Continuation Proposal to the TAMU Turbomachinery Research Consortium

NOVEL CARBON-GRAPHITE GAS BEARINGS AND SEALS FOR TURBOMACHINERY

(YEAR II)

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SIGNIFICANCE

High performance turbomachinery (TM), operating at high speeds, demands of stable operation and accurate position control to achieve higher power density. Oil free turbomachinery has a smaller foot-print with savings in weight and part count. Porous gas bearings (PGBs) are a promising technology, enabling oil free operation at high speeds and extreme temperatures with significant reduction in drag power loss and an increase in system efficiency. In particular, externally pressurized PGBs allow operation with minute films, offer high stiffness for accurate rotor positioning. In comparison to a cylindrical carbon bushing, tilting pad PGBs also provide enhanced stability by eliminating cross-coupling hydrodynamic forces. While PGBs are not a new technology (around since 1950), advances in manufacturing made them available at a low cost. Recently, San Andrés *et al.* [1] show that a small rotor supported on tilting pad PGBs has a large damping ratio ($\zeta = 0.172$) despite the low viscosity of the lubricant: air. In rotor speed coast down tests from 55 krpm (82 m/s), the bearing drag friction coefficient $f = 0.007 \rightarrow 0.004$ as the supply pressure into the bearings increases. In the tests, rotor operation is nearly friction-free and its vibration response purely synchronous.

SUMMARY OF WORK 2015-2016

In 2015, TRC funded a test program to quantify the rotordynamic performance of carbon-graphite porous bearings. New Way Bearings donated the test rig, shown in Fig. 1, that comprises a solid steel rotor (457 mm in length, 100 mm in diameter *D*, and 285 N in weight *W*) and a pair of five tilting pad porous bearings. A bearing pad has length L=73.1 mm, 60° arc length, and 50% offset. A variable frequency drive (VFD) controls a 3-phase AC motor (7.46 kW, max. 18 krpm) that drives the rotor through a quill shaft. The instrumentation includes sets of orthogonally placed eddy current sensors, pressure gauges and thermocouples.

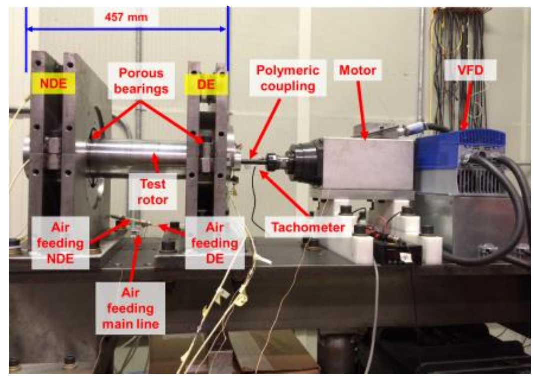

Fig.1 Test rig for rotordynamic evaluation of Carbon-Graphite porous gas bearings.

The first tasks included installation of the test rig and air supply lines, instrumentation for pressure delivery and rotor motion displacements, calibration of a static loader (air bearing) device, and identification of the rotor free-free mode shapes and natural frequencies. Note the specific load is just ½ $W/(LD)$= 19.5 kPa on each bearing.

Technical report TRC-B&C-01-16 [2] describes the tests and data analysis that includes estimation of the bearing pads permeability coefficient, bearing drag torque from shaft speed coast down tests, evaluation of bearing centering stiffnesses from impact load tests and an applied static load mechanism, and rotordynamic response due to added mass imbalances. Fig. 2 shows the (porosity) permeability coefficient (κ) of a bearing remains uniform as the supply/ambient pressures (P_s/P_a) increases well above a "nominal" orifice choke condition. Fig. 3 evidences from rotor speed (Ω/Ω_0) coast down tests the major benefit of air bearings: a nearly friction free operation, longer in duration as the supply pressure into the bearings increases. Recorded synchronous rotor responses in Fig. 4 for three imbalance masses show amplitude growth as the rotor approaches and crosses a critical speed (rigid body mode).

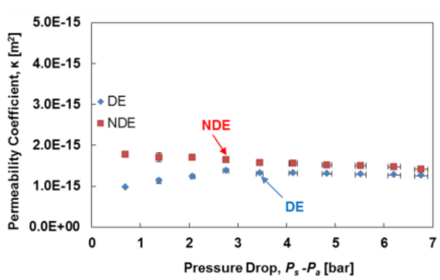

Fig. 2 Estimated bearing pads permeability (κ) versus pressure drop ($P_s - P_a$). No shaft rotation. Drive end (DE) and non-drive end (NDE) bearings.

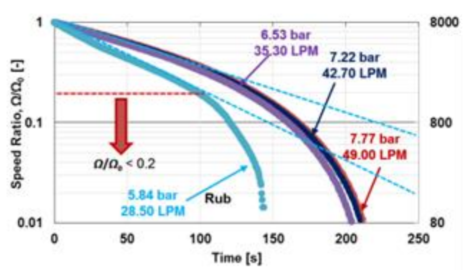

Fig. 3 Rotor speed ratio (Ω/Ω_0) vs. deceleration time. Bearings supplied with P_s = 5.84, 6.53, 7.22 and 7.77 bar (abs). Rotor free deceleration from 8 krpm.

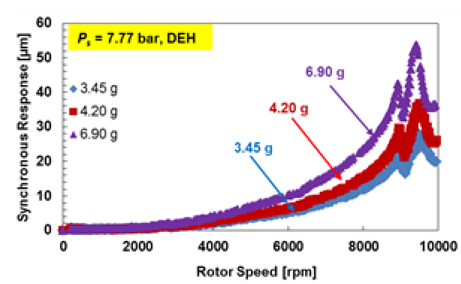

Fig. 4 Amplitude of synchronous rotor response at DE bearing - horizontal direction. Three mass imbalances. Bearings supplied with P_s = 7.77 bar, T_s = 21 °C.

PROPOSED WORK 2016-2017

The project objectives are: (a) to develop a computational physics model for performance prediction of porous gas bearings and its verification against experimental results, and (b) to quantify the performance of a carbon-graphite thrust gas seal with nearly zero leakage. A prior model [3] will be extended to include porous surfaces. Detailed tasks are:

a) Perform coast down speed tests and mass imbalance response tests for various static loads applied on the rotor with an ad-hoc (non-contact) mechanism shown in Fig. 5. The peak rotor speed will be 18 krpm (surface speed =94 m/s) and the bearings will be supplied with air at 7.77 bar(a). The rotordynamic responses will aid to the estimation of the bearings' drag friction factor and film thickness, and the equivalent force coefficients.

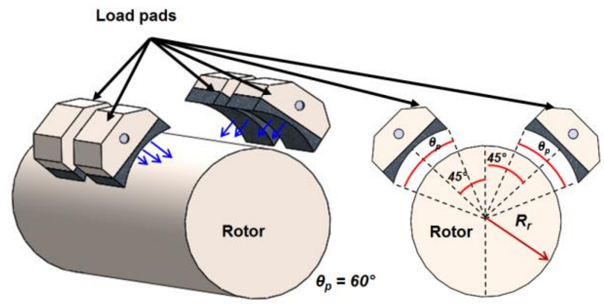

Fig. 5 Section of mechanism to apply a static load on rotor: porous pads supplied with external pressure push on the rotor.

b) Solve the thin film Reynolds equation for a compressible lubricant (gas) and extended to allow flow through a porous media substrate. The equation establishes the balance of pressure and shear driven mass flows and the mass flow through the porous material pushed from an external pressure source with pressure P_s [4]. The nonlinear equation relating the film pressure (P) and film thickness (h) to the journal surface rotation (ΩR) is

$$\nabla\left(\frac{-h^3\rho}{12\mu}\nabla P\right)+\frac{\Omega R}{2}\frac{\partial}{\partial x}(\rho h)+\frac{\partial}{\partial t}(\rho h)=\frac{\rho}{\mu}\frac{\kappa}{t}(P_s-P) \qquad (1)$$

where μ and $\rho=P/R_gT$ are the gas viscosity density at temperature T; and κ is the permeability of a porous pad with thickness t. The steady-state solution will deliver the bearing load capacity, drag torque and flow rate. A small amplitude journal center displacements perturbation of Eq. (1) will predict the bearing rotordynamic force coefficients, frequency dependent for operation with either a gas and/or a tilting-pad configuration. Comparisons to the results of measurements in the laboratory will validate the model.

c) A carbon-graphite thrust gas seal is also available, see Fig. 6. This seal leaks minimally (~0) by proper management of gas supply and suction valves creating a near vacuum. Although the seal can sustain large (suction) loads, it can also show pneumatic hammer for too large pressure differences (supply-vacuum). Impact loads on the seal will excite the element at its natural frequency. Acceleration measurements will aid to identify the seal axial stiffness and damping coefficients.

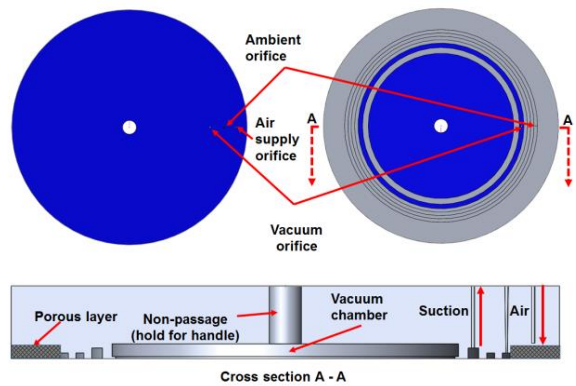

Fig. 6 Schematic view(s) of thrust gas seal.

Pressurized gas bearings are becoming a common engineered choice as they operate nearly friction free (without wear) and offer high centering stiffness for rotor positioning. Besides reducing energy consumption, gas bearings have a positive environmental impact. Envisioned applications include compressors, turbochargers and turbo expanders, blowers, high speed spindles, and other to come.

BUDGET FROM TRC FOR 2016-2017 — YEAR II

Support for graduate student (20 h/week) x $ 2,400 x 12 months	$28,800
Tuition three semesters ($ 363 credit hour x 24 ch/year)	$9,090
Fringe benefits (2.5%) and medical insurance ($360) x 12 months	$5,040
Registration and travel to technical conference (partial support)	$1,200
Supplies for test rig (Impact hammer tips, load cell, MATHCAD + Misc. supplies)	$850
Total BUDGET	**$44,980**

REFERENCES

[1] San Andrés, L., Jeung, S.-H., Rohmer, M., Devitt, D., 2015 "Experimental Assessment of Drag and Rotordynamic Response for A Porous Type Gas Bearing," STLE Annual Meeting, Dallas, TX May 17-21.

[2] San Andrés, L., Zheng, Y., 2016, "Rotordynamic Performance of a Rotor Supported on Carbon-Graphite Tilting-Pad Air Bearings," (TRC-B&C-01-16**)**, Progress Report to the Turbomachinery Research Consortium, May.

[3] San Andrés, L., 2006, "Hybrid Flexure Pivot-Tilting Pad Gas Bearings: Analysis and Experimental Validation," ASME J. Trib., **128,** pp. 551-558.

[4] Sneck, H., and Yen, K., 1964, "The Externally Pressurized, Porous Wall, Gas-Lubricated Journal Bearing," ASLE Trans., **7**(3), pp. 288-298.