Mechanical Engineering Department
Texas A&M University

2007/2008
Research Progress Report
Tribology Group

Year XVII

28th Annual
Turbomachinery Research Consortium Meeting

May 2008

Luis San Andrés
Leader

http://phn.tamu.edu/TRIBGroup

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In 2007/8, Dr. San Andrés managed ten (10) research projects! The new funds in this past year add to **$740,730** with research expenditures amounting to **$346, 00**. The MEEN administration is happy! In 07/08, students and Dr. San Andrés published **thirty-four** technical papers (19 journal and 13 conference – all peer reviewed). Students in the Tribology Group quickly master their technical field, practice communication skills (oral and written), demonstrate leadership in teams that deliver, serve the professional society, and have uncompromising professional integrity with fully awareness of multi-cultural environments and opportunities.

The current status on the various research projects, the students involved, and the sources of funding follow:

- **Nonlinear Rotordynamics of Turbochargers**
  OBJECTIVE: To advance (experimentally validated) computational tools for prediction of the dynamic forced response of turbocharger rotors supported on (S)FRBs.
  STATUS: Virtual Laboratory (XLBRG v 7.0) released with improvements to model arbitrary geometry floating ring journal bearings, multiple thermal transport models, and realistic boundary temperatures at turbine and compressor sides.
  SPONSOR: HONEYWELL TURBO TECHNOLOGIES (2003-2008), **$ 432,541**
  Student: Ash Maruyama[G], Arian Vistamehr (M.S.)

- **Hybrid Brush Seals to Improve Gas Turbine Efficiency**
  OBJECTIVE: Measurements of leakage, power loss and structural parameters in a hybrid brush seals for gas turbine applications
  STATUS: High temperature (300 C) test rig constructed for measurements of brush seal and labyrinth seal leakage vs. supply pressure at increasing rotor speeds. Hybrid brush seals have significantly less leakage and reduced drag due to pad lift off effect, even without shaft rotation.
  SPONSOR: SIEMENS POWER GENERATION (2006-2008), **$ 142,973,** Seal from ADVANCED TURBOMACHINERY GROUP (ATG)
  Students: Adolfo Delgado (Ph.D.), Jose Baker (M.S.)[G] , Brian Butler (UG)

- **Gas Bearings for Oil-Free Turbomachinery**
  OBJECTIVE: To advance the technology of inexpensive reliable gas bearings for micro gas turbines and micro power systems
  STATUS: Demonstrated reliability of hybrid gas bearings to intermittent shocks from base or foundation.
  SPONSORS: TRC (TURBOMACHINERY RESEARCH CONSORTIUM), **$35,000**
  Personnel: Yaying Niu (M.S.), Keun Ryu (PhD),

- **Foil Gas Bearings for Oil-Free Turbomachinery**
  OBJECTIVE: To quantify the physical parameters of bump foil gas bearings for micro turbine applications
  STATUS: Computational analysis extended to model thermal management of foild bearings for micro gas turbine applications. High temperature test rig (max 500 C) under construction: MiTi Korolon® bearings and Foster-Miller bearings. Cooperation with KIST Korean Institute of Science and Technology).
  SPONSORS: NASA GRC (2007-2009), **$284,577**, NATIONAL SCIENCE FOUNDATION (2003-2007), **$255,475**, TRC, **$35,000,**
  Students: Tae-Ho Kim[G] (Post-Doc), Keun Ryu (Ph.D.), Chad Jarret (M.S.), Kat Hagen (UG)

- **Metal Mesh Foil Bearings for Microturbomachinery**

  OBJECTIVE: Further development of predictive models anchored to test data for predition of mechanical parameters of metal mesh foil bearings.
  STATUS: high speed (> 100 krpm) test rig under construction. Two metal mesh foil bearings constructed and tested to identify their structural stiffness and mechanical energy dissipation characteristics.
  SPONSOR: TRC, **$35,000,** Honeywell Turbocharging Systems donated two PV ball bearing turbochargers to drive test rig.
  Students: Tae-Ho Kim[G] (Post-Doc), Thomas Chirathadam (M.S.), Alex Martinez & Sungh Hu[G] (UG)

- **Dynamic Force Performance of Sealed Squeeze Film Dampers**

  OBJECTIVE: To assess effect of mechanical end seal on dynamic forced performance of a test SFD.
  STATUS: Test rig accommodates a SFD with a (nonrotating) mechanical seal that adds dry friction to system while containing lubricant for extended periods of time and without side leakage. Measurements with increasing contact forces conducted. Nonlinear parameter identification techniques developed and anchored to test data acquired for multiple frequency load functions.
  SPONSOR: TRC, **$35,000**
  Student: Adolfo Delgado (Ph.D.)

- **Bulk flow model for Oil Seal Rings**

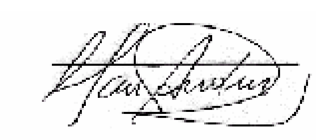
  OBJECTIVE: To improve predictions of force coefficients in grooved oil seal rings
  STATUS: Novel FE bulk-flow model predictions for stiffness, damping, and inertia coefficients of grooved oil seals show great agreement with test data from Childs. In a nut shell, force coefficients are (test) device dependent with effective groove depths at a fraction of their actual physical depth.
  SPONSOR: TRC, **$35,000**
  Student: Adolfo Delgado (Ph.D.)

- **Upgrade to $XLTRC^2$ bearing predictive tools**

  OBJECTIVE: To add thermal effects into journal (multiple pad) bearing code, and to include effects of pivot stiffness in code for tilting pad journal bearings.
  STATUS: Tilting pad bearing code near completion. Journal bearing program completed, GUI in progress.
  SPONSOR: TRC, **$35,000**
  Student: Jared Goldsmith (M.S.)

- **Research Experiences for Undergraduates: Development of Microturbomachinery**

  OBJECTIVE: The REU Summer Program funds 30 junior-level students to conduct hand-on training and research in mechanical, manufacturing, industrial, or materials engineering topics related to technological advances in microturbomachinery.
  STATUS: Ten qualified UGS participated in Summer 2007. Three students worked with Tribology Group students. Two remained during rest of year. Seven students will initiate further research in June 2008.
  SPONSOR: NATIONAL SCIENCE FOUNDATION (2006-2010), **$259,249**
  Investigators: PI: Wayne Hung (Engineering Technology), co-PI: Luis San Andrés



Luis San Andrés, Leader

Tribology Group

Team Members 2007/2008

Name	Research Project	Degree	Graduation date
Ash Maruyama Arian Vistamehr+	Nonlinear Rotordynamics of PV & CV Turbo-chargers	M.S. M.S.	December 2007 May 2009
Tae-Ho Kim, Keun Ryu	Gas Foil Bearings – Computational Analysis & High Temperature Test Rig	Ph.D Ph.D	December 2007 December 2009
Chad Jarrett, Kat Hagen*+	Nonlinear Force Response of Gas Foil Bearings	M.S B.S.	May 2009 August 2008
Yaying Niu	Flexure Pivot Gas Bearings for Oil Free TM	M.S.	August 2009
José Baker+ Zach Ashton	–High Temperature Hybrid Brush Seal	M.S. M.S.	December 2008 May 2009
Adolfo Delgado+	Identification of Force Coefficients in SFDs Hybrid Brush Seals for Gas Turbines	Ph.D.	August 2008
Jared Goldsmith	Pad Pivot Effects on Dynamic Performance of Tilting Pad Bearings	M.S.	August 2008
Thomas Chirathadam Alex Martinez+* Sungh Hu*+	Metal Mesh Foil Bearings & High Speed TC Driven Test Rig	M.S. B.S. B.S	August 2009 December 2009 May 2008

(*) undergraduate student, (+) minority student (female, Hispanic, Asian, African-American)

L to R:
Thomas Chirathadam, Tae Ho Kim, Jared Goldsmith, Yaying Niu, Adolfo Delgado, Sungh Hu, Arian Vistamehr, Chad Jarrett, Alex Martinez, Keun Ryu, Jose Baker

2008 RESEARCH PROGRESS REPORTS

2008-2009 RESEARCH PROPOSALS

CONTINUATIONS

Identification of Force Coefficients in an End Sealed SFD with Offset Multiple-Frequency Orbits (continuation II)

Rotordynamic Performance of Foil Gas Bearings: High Temperature Tests and Analysis (continuation II – joint with NASA GRC funded project)

Gas Bearings for Oil-Free Turbomachinery –Foundation Excitations (continuation III)

Rotordynamic Performance of Metal Mesh Bearings for Oil-Free Turbomachinery (continuation II)

Upgrade XLTRC^2 Journal Bearings: EFFECT of TEMPERATURE on Operating clearance and overall bearing performance. (continuation II)

PROGRESS REPORTS – EXECUTIVE SUMMARIES

TRC-B&C-1-08 Dynamic Forced Response of a Rotor-Hybrid Gas Bearing System due to Intermittent Shocks

Gas bearings in Micro-turbomachinery (MTM) offer significant system level benefits, such as improved fuel efficiency reductions in weight and number of components, extending life cycle and maintenance intervals, and reducing NOX emissions with a lower CO_2 footprint. Emerging opportunities of gas bearings range from automotive turbochargers to engines for business jet aircraft, for example. Gas bearings, because of the inherently low gas viscosity, have low damping relative to oil-lubricated bearings and are prone to wear during rotor start-up and shut down procedures. The lack of damping brings concerns about rotor-gas bearing system robustness and endurance to tolerate shock induced loads, sudden while landing in jet engines or intermittent while moving across rough terrain in vehicles, for example.

In 2008, sporadic shock loads are exerted to the base of an existing rotor-gas bearing system while coasting down from a top speed of 60 krpm (1000 Hz). In the tests, (1) an electromagnetic pusher delivers impacts to the rig base, or (2) the whole rig is manually tilted and dropped. The test rig consists of a rigid rotor, 0.825 kg and 28.6 mm in diameter, supported on two hybrid, flexure pivot tilting pad type, gas bearings, each with four pads and 60% pivot offset and 0.6 mm feeding holes. The bearings are supplied with feed pressure of 2.36, 3.72, and 5.08 bar (ab). Intermittent shocks, up to 30 g pk-pk and broad frequency range to 400 Hz, produce a remarkable momentary increase of the overall rotor response amplitude, up to 50 µm (pk-pk). The shocks readily excite the natural frequency of the rotor-bearing system (150-200 Hz), and on occasion the natural frequency (40 Hz) of the whole test rig. For operation at rotor speeds above the system critical speed, the rotor synchronous response is isolated; with transient motions induced by a shock, subsynchronous in whirl frequency, quickly disappearing. Full recovery takes place in ~0.10 second. The measurements demonstrate that the hybrid gas bearings have enough damping to rapidly attenuate rotor transient motions and to dissipate the energy induced from intermittent shocks. Note that shocks acted while the rotor traversed its critical speeds! The reliability of the gas bearings to forced transient events is no longer in question.

TRC-B&C-2-08 Thermohydrodynamic Analysis of Bump Type Gas Foil Bearings: Model and Predictions

Ready use of gas foil bearings (GFBs) into high temperature applications requires accurate model prediction accounting for transport and disposal of thermal energy. Adequate thermal management is a pervasive performance problem and engineering design challenge in micro gas turbines, for example. The current research introduces a thermohydrodynamic (THD) model for mechanical energy dissipation and thermal energy transport by the thin gas film and cooling gas streams (inner or outer), as well as heat conduction into the bearing cartridge. A bulk-flow model describes the transport of momentum and thermal energy within the gas film. Equivalent heat transfer coefficients represent multilayer convection/conduction paths. The model also accounts for shaft thermal expansion and centrifugal growth due to increases in rotor temperature and rotor speed. Material properties of the underlying foil structure degrade as the temperature increases.

THD model predictions show a larger minimum film thickness (and smaller journal eccentricity) when compared to those for the isothermal flow model, in particular with large static loads, because increases in gas film temperature result in net increases in gas viscosity. Larger shaft temperatures mean larger gas film temperatures with shaft thermal expansion reducing the operating bearing clearance, and leading to increases in drag torque. As the shaft temperature increases, the journal eccentricity and the minimum film thickness decrease due to the reduction in the operating bearing clearance. A cooling flow stream on the back of the top foil increases the heat flow transport to reduce the film temperature.

TRC-B&C-3-08 Rotordynamic Measurements on a High Temperature Rotor Supported on Gas Foil Bearings

Exhaustive experimentation and accurate model prediction will lead to successful implementation of gas foil bearings (GFBs) into high temperature applications. This report presents rotordynamic measurements in a gas bearing test rig revamped for high temperature operation. The tests aim to determine the effect of temperature on the system performance. An electric cartridge heater loosely installed inside the rotor acts as a heat source. Two GFBs support a hollow rotor, one of the GFB (drive end) is Teflon® coated while the other (free end) is uncoated. K-type thermocouples measure the GFB cartridge temperatures, and infrared thermometers measure the shaft and bearing support temperatures. If needed, an axial air flow cools the rotor and GFBs.

Heater temperatures, as high as 130 °C, are set in the system. Long times, on the order of hours, are required to reach thermal steady state condition. The tests show the bearing temperatures increase as the heater temperature increases and as the rotating speed increases. Rotor speed-up tests without shaft heating reveal the rotor amplitude drops suddenly just above its critical speed, thus implying nonlinear system response. As the rotor temperature increases, the rotor amplitudes of motion decrease and show no jumps. During rotor speed coastdown tests, the critical speed increases slightly as the heater temperature increases. Waterfall plots of the direct rotor amplitude of synchronous response show dominant synchronous rotor motions. During coastdown, from 26 krpm to ~ 8 krpm, the rotor speed decays exponentially as time elapses, thus evidencing operation with "viscous" drag. However, in all cases, the decay rate of rotor speed changes at ~ 15 krpm (near the critical speeds).

TRC-B&C-4-08 The Effect of (Nonlinear) Pivot Stiffness on Tilting Pad Bearing Dynamic Force Coefficients

Not yet available. Final report will be completed and released by end of August 2008

TRC-B&C-5-08 Development of a Test Rig for Metal Mesh Foil Gas Bearing and Measurements of Structural Stiffness and Damping in a Metal Mesh Bearing

Metal Mesh Foil Bearings (MMFBs) are a cost effective gas bearing technology for use in oil-free microturbomachinery. These bearings will ensure low friction, long operating life, and with significant material damping for mechanical energy dissipation. In a MMFB, a donut shaped metal mesh (MM) provides a soft support to a smooth top foil wrapped around a rotating journal. The report details the construction of a MMFB and static and dynamic load tests conducted on the bearing for estimation of its structural stiffness and material damping coefficient. The MMFB, 28.30 mm in diameter and 28.05mm in length, is made of 0.3 mm Cupper wire with a compactness of 20 %. The static load versus bearing deflection measurements evidence a typical cubic nonlinearity with large hysteresis, thus leading to a hardening structural stiffness, quite distinct during both loading and unloading processes. Shaker loads of controlled amplitude and over a frequency range act on the test bearing. The dynamic bearing displacements show a single frequency, equal to that of the applied load. Analysis of the applied force and displacements in the frequency domain renders the bearing mechanical impedance, whose real and imaginary parts determine the bearing stiffness and damping coefficients, respectively. The MMFB structural stiffness decreases significantly with the amplitude of motion and, a little less, as the excitation frequency increases. The MMFB equivalent viscous damping is both frequency and amplitude dependent, decreasing rapidly with both parameters. On the other hand, a structural loss factor (material damping) represents best the mechanical energy dissipation characteristics of the test MMFB. The measurements show a loss factor as high as 0.50, a significant magnitude for the simple mechanical system, and with little dependency on the excitation frequency. Empirically based formulas, properly modified as per the test MMFB material density, predict stiffness and damping coefficients agreeing well with the experimentally derived coefficients.

The report also describes progress on the construction of a test rig for demonstration of high speed prototype miniature gas foil bearings. A ball-bearing supported turbocharger (TC), donated by a TRC member, drives the system to a top speed of 110 krpm. The test bearing section replaces the compressor impeller and volute of the original TC. A 28.08 mm diameter journal, 55 mm in length and mounted in the free end of the transmission shaft, will carry the test gas bearing. A centering elastic support, affixed to a two axes positioning table with electronic control, also holds the test gas bearing cartridge. The bearing support structure has eddy current sensors to record journal dynamic displacements, and ad-hoc mechanisms to impose a static load on the bearing and to measure the rotor lift off speed and drag torque. Upon construction completion, end of 2008, experiments will be conducted to measure the rotordynamic performance and endurance of MMFBs for high speed operation.

TRC-SEAL-1-08 A Novel FE Bulk-Flow Model for Improved Predictions of Force Coefficients in Off-Centered Grooved Oil Seals

Oil seals in centrifugal compressors prevent leakage of the process gas into the support bearings and ambient. Under certain operating conditions of speed and pressure, oil seals lock, becoming a source of hydrodynamic instability due to excessively large cross coupled stiffness coefficients. It is a common practice to machine circumferential grooves, breaking the seal land, to isolate shear flow induced film pressures in contiguous lands, and hence reducing the seal cross coupled stiffnesses. Exhaustive oil seal testing performed by Childs and students shows that inner land grooves, shallow or deep, do not actually reduce the cross-stiffnesses as much as conventional models predict. In addition, the tested grooved oil seals have overly large added mass coefficients; while predictive models, based on classical lubrication theory, miss entirely the fluid inertia effect.

A 2007 TRC report introduces a fluid inertia, bulk-flow model that properly accounts for the flow and moment transport at the groove-land interfaces. The novel model predicts with exactness the force coefficients of multiple-groove laminar flow oil seals at their centered condition. The analysis relies on an effective groove depth, different from the physical groove depth, which delimits the upper boundary for the flow induced by dynamic (fluid squeezing) motions in the grooved region of a seal.

The current report extends the bulk-flow analysis to predict the leakage, reaction forces and dynamic force coefficients of grooved oil seals operating at an off-centered (eccentric) locked condition. Predictions of rotordynamic force coefficients are compared to published test coefficients for a smooth land seal and a seal with a single groove seal with a depth of 15 times the land clearance (c=85.9 μm). The test data represents operation at 10 krpm and 70 bar oil feed pressure, and four journal eccentricity ratios (e/c= 0, 0.3, 0.5, 0.7). The enhanced model predicts accurately the smooth and grooved seals' leakage, reaction force, and rotordynamic force coefficients for the lowest eccentricities (e/c= 0, 0.3). The model yields moderate to good correlation with the test force coefficients for e/c=0.5. For the largest journal eccentricity, e/c=0.7, significant discrepancies between the predictions and experimental results arise. The test data technical report does not offer details on operating conditions leading to large power dissipation that may have affected the lubricant properties and seal clearance.

The model completed is a significant improvement that predicts accurately the rotordynamic force coefficients of locked multiple-grooved oil seals. Prior to the current results, the cross-coupled stiffness coefficients of grooved oil seals were largely under predicted, and the direct added mass coefficients ignored or largely under predicted (up 10 times). The computational model uses a FEM for solution of the flow equations and offers a GUI for direct integration into XLTRC2.

TRC-SFD-1-08 Dynamic Performance of a Squeeze Film Damper with Non-Circular, Multi-Frequency Motions Reproducing Multi-Spool Engine Operating Conditions

Squeeze film dampers (SFDs) in rotating machinery provide structural isolation, reduce amplitudes of response to imbalance, and increase the threshold speed of rotor-bearing system instability. SFDs are usually installed at the bearing supports, either in series or in parallel. In multi-spool engines, SFDs are also located in the interface between rotating shafts. These *intershaft dampers* show multiple frequency whirl motions resulting from the combined imbalance responses of both the low speed rotor and the high speed rotor.

The report presents an experimental investigation simulating the dynamic forced response of a SFD subject to multiple frequency motions, as in a jet engine intershaft damper. For these operating condition, the forced response of the damper is non linear since its mechanical parameters, damping and inertia, are a function of the instantaneous journal position, static or dynamic.

The TRC-SFD test rig comprises of a vertical (stationary) journal and a flexibly supported housing that holds the test damper and instrumentation. The open ends SFD is 127 mm in diameter, 25.4 mm in film land length, and radial clearance of 0.127 mm. The damper is lubricated with an ISO VG 2 oil and operated at room temperature. In the experiments, two orthogonally positioned shakers are programmed to deliver dynamic forces to the test damper that produce certain controlled amplitude motions and, by using multi-frequency sine sweep excitations, to cover a frequency response range that includes the natural frequency of the test system. In the tests, a low frequency is maintained at 25 Hz, while a second frequency ramps from 30 Hz to 120 Hz over a specified time span. The test data collected, forces and motions versus time, is converted into the frequency domain for parameter identification, The SFD force coefficients are identified from system impedance functions and considering only the frequency component that coincides with the forced excitation frequency, since this is the only component that dissipates mechanical energy. The frequency dependent, identified viscous damping coefficients are strong functions of the amplitude of journal motion. In the tests, the damper operates free of oil cavitation or air entrainment, and hence, the identified cross-coupled coefficients are negligible. The experimental damping coefficients are within the range of predictions derived from classical formulas for circular centered orbits or small amplitude motions about an eccentric journal position. The test added mass coefficients are three times larger than those predicted by classical theory, which ignores the influence of the inlet and discharge annular grooves. On the other hand, an improved bulk-flow model developed earlier (TRC-SFD-2-07) predicts added mass coefficient within 15% of the experimental values.

Tribology Group - Funded Research 2007-2008

TOTAL NEW funds 07/08: $ 740,430

External NEW funds (07/08) $ 460,430

Sponsor Project #	Amounts	Total – life of project	Project	Dates (GS support)
NASA - Glenn RC 32525/39600/ME	**$284,577**	**$284,577**	Prediction of Foil Bearing Performance: A Computational Model Anchored to Test Data	09/01/07-08/26/09 (2)
Honeywell Turbocharging 32525/6865A//ME	**$101,104 + 40,694**	**$ 432,541**	A Virtual Tool for Nonlinear Rotordynamics of Turbochargers	01/15/2003 10/31/2008 (1)
Siemens Power Generation 32525/34650	**$ 27,355+ 67,000**	**$ 142,973**	Hybrid Brush Seals to Improve Gas Turbine Efficiency	12/09/2005 10/30/2008 (1)
National Science Foundation		**$259,249**	Research Experiences for Undergraduates: Development of Microturbomachinery	10UG/year 04/24/2006 05/31/2010

Projects Completed

Capstone Turbine Corp. 32525/37550	**$ 64,762**	Capabilities with Foil Bearings	12/1/2006-11/30/2007 (1)
NSF 32525/53900//ME	**$255,475**	Gas Foil Bearings for Oil-Free Rotating Machinery – Analysis Anchored to Experiments	06/15/2000 05/31/2007(2)

Internal, $245,000 (TRC)

Sponsor	Amount	Project	Dates
TRC 32514/1519B4/ME	$35,000	Gas Bearings for Oil-Free Turbomachinery – Identification of Force Coefficients from Impact Loads	06/30/07 05/31/08
TRC 32514/1519C4/ME	$35,000	Rotordynamic Performance of Foil Gas Bearings: High Temperature Tests and Analysis	06/30/07 05/31/08
TRC 32514/1519S7/ME	$35,000	Identification of Force Coefficients in an End Sealed SFD Non-Circular Orbits	06/30/07 05/31/08
TRC 32514/1519S7/ME	$35,000	Upgrade $XLTRC^2$ Computational Model for Hydrodynamic Journal Bearings – Thermohydrodynamic Analysis	09/01/07 08/31/08
TRC 32514/1519S7/ME	$35,000	Upgrade $XLTRC^2$ Computational Model for Tilting Pad Journal Bearings to include (Nonlinear) Pivot Stiffness Seal Assembly Preloads	09/01/07 08/31/08
TRC 32514/1519S7/ME	$35,000	Metal Mesh-Top Foil Gas Bearings for Oil-Free Turbomachinery: Test Rig for Prototype Demonstrations	09/01/07 08/31/08
TRC 32514/1519T7/ME	$35,000	Upgrade $XLTRC^2$ Computational Model for Grooved Oil Seal Rings to predict Added Mass Coefficients	12/10/07 11/30/08

Support for equipment acquisition and donations:

Source	Amount	Purpose	Date
Honeywell AeroSpace	**$35,000**	GIFT: Acquisition of Equipment for Squeeze Film Damper Test Rig	February 2008

Research Expenditures Calendar year 2007: ~ $ 346,000 **Source: MEEN Head**

Tribology Group Publications 2007/2008

(bold face- student co-author**)**

	2007	2008	Total
Journal (peer reviewed)	15	4	**19**
Conference (peer reviewed)	6	6	**13**
Conference (NOT peer reviewed)	1		**1**
Accepted/awaiting publication		2	
Extended Abstracts Student posters	2 1	1	**3**

2008

Journal publications (peer reviewed)

4 San Andrés, L., and **Kim, T.H.,** 2007, "Forced Nonlinear Response of Gas Foil Bearing Supported Rotors," Tribology International, **41**(8), pp. 704-715.

3 San Andrés, L., and **K. Ryu, 2008,** "Flexure Pivot Tilting Pad Gas Bearings: Operation with Worn Clearances and Two Load-Pad Configurations," ASME Journal of Engineering for Gas Turbines and Power, Vol. 130, pp. 042506-1-10.(ASME Paper No GT2007-27127)

2 San Andrés, L., and **A. Delgado**, 2008, "Squeeze film Damper with a Mechanical Seal: Experimental Force Coefficients Derived from Circular Centered Orbits," ASME Journal of Engineering for Gas Turbines and Power, Vol. 130, pp. 042505-1-8. (ASME Paper No GT2007-27436)

1 **Kim, T.H.,** and L. San Andrés, 2008, "Heavily Loaded Gas Foil Bearings: a Model Anchored to Test Data," ASME Journal of Engineering for Gas Turbines and Power, Vol. 130(1), pp. 012504-1-8.

Peer reviewed Conference publications

ASME Turbo Expo 2008, June 2008, Berlin

J **Kim, T.H.,** and San Andrés, L., 2008 "Effect of Side Pressurization on the Performance of Gas Foil Bearings – A Model Anchored to Test Data," ASME Paper GT2008-50571

J San Andrés, L., **Baker, J.,** and **Delgado, A.,** 2007, "Measurements of Leakage and Power Loss in a Hybrid Brush Seal," ASME Paper GT2008-50532

J San Andrés, L., and **Ryu, K.,** 2008, "Hybrid Gas Bearings with Controlled Supply Pressure to Eliminate Rotor Vibrations while Crossing System Critical Speeds," ASME Paper GT2008-50393

J **Delgado, A.,** and San Andrés, L., 2008, "Nonlinear Identification of Mechanical Parameters on a Squeeze Film Damper with Integral Mechanical Seal," Paper GT2008-50528

Kim, T.H., San Andrés, L., and **Breedlove, A.,** 2008, "Characterization of Foil Bearing Structure for Increasing Shaft Temperatures: Part II – Dynamic Force Performance," Paper GT2008-50570

Kim, T.H., Breedlove, A., and San Andrés, L., 2008, "Characterization of Foil Bearing Structure for Increasing Shaft Temperatures: Part I – Static Load Performance," Paper GT2008-50567

J: accepted for publication at ASME Journal of Gas Turbines & Power

Invited Plenary Lecture

Issues on Stability, Forced Nonlinear Response and Control in Gas Bearing Supported Rotors for Oil-Free Turbomachinery, International Conference in Rotating Machinery, ISROMAC 12, February 2008.

Presentation available at **http://www.isromac.org/symposia/browse/ISROMAC-12/38/en**

Extended Abstracts

San Andrés, L., **Baker, J**., and **Delgado, A.,** 2008, "Measurements of Leakage and identification of Structural Force Coefficients in a Hybrid Brush Seal," STLE Annual Meeting, Cleveland, OH, May.

2007

Journal publications (peer reviewed)

15 **Delgado, A.,** and L. San Andrés, 2007, "Identification of Structural Stiffness and Damping in a Shoed Brush Seal," ASME Journal of Vibrations**,** Vol. 129(5), pp. 648-655.

14 San Andrés, L., **J.C. Rivadeneira,** K. Gjika, C. Groves, and G. LaRue, 2007, "A Virtual Tool for Prediction of Turbocharger Nonlinear Dynamic Response: Validation Against Test Data," ASME Journal of Engineering for Gas Turbines and Power, 129(4), pp. 1035-1046

13 **Zhu, S.** and L., San Andrés, 2007, "Rotordynamic Performance of Flexure Pivot Hydrostatic Gas Bearings for Oil-Free Turbomachinery," Journal of Engineering for Gas Turbines and Power, 129(4), pp. 1020-1027.

12 San Andrés, L., and **A. Delgado**, 2007, "Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical Seal, I: Unidirectional Load Tests," ASME Journal of Engineering for Gas Turbines and Power, 129(3), pp. 858-864

11 San Andrés, L., **D. Rubio**, and **T.H. Kim,** 2007, "Rotordynamic Performance of a Rotor Supported on Bump Type Foil Gas Bearings: Experiments and Predictions," ASME Journal of Engineering for Gas Turbines and Power, 129(3), pp. 850-857.

10 San Andrés, L., and **A. Delgado**, 2007, "Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical Seal, Centered Circular Orbit Tests," ASME Journal of Tribology, Vol. 129(3), pp. 660-668.

9 San Andrés, L., **J.C. Rivadeneira,** K. Gjika, C. Groves, and G. LaRue, 2007, "Rotordynamics of Small Turbochargers Supported on Floating Ring Bearings – Highlights in Bearing Analysis and Experimental Validation," ASME Journal of Tribology, 129, pp. 391-397

8 **Kim, T-H,** and L., San Andrés, 2007, "Analysis of Gas Foil Bearings with Piecewise Linear Elastic Supports**."** Tribology International, **40**, pp. 1239-1245.

7 De Santiago, O., and L., San Andrés, 2007, "Experimental Identification of Bearing Dynamic Force Coefficients in a Flexible Rotor – Further Developments," *Tribology Transactions*, v. 50(1), p. 114-126.
Editor's Choice – Tribology & Lubrication Technology, June 2007, pp. 40-50.

6 **Rubio, D.,** and L. San Andrés, 2007, "Structural Stiffness, Dry-Friction Coefficient and Equivalent Viscous Damping in a Bump-Type Foil Gas Bearing," ASME Journal of Engineering for Gas Turbines and Power, 129, pp. 494-502. (ASME Paper GT 2006-90873)

5 San Andrés, L**., J.C. Rivadeneira,** M. Chinta, K. Gjika, G. LaRue, 2007,"Nonlinear Rotordynamics of Automotive Turbochargers – Predictions and Comparisons to Test Data," ASME Journal of Engineering for Gas Turbines and Power, 129, pp. 488-493 (ASME Paper GT 2005-68177)

4 San Andrés, L., and **T. Soulas**, 2007, "A Bulk Flow Model for Off-Centered Honeycomb Gas Seals," ASME Journal of Engineering for Gas Turbines and Power, 129, pp. 185-194.

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Luis San Andrés, 2008 ®

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