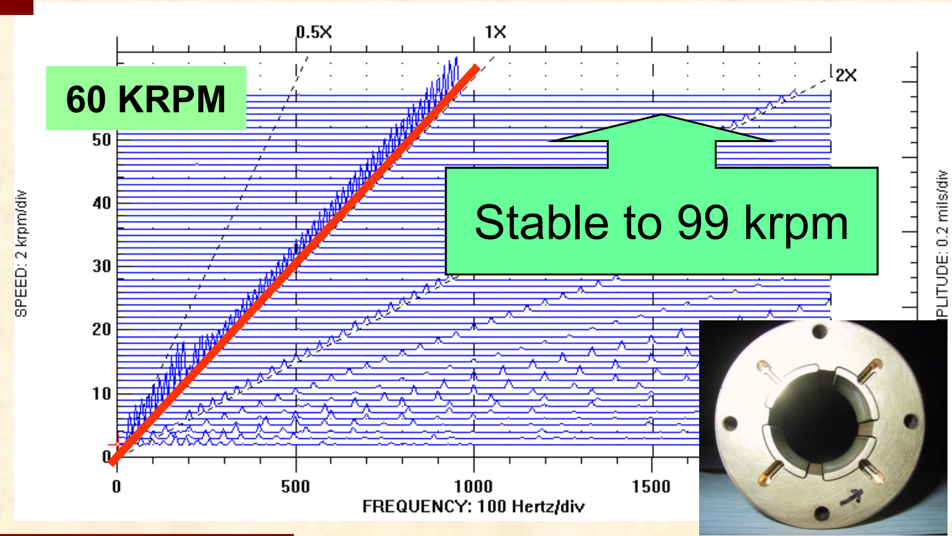
Zhu & San Andres **GT 2004-53621**

Rigid surface gas bearing for oil-free application.

Delgado & San Andres

GT 2004-53614

Computational model for hydrodynamic operation, with application to hybrid brush seals.



San Andres (2006) **Journal of Tribology, 129**

Computational model for hybrid operation validated by Zhu (2004) measurements. Code used by 20+ companies.

San Andres and *et al*. (2007-2010)

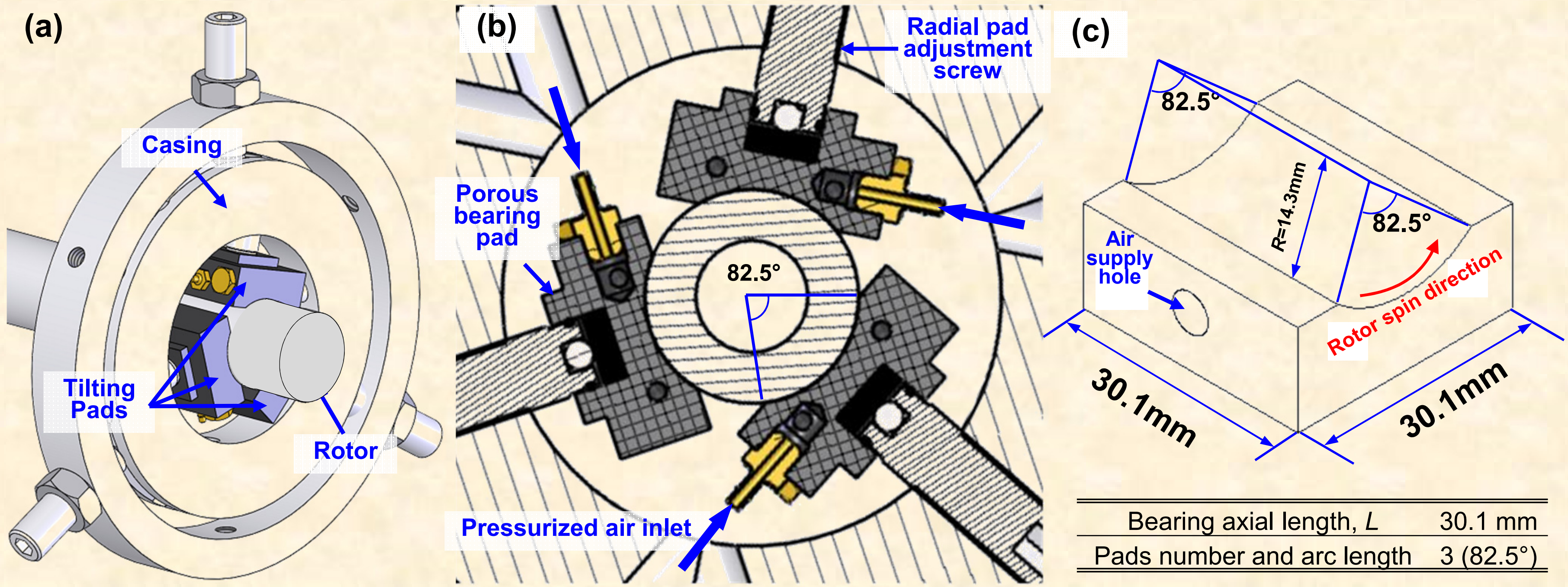
(1) Operation with worn clearances and LOP/LBP configuration. Dynamic response with (2) intermittent shock excitation and (3) multiple periodic load excitation

(1) J. Eng. Gas Turbines and Power, 2008, 130.

(2) GT 2009-59199

(3) GT 2010-22277

Bearing with Flexibly Supported Tilting Pads



Bearing axial length, *L*	30.1 mm
Pads number and arc length	3 (82.5°)

Clearance *c* =36 μm

(a) Isometric view of three pad PTGB supporting rotor
(b) Cross-sectional view three-pad PTGB and air supply
(c) Dimensions of each PTGB pad

Pads flexibly supported on pivots. A mechanism allows installation with a set clearance or specific preload.

Upon supply of an external pressurized gas, the pads push against their pivots and retract, enabling friction free operation.

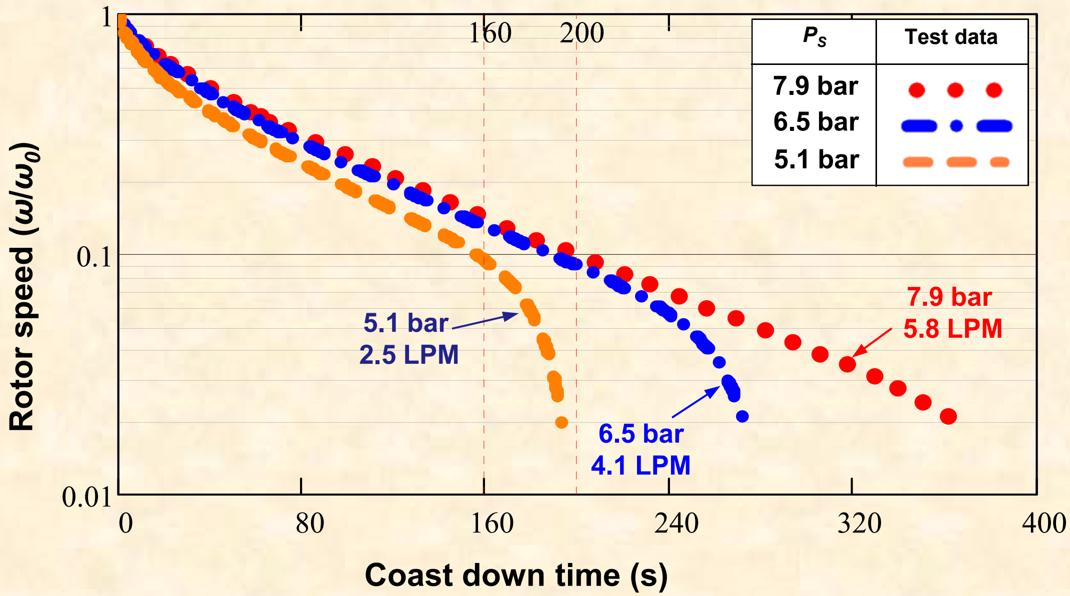
Bearing Rotational Drag Coefficient

$$I_P \frac{d\omega}{dt} + T_{drag} = I_P \frac{d\omega}{dt} + 2T_{bearing} + T_{windage} = 0$$

$$T_{bearing} = C_\theta \, \omega$$

$$T_{windage} = \tfrac{1}{4} C_D \, \rho \left(\tfrac{1}{2}\omega D\right)^2 Area$$

Rotor Speed (krpm)	Supply Pressure (bar)	$\frac{T_{windage}}{2\,T_{bearing}}$
55	**7.9**	**2.5**
	5.1	1.5
5.5	7.9	0.4
	5.1	0.2

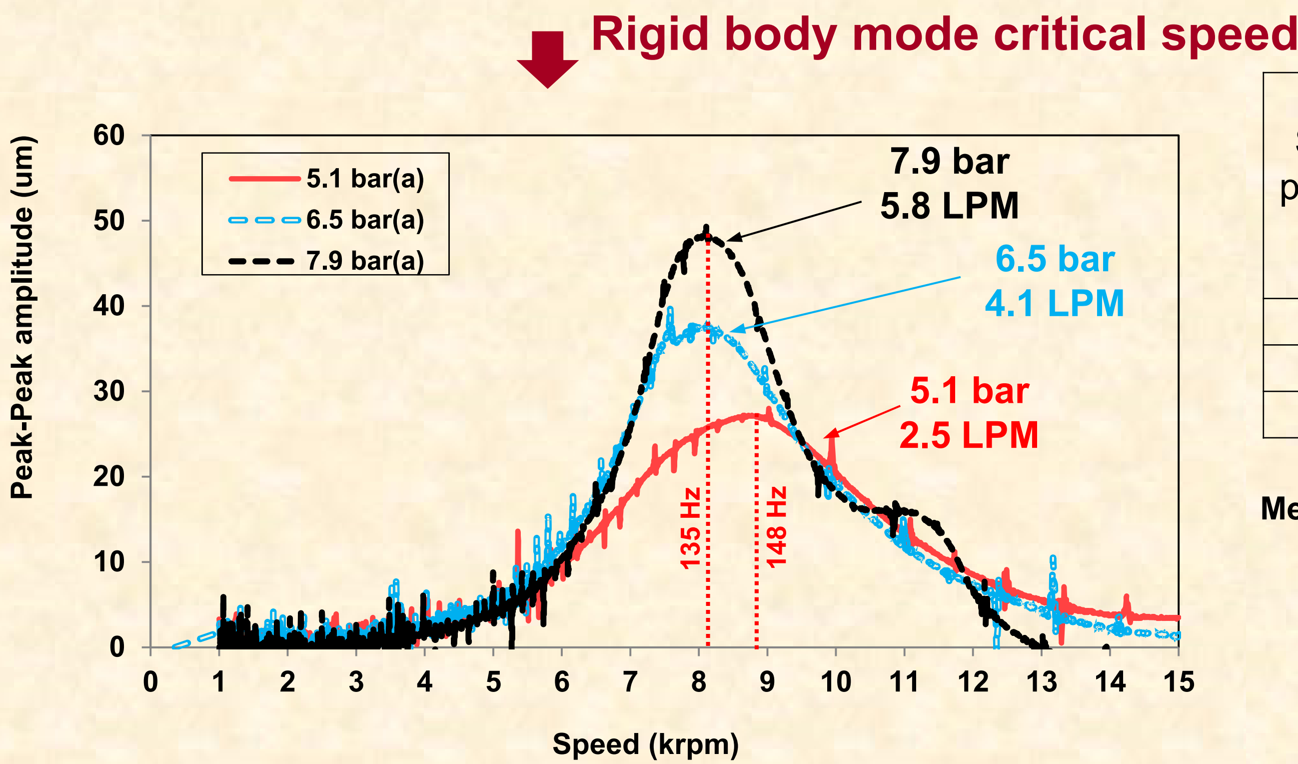


$$\mu_f = \frac{T_{bearing}}{WR}$$

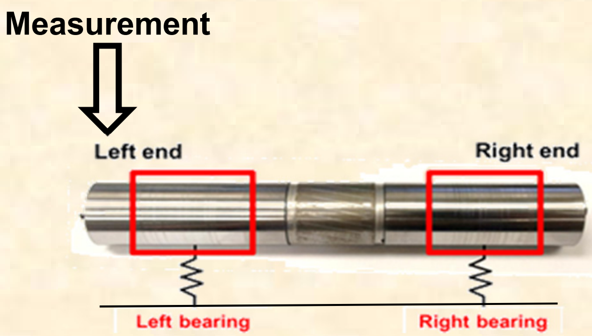
Supply pressure (bar)	Bearing drag coefficient, C_θ (N.μm.s/rad)	Friction coefficient, μ_f @ 10 krpm
7.9	**0.25**	**0.004**
6.5	0.30	0.005
5.1	0.43	0.007

Findings: Gas bearings' drag coefficient (friction factor) decreases with an increase in gas pressurization. Rotor windage has a dominant effect at high shaft speed.

Synchronous response & damping ratio

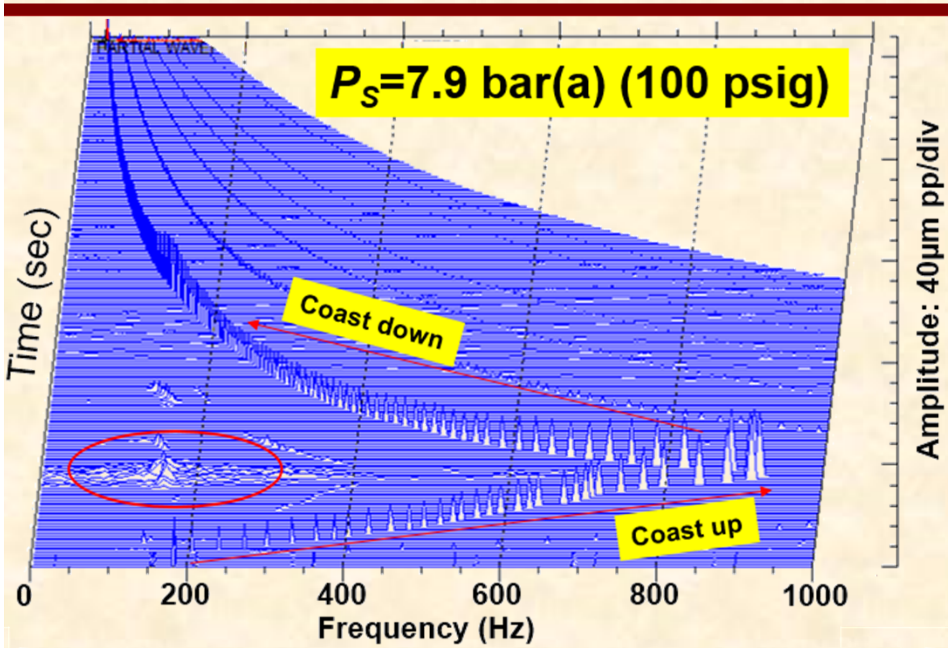


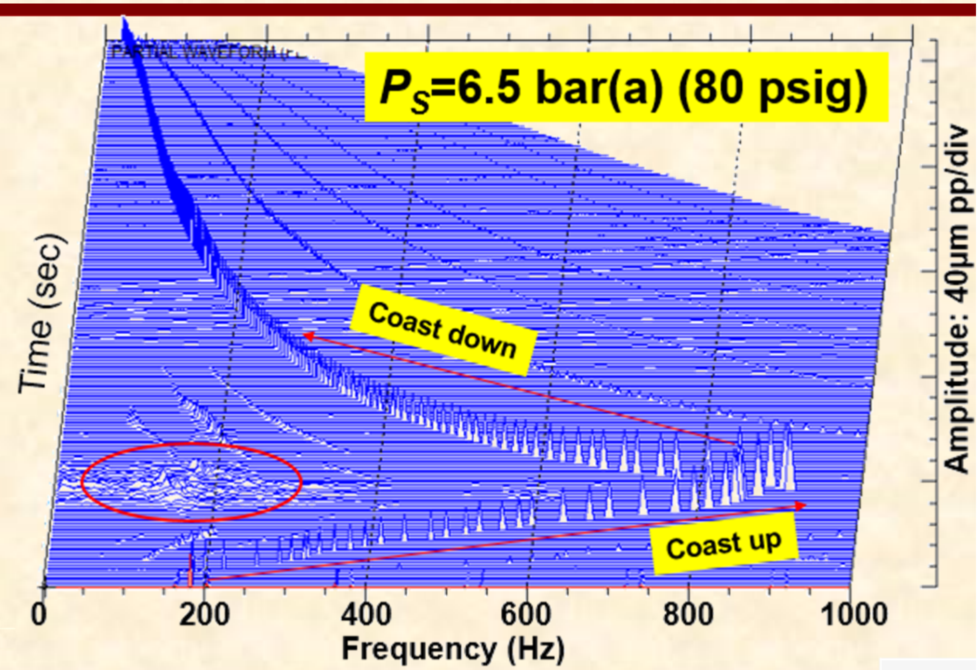
Supply pressure (bar)	Damping ratio, ζ	1st undamped natural frequency, (Hz)
5.1	0.17	148
6.5	0.14	136
7.9	**0.11**	**135**

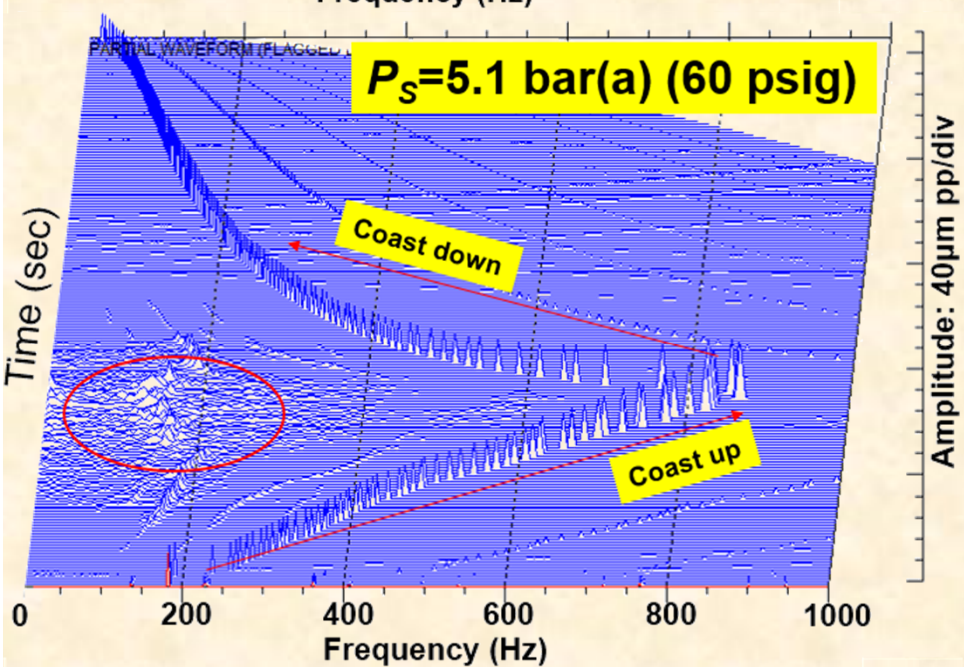


Findings: External gas pressure has a small effect on the natural frequency but a large one on the system damping ratio (ξ) that decreases as pressure supply increases.

Vibration measurement: Waterfall



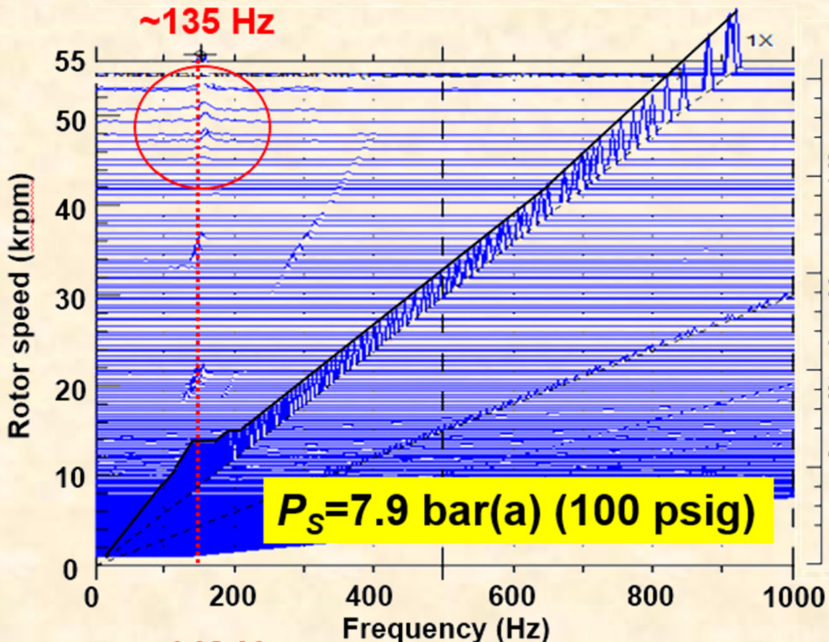


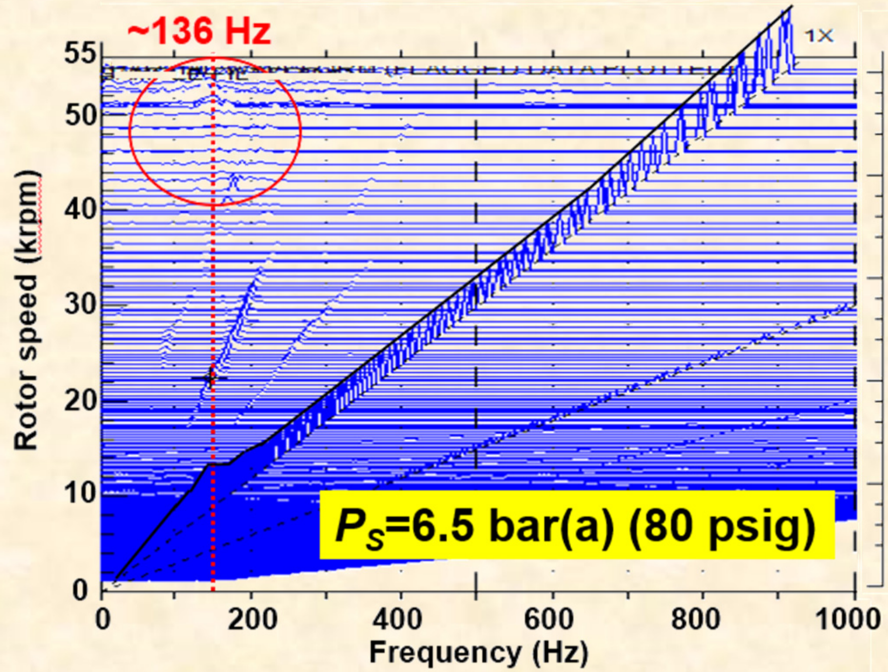


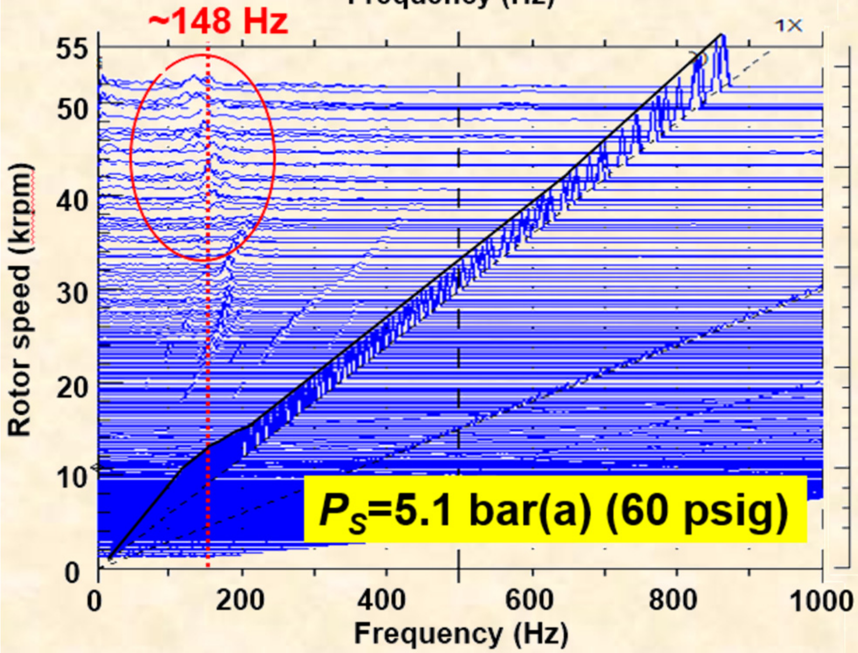
Procedure: Rotor accelerates the rotor to 55 krpm (910 Hz). Motor is shut off and rotor coasts down to rest. **Imbalance condition unknown.**

Findings: **The rotor response is mainly synchronous (1X).** As the supply pressure decreases, the rotor shows minuscule subsynchronous whirl.

Vibration measurement: Cascade







Findings: The rotor response is mainly synchronous (1X). Incipient subsynchronous motion appear at speed above 2 x natural frequency. Whirl then locks at the natural frequency. The rotor-bearing system does not show a self-excited whirl instability.

Conclusions

From estimated drag coefficients

(a) Porous gas bearing operates with viscous drag.

(b) Drag torque decreases as gas supply pressure increases.

(c) Windage has significant effect at high speed, in particular at a high supply pressure.

From rotordynamic response measurements

(a) System natural frequency changes little as pressure supply increases.

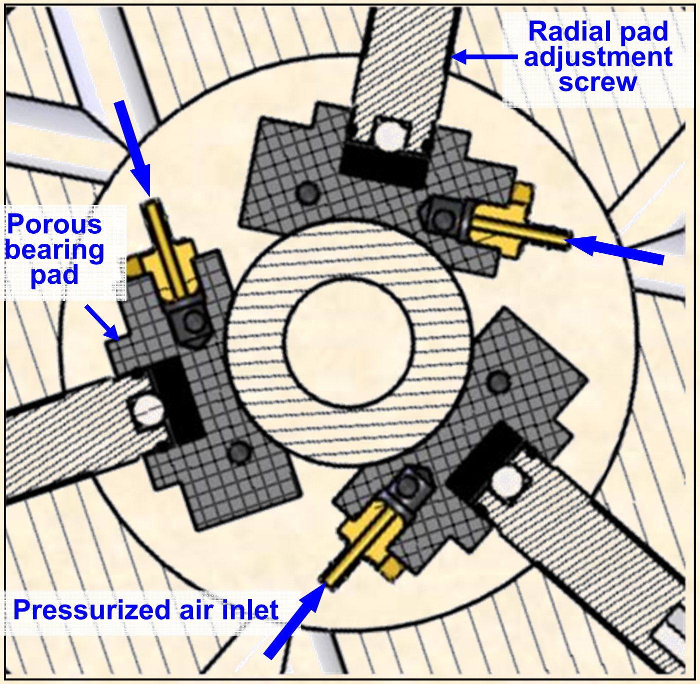
(b) Damping ratio decreases as gas pressurization into bearings increases.

(c) Rotordynamic response is primarily synchronous.

(d) Incipient subsynchronous whirl motions lock at the natural frequency and are benign, not a precursor to rotordynamic instability.

Future work

Study the effect of pad mechanical preload on the drag torque and identification of rotordynamic force coefficients for this type of bearing.



Thank you

Acknowledgments

Thanks to New Way Bearings and

TAMU Turbomachinery Laboratory

Questions:

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