Mechanical Engineering Department
Texas A&M University

2006/2007
Research Progress Report
Tribology Group

Year XVI

27th Annual
Turbomachinery Research Consortium Meeting

May 2007

Luis San Andrés
Leader

http://phn.tamu.edu/TRIBGroup

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In 2006-2007, Dr. San Andrés managed nine (9) research projects with a total value of **$1,871,792**. During 2006 Fiscal Year research expenditures amounted to **$500, 813**. Current and former students and Dr. San Andrés co-authored **twenty-four** technical papers (fourteen journal publications and ten conference papers – all peer reviewed). Seven papers await journal publication. 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:

- **CLIN 006 - Tool/Method Development of the AFRL Upper Stage Technology Program (USET) Turbopump USET Development**

  OBJECTIVE: Experimental validation and enhancements of computational models for prediction of dynamic forced performance of cryogenic liquid hydrostatic bearings - USAF Upper Stage Engine Technology Program.
  (b): Create capability for modeling speed dependent non-linear operation in mixed flow regime (fluid and solid contact), including prediction of lift-off speed
  (c): Experimental Study of Hydrostatic / Hydrodynamic Thrust Bearings: 25 krpm, 250 psi, 600 lbf, water bearings.
  STATUS: (a) completed, (b) completed – final report in preparation, (c) construction of test rig completed, troubleshooting with air pressurization completed, static load tests with water lubrication in progress.
  SPONSOR: NORTHROP GRUMMAN (2005-2008), **$767,821**
  Personnel: Luis San Andrés, Steve Phillips (Research Engineer), Student: Nicholas Tydlacka (M.S.), Michael Forsberg (M.S.), Fernando Ramirez (M.S.), Jason Haynes (UG), Scott Wilson (UG).

- **Computational Analysis of Floating Ring Journal Bearings (FRBs) and Experimental Validation in a Turbocharger Test Rig**

  OBJECTIVE: To advance (experimentally validated) computational tools for prediction of the dynamic forced response of turbocharger rotors supported on FRBs.
  STATUS: Virtual Laboratory (computational software) enhanced to model effect of engine induced excitations on TC forced response.
  SPONSOR: HONEYWELL TURBO TECHNOLOGIES (2003-2008), **$ 391,847**
  Student: Ash Maruyama (MS), Arian Vistamehr (UG)

- **Shoed 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: Rotating test rig constructed for shaker load measurements. Leakage vs. supply pressure tests at increasing rotor speeds completed. Hybrid brush seals offer markedly low leakages and reduced power losses as pressure supply increases with little detrimental effect from rotor speed.
  SPONSOR: SIEMENS UNIVERSITY EMBRYONIC PROJECT (2006-2007), **$ 48,638 + $27,955**
  Student: Adolfo Delgado (Ph.D.), Jose Baker (M.S.)
  HARDWARE FROM ADVANCED TURBOMACHINERY SOLUTIONS (ATS)

- **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 controlled pressurization avoids excitation of critical speeds with smooth operation over extended rotor speed zones.
SPONSORS: TRC (TURBOMACHINERY RESEARCH CONSORTIUM), **$28,000**
Personnel: Keun Ryu (M.S.)

- **Foil Gas Bearings for Oil-Free Turbomachinery**

OBJECTIVE: To quantify the physical parameters of bump foil gas bearings for micro turbine applications
STATUS: 1D & 2D top foil computational models available to TRC members. Computational analysis with validation measurements for effects of side pressurization completed. Computational analysis with validation measurements for shimmed gas foil bearings completed.
SPONSORS: NATIONAL SCIENCE FOUNDATION (2003-2007), **$255,475**, TRC, **$28,000**
Students: Tae-Ho Kim (PhD), Anthony Breedlove (M.S.), Chad Jarret (M.S.)
In April 2007,Anthony Breedlove completed his MS degree. His thesis "**Experimental Identification of Structural Force Coefficients in a Bump-Type Foil Bearing**" is available to TRC members. NSF, TRC, GEM (National Consortium for Graduate Degrees for Minorities in Engineering and Science), and USAF-Universal Technology Corp. sponsored Anthony's work. In June, Anthony joins Schlumberger with a first assignment in Brazil. Best to him!

Capabilities with Foil Gas Bearings

OBJECTIVE: To advance experimentally validated computational models for prediction of a proprietary gas foil bearing design.
STATUS: Model for prediction of foil bearing stiffness completed. Static load tests for validation in progress. .
SPONSORS: CAPSTONE TURBINE CORP (2007), **$ 64,762**
Students: Tae-Ho Kim (PhD), Chad Jarrett (M.S.)

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

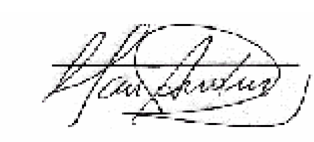
OBJECTIVE: To assess effect of mechanical end seal on dynamic forced performance of a test SFD.
STATUS: Test rig accommodates a SFD with a (nonrotating) mechanical seal that adds dry friction to system while containing lubricant for extended periods of time and without side leakage. Measurements with closed outlet ports conducted at high loads and frequencies to establish onset of air entrainment. Analysis for prediction of damping and inertia force coefficients in multiple grooved SFD/seal configurations completed.
SPONSOR: TRC, **$28,000**
Students: Adolfo Delgado (Ph.D.), Mathew Christley (UG)

- **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: Nation-wide advertisement and search. Ten qualified UG students selected for Summer 2007. Three students working for the Tribology Group
SPONSOR: NATIONAL SCIENCE FOUNDATION (2006-2010), **$259,249**
Investigators: PI: Wayne Hung (Engineering Technology), co-PI: Luis San Andrés

Dr. San Andrés and students attended:

- ASME Turbo-Expo'06 Conference, May 2006, Barcelona, Spain,
- ASME-STLE International Joint Tribology Conference, October 2006, San Antonio, TX
- Congreso Latinoamericano de Turbomaquinaria, November 2006, Veracruz, Mexico
- ASME Turbo-Expo'07 Conference, May 2007, Montreal, Canada



Luis San Andrés, Leader

Tribology Group

Team Members 2006/2007

Name	Research Project	Graduation date
Ash Maruyama[+] **Arian Vistamehr*[+]**	**Dynamic Response of Turbocharger Rotors Supported on Floating Ring Journal Bearings**	**August 2007** Start June 2007
Tae-Ho Kim, **Anthony Breedlove[+],** **Chad Jarrett,**	**Gas Foil Bearings – Computational Analysis & Test Rig Development and Identification of System Parameters**	December 2007 **May 2007** August 2008
Keun Ryu	**Flexure Pivot Gas Bearings for Oil Free TM**	August 2007
José Baker[+]	**Reverse Rotation Brush Seals - Testing**	December 2007
Adolfo Delgado[+] **Mathew Christley***	**Identification of Force Coefficients in Sealed SFD**	May 2008
Nicholas Tydlacka[*]	**Mixed Lubrication Lift off Model for Hydro-static Bearings (USET program)**	**August 2007**
Michael Forsberg, **Fernando Ramirez,** **Jason Haynes*,** **Scott Wilson[*]**	**Design and Construction of Hydrostatic Thrust Bearing Test Rig (USET program)**	December 2007 December 2007

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

L to R: Tae Ho Kim, Nick Tydlacka, Anthony Breedlove, Chad Jarrett, Keun Ryu, Adolfo Delgado, Jose Baker, Ash Maruyama. Missing: Mike Forsberg, , Fernando Ramirez.

2007 RESEARCH PROGRESS REPORTS

Hybrid Gas Bearings with Controlled Supply Pressure to Eliminate Rotor Vibrations while Crossing System Critical Speeds Luis San Andrés and Keun Ryu **TRC-B&C-1-07**
Effect of Side Feed Pressurization on the Performance of Shimmed Foil Gas Bearings – Part I: Experimental Verification Tae-Ho Kim and Luis San Andrés **TRC-B&C-2-07**
Effect of Side Feed Pressurization on the Performance of Shimmed Foil Gas Bearings – Part II: Model, Predictions and Comparisons to Rotordynamic Measurements Tae-Ho Kim and Luis San Andrés **TRC-B&C-3-07**
Parameter Identification of an End Sealed SFD: **Identification of Force Coefficients and Operating Conditions Leading to Air Ingestion** Luis San Andrés and Adolfo Delgado **TRC-SFD-1-07**
Parameter Identification of an End Sealed SFD: **Improved Predictions of Added Mass and Damping Coefficients for Grooved SFDs and Oil Seals** Luis San Andrés and Adolfo Delgado **TRC-SFD-2-07**

2007-2008 RESEARCH PROPOSALS
CONTINUATION
Identification of Force Coefficients in an End Sealed SFD Executing Eccentric Non-Circular Orbits for increasing End Seal Assembly Preloads (CONTINUATION IV)
Rotordynamic Performance of Foil Gas Bearings: High Temperature Tests and Analysis (CONTINUATION III)
Gas Bearings for Oil-Free Turbomachinery – Identification of Force Coefficients from Impact Loads (CONTINUATION II)
NEW
Upgrade XLTRC^2 Computational Model for Hydrodynamic Journal Bearings – Thermohydrodynamic Analysis
Upgrade XLTRC^2 Computational Model for Tilting Pad Journal Bearings to include (Nonlinear) Pivot Stiffness
Upgrade XLTRC^2 Computational Model for Grooved Oil Seal Rings to predict Added Mass Coefficients
TENTATIVE
Metal Mesh-Top Foil Gas Bearings for Oil-Free Turbomachinery: Test Rig for Prototype Demonstrations

PROGRESS REPORTS – EXECUTIVE SUMMARIES

TRC-B&C-1-07 Hybrid Gas Bearings with Controlled Supply Pressure to Eliminate Rotor Vibrations while Crossing System Critical Speeds

Micro-turbomachinery implements gas bearings in compact units of enhanced mechanical reliability. Gas bearings, however, have little damping and are prone to wear during frequent rotor start-up and shut down conditions. Externally pressurized gas bearings provide a simple solution to overcome excessive drag and allowing rub-free operation during transient response events. Flexure pivot tilting pad bearings offer little or no cross-coupled stiffnesses with enhanced rotordynamic stability. At TAMU, these bearings modified for hydrostatic pressurization demonstrated superior rotordynamic performance over other simple gas bearing configurations. The test rig comprises of a rigid rotor, 0.825 kg and 28.6 mm in diameter, supported on two hybrid flexure pivot hybrid gas bearings, each with four pads and 60% pivot offset and 0.6 mm feeding holes. Experimental results show that external pressurization stiffens the gas bearings, increasing the system critical speed while reducing the modal damping. Most importantly, the tests demonstrate that external pressurization is not needed for super critical speed operation.

In 2007, the test rig integrates an inexpensive automatic air pressure regulator controlling the supply pressure into the gas bearings. The measured rotor dynamic response determines the regulator control scheme with a programmed schedule over a rotor speed region enclosing the system critical speeds. Rotor speed coast-down tests with controlled supply pressure into the bearings demonstrate the effective elimination of large rotor motion amplitudes while crossing the system critical speeds. The simple on-off control with a step increase in pressure while approaching a critical speed offers the best system response since it changes abruptly the bearing stiffness coefficients and moves the system critical speed to a higher speed.

A rotordynamic analysis, integrating bearing force coefficients predicted by an existing TRC computational model, forwards critical speeds in agreement with the test results. Predicted rotor synchronous responses for the cases with controlled supply are in excellent agreement with the measured responses. The experiments validate the predictive tools and demonstrate the controllable rotordynamic characteristics of the flexure pivot hybrid gas bearings.

TRC-B&C-2-07 Effect of Side Feed Pressurization on the Performance of Shimmed Foil Gas Bearings – Part I: Experimental Verification

Gas Foil bearings (GFBs) often require thermal management with pressurized gas, supplied through one bearing end, to force a cooling stream that carries away thermal energy from a hot shaft, for example. In 2006, measurements in a rotor-GFB system tested to a speed 25 krpm show linear synchronous responses for small mass imbalances for operation with a low feed pressure of 0.34 bar (5 psig). Larger imbalances induced large subsynchronous rotor motions with a whirl frequency coinciding with a system natural frequency. Gas side pressurization demonstrated a surprising reduction in rotor amplitudes of motion, subsynchronous in particular. In tests to a higher speed (50 krpm), whirl motions reached limit cycles of large amplitude and with frequencies associated to low natural frequency rigid body modes. In 2007, more rotordynamic response measurements are conducted during rotor speed-up and coastdown tests for GFBs supplied with increasing feed pressures to 4.1 bar (60 psig). The tests show the dramatic effect of bearing side gas pressurization on reducing the total amplitude of rotor motion, mainly composed of one subsynchronous whirl frequency. At a given rotor speed and with a sufficiently high feed pressure, the rotor subsynchronous whirl motions disappear; i.e. the test system becomes rotordynamically stable. With a side feed pressure of 0.34 bar (5 psig), speed coastdown rotor responses from 25 krpm and for large imbalances demonstrate a nonlinear effect with an evident reduction in system damping. In general, side gas pressurization has little effect on ameliorating the amplitudes of rotor synchronous response.

Installation of metal shims under the GFB bump strip layers and in contact with the bearing cartridge introduces a mechanical preload into the test bearings. The preload makes the bearings stiffer and aids to increase the system threshold speed of instability. At high shaft speeds, however, subsynchronous motions become dominant, with rotor imbalance exacerbating the rotor motion amplitudes. A feed gas pressure of 4.1 bar (60 psig) delays significantly the threshold speed of subsynchronous motions. For small imbalances, normalization of the amplitudes of synchronous motion demonstrates the test system linearity. Recorded loci of rotor static centerline show that side gas pressurization reduces cross-coupled force effects that destabilize the rotor-GFB system at high rotational speeds.

TRC-B&C-3-07 **Effect of Side Feed Pressurization on the Performance of Shimmed Foil Gas Bearings – Part II: Model, Predictions and Comparisons to Rotordynamic Measurements**

Oil-free micro turbomachinery implementing gas foil bearings (*GFBs*) have improved mechanical efficiency and reliability, although often requiring adequate thermal management via a cooling gas flow, axially fed through one end of the bearings, to transport the heat conducted from a hot shaft, for example. Tests have shown that side gas pressurization aids to reduce amplitudes of motion, in particular subsynchronous (TRC-B&C-2-07).

A computational gas film model implementing the evolution of gas circumferential velocity as a function of the imposed side pressure is advanced. For the test *GFBs*, predicted direct stiffnesses and damping coefficients increase as the magnitude of feed pressure raises, while the difference in cross-coupled stiffnesses, directly related to rotor-bearing system stability, decreases. Predictions of threshold speed of instability and whirl frequency ratio are in close agreement with measurements (TRC-B&C-2-07).

A model for GFBs with shims is introduced. The shimmed GFB, whose film clearance resembles a three lobe bearing, generates significantly larger hydrodynamic pressures than those in a conventional GFB. Shimmed GFBs operate with a smaller journal eccentricity and attitude angle than conventional GFBs, and with increased direct stiffness and damping coefficients. A linear finite element rotordynamic analysis (XLTRC^2) models the test rotor supported on GFBs and predicts the system rotordynamic stability and synchronous rotor responses, phase angle and amplitude. Predicted synchronous responses are in very good agreement with the test measurements, in particular for small to moderate imbalances.

Although external pressurization aids to improve GFB rotordynamic performance; a too large supplied gas flow rate for cooling an actual high temperature application may penalize sensibly the efficiency and performance of the turbomachinery.

TRC-SFD-1-07 Parameter Identification of an End Sealed SFD: **Identification of Force Coefficients and Operating Conditions Leading to Air Ingestion**

Open end squeeze film dampers (SFDs) operating with low levels of pressurization are prone to air ingestion and entrapment that drastically reduce their damping capability. End seals can significantly reduce the severity of air ingestion. A 2006 TRC report details dynamic load tests inducing damper circular orbits and a method to identify the SFD force coefficients in a two step procedure. The seal friction force is found first prior to pumping oil through the damper (dry system). Next, with lubricant flowing through the damper, system damping and inertia coefficients are determined; and from which, the SFD dynamic force parameters are extracted.

In 2007, an identification method applicable to nonlinear systems is implemented for the simultaneous determination of the squeeze film force coefficients and the seal dry friction force. The frequency domain procedure saves considerably time in testing and data post-processing. Dynamic load tests are conducted with the damper outlet ports closed, i.e. with no lubricant thru flow, a condition of interest in UAVs. The method delivers a seal dry friction force nearly invariant to amplitude and frequency of motion. Identified SFD force coefficients are slightly larger (~10%) than coefficients determined from tests with oil flowing through the damper. Measured dynamic pressures of the lubricant at the damper film land and discharge groove show the paramount effect of fluid inertia. Dynamic film land pressures are proportional to the damper amplitude of motion and frequency. Discharge groove pressures are comparable to film pressures for operation with small orbit radii. Importantly, enough, the pressures recorded show sub-ambient film pressures without signs of lubricant gas cavitation or ingestion of air into the film; thus demonstrating the effectiveness of the mechanical seal in preventing air entrapment. At the largest test orbit amplitude (74 um at 50 Hz), some minute air bubbles are visually detected in the squeeze film. These bubbles ingress through the threads of the instrumentation fittings and outlet port connections and migrate into the squeeze film section.

TRC-SFD-2-07 Parameter Identification of an End Sealed SFD: **Improved Predictions of Added Mass and Damping Coefficients for Grooved SFDs and Oil Seals**

Extensive experimental evidence available in the open literature notes large differences between measured and predicted added mass (fluid inertia) force coefficients in squeeze film dampers (SFDs) that incorporate feed and discharge grooves and plenums. Childs et al. demonstrate the discrepancies also apply to laminar flow, grooved floating ring oil seals. In oil seals, internal grooves are introduced to reduce cross-coupled stiffnesses, thus improving the seal stability. Childs et al. tests show that narrow grooves, deep or shallow, do reduce an oil seal cross-coupled stiffness and direct damping coefficients, following closely model predictions; however, added mass coefficients are, at times, even larger than those from a smooth or ungrooved seal. Furthermore, predictive tools for oil seals do not account for fluid inertia effects while the experimental data estimates large added mass coefficients.

The report advances a bulk-flow model for small amplitude journal motions about a centered condition in a multiple-groove annular seal or SFD configurations. Zero_{th} and first order (equilibrium and perturbed) flow equations are stated for regions of characteristic clearance (*c*), film land and grooved. The procedure leads to a set of ODEs for the pressure fields with a unique boundary pressure and axial flow rate at the interfaces between adjacent flow sections. Specified inlet (and discharge) pressure OR axial flow condition depend on the actual physical configuration of the modeled SFD or oil seal arrangement. Force coefficients (stiffness, damping and inertia) are obtained from integration of the dynamic pressure fields acting on the rotor (journal) surface. At a grooved or plenum region, the characteristic groove depth (effective clearance) may be a fraction of the actual depth, as derived from qualitative observations of the laminar flow pattern through annular cavities.

Predictions of force coefficients for a grooved oil seal tested by Childs et al. are obtained for a number of characteristic groove depths. The predicted direct damping and inertia coefficients correlate best with the experimental data when using a fraction (~ ½) of the actual groove depth. The model predictions show that damping and cross-coupled stiffness coefficients are roughly proportional to $1/c^3$, decreasing rapidly as the effective clearance (groove depth) increases. However, added mass coefficients are ~ $1/c$, and hence do not vary as rapidly as the damping or stiffness coefficients. Most importantly, however, current predictions, as well as the test results, demonstrate that narrow internal grooves do not reduce fluid inertia forces. For some particular groove depths, added mass coefficients actually increase.

Tribology Group - Funded Research **2006-2007**

External funds $ 1,787,792

Principal Investigator(s)	Sponsor Project #	Amount	Project	Dates (GS support)
L. San Andrés	Capstone Turbine Corp. 32525/37550	**$ 64,762**	Capabilities with Foil Bearings	12/1/2006-11/30/2007 (1)
L. San Andrés	Honeywell Turbocharging 32525/6865A//ME	**$ 391,847**	Computational Analysis of Floating Ring Journal Bearings and Experimental Validation in a Turbocharger Test Rig – Phase IV	01/15/2003 01/31/2008 (1)
W. Hung (ENT), L. San Andrés	National Science Foundation	**$259,249**	Research Experiences for Undergraduates: Development of Microturbomachinery	10UG/year 04/24/2006 05/31/2010
L. San Andrés	Northrop Grumman 32525/24330/ME	**$767,821**	Thrust Bearing Rig for validation of liquid hydrogen TP bearings. Mixed Lubrication Model for Start Up of Cryogenic Turbopumps	02/01/2005 09/30/2008 (3)
L. San Andrés	Siemens - Westinghouse 32525/34650	**$ 48,638**	Brush Seals with Reverse Rotation	12/09/2005 03/15/2007 (1)
L. San Andrés	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, $ 84,000 (TRC)

Principal Investigator(s)	Sponsor	Amount	**Project**	Dates
L. San Andrés	TRC 32514/1519/C4	**$28,000**	Rotordynamic Performance of Foil Gas Bearings: Tests and Analysis	07/01/2006 08/31/2007
L. San Andrés	TRC 32514/1519/S7	**$28,000**	Experimental Force Coefficients for a Sealed Squeeze Film Damper	07/01/2006 08/31/2007
L. San Andrés	TRC 32514/1519/B4	**$28,000**	Gas Bearings for Oil-Free Turbomachinery – Controlled External Pressurization to Eliminate Critical Speeds	07/01/2006 08/31/2007

Research Expenditures Fiscal year 2006: ~ $ 500,813

Tribology Group Publications 2006/2007

	2006	2007	Total
Journal (peer reviewed)	5	9	**14**
Conference (peer reviewed)	5	5	**10**
Conference (NOT peer reviewed)	2	1	**3**
Accepted/awaiting publication		7	**7**
Extended Abstracts	2	1	**3**
Student posters	2		

2007

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

Journal publications (peer reviewed)

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 Magazine, June 2007, pp. 40-52.

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.

3 San Andrés, L., **T. Soulas**, and P. Fayolle, 2007, "A Bulk Flow Model of Angled Injection Lomakin Bearing" ASME Journal of Engineering for Gas Turbines and Power, 129, pp. 195-204.

2 **De Santiago, O.,** and L., San Andrés, 2007, "Field Methods For Identification of Bearing Support Parameters. Part I-Identification from Transient Rotor Dynamic Response Due to Impacts," ASME Journal of Engineering for Gas Turbines and Power, 129, pp. 205-212.

1 **De Santiago, O.,** and L., San Andrés, 2007, "Field Methods For Identification of Bearing Support Parameters. Part II-Identification from Rotordynamic Response due to Imbalances," ASME Journal of Engineering for Gas Turbines and Power, 129, pp. 213-219.

Peer reviewed Conference publications

ASME Turbo Expo 2007, May 14-17, 2007, Montreal, Canada

San Andrés, L., and **A. Delgado**, "Squeeze film Damper with a Mechanical Seal: Experimental Force Coefficients Derived from Circular Centered Orbits," ASME Paper No GT2007-27436

San Andrés, L., and **T-H Kim,** "Improvements to the Analysis of Gas Foil Bearings: Integration of Top Foil 1D and 2D Structural Models," ASME Paper No GT2007-27249

San Andrés, L., and **K. Ryu,** "Flexure Pivot Tilting Pad Gas Bearings: Operation with Worn Clearances and Two Load-Pad Configurations," ASME Paper No GT2007-27127

2007 ASME IDETC/CIE Conference, Las Vegas, Nevada, September 4-7, 2007

Gjika, K., C. Groves, L. San Andrés, and G. LaRue, "Nonlinear Dynamic Behavior of Turbocharger Rotor-Bearing Systems with Hydrodynamic Oil Film and Squeeze Film Damper in Series: Prediction and Experiment," ASME Paper DETC2007-34136

2007 STLE/ASME Internacional Joint Tribology Conference, San Diego, California, October 22-24, 2007

San Andrés, L., and T.H. Kim, "Effect of Side Pressurization on the Dynamic Performance of Gas Foil Bearings," Paper IJTC2007-44047

Accepted/in print journal publications

7 **Delgado, A.,** and L. San Andrés, "Identification of Structural Stiffness and Damping in a Shoed Brush Seal," ASME Journal of Vibrations

6 **Zhu, S.** and L., San Andrés, "Rotordynamic Performance of Flexure Pivot Hydrostatic Gas Bearings for Oil-Free Turbomachinery," ASME Journal of Engineering for Gas Turbines and Power

5 San Andrés, L., **D. Rubio**, and **T.H. Kim,** "Rotordynamic Performance of a Rotor Supported on Bump Type Foil Gas Bearings: Experiments and Predictions," ASME Journal of Engineering for Gas Turbines and Power

4 San Andrés, L., and **A. Delgado**, "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

3 San Andrés, L., **J.C. Rivadeneira,** K. Gjika, C. Groves, and G. LaRue, "A Virtual Tool for Prediction of Turbocharger Nonlinear Dynamic Response: Validation Against Test Data," ASME Paper GT 2006-90873, ASME Journal of Engineering for Gas Turbines and Power

2 **Kim, T.H.,** and L. San Andrés, "Heavily Loaded Gas Foil Bearings: a Model Anchored to Test Data," ASME Journal of Engineering for Gas Turbines and Power

1 San Andrés, L., and **A. Delgado**, "Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical Seal, Centered Circular Orbit Tests," ASME Journal of Tribology

2006

Journal publications (peer reviewed)

5 **Wilde, D.A.,** and San Andrés, L., 2006, "Comparison of Rotordynamic Analysis Predictions with the Test Response of Simple Gas Hybrid Bearings for Oil Free Turbomachinery," ASME Journal of Engineering for Gas Turbines and Power, 128, pp. 634-643 (ASME Paper No. GT2003-38859, 2003 BEST Rotordynamics Paper Award –ASME (IGTI))

4 **Rubio, D.,** and L., San Andrés, 2006, "Bump-Type Foil Bearing Structural Stiffness: Experiments and Predictions", ASME Journal of Engineering for Gas Turbines and Power, **128,** pp. 653-660. (ASME Paper GT 2004-53611 – 2004 BEST Rotordynamics Paper Award – ASME (IGTI))

3 San Andrés, L., 2006, "Hybrid Flexure Pivot-Tilting Pad Gas Bearings: Analysis and Experimental Validation," ASME Journal of Tribology, **128,** pp. 551-558.

2 **Kim, T.H.,** and L. San Andrés, 2006, "Limits for High Speed Operation of Gas Foil Bearings," ASME Journal of Tribology, **128,** pp. 670-673.

1 San Andrés, L., and **O. de Santiago,** 2006, "Dynamic Response of Squeeze Film Dampers Operating with Bubbly Mixtures," ASME Journal of Engineering for Gas Turbines and Power, **126**, pp. 408-415. (ASME Paper 2002-GT-30317)

A Conference Proceedings - Peer Reviewed

ASME/STLE International Joint Tribology Conference, San Antonio, TX, October 2006

5 San Andrés, L., 2006, "Hybrid Flexure Pivot-Tilting Pad Gas Bearings: Analysis and Experimental Validation," Paper IJTC 2006-12026 (accepted for publication at ASME Journal of Tribology)

4 San Andrés, L., and **A. Delgado**, 2006, "Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical Seal, Centered Circular Orbit Tests," Paper IJTC 2006-12041. (accepted for publication at ASME Journal of Tribology)

ASME Turbo Expo 2006, May 8-11, 2006, Barcelona, Spain

3 San Andrés, L., **D. Rubio**, and **T.H. Kim,** 2006, "Rotordynamic Performance of a Rotor Supported on Bump Type Foil Gas Bearings: Experiments and Predictions," ASME Paper GT 2006-91238 (accepted for publication at ASME Journal of Engineering for Gas Turbines and Power)

2 San Andrés, L., and **A. Delgado**, 2006, "Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical Seal, I: Unidirectional Load Tests," ASME Paper GT 2006-90782

(accepted for publication at ASME Journal of Engineering for Gas Turbines and Power)

1 San Andrés, L., **J.C. Rivadeneira,** K. Gjika, C. Groves, and G. LaRue, 2006, “A Virtual Tool for Prediction of Turbocharger Nonlinear Dynamic Response: Validation Against Test Data,” ASME Paper GT 2006-90873 (accepted for publication at ASME Journal of Engineering for Gas Turbines and Power)

B Conference Proceedings - Not Peer Reviewed & other publications

2 San Andrés, L., **J.C. Rivadeneira**, K. Gjika, C. Groves, and G. LaRue, 2006, “Rotordynamics of Small Turbochargers Supported on Floating Ring Bearings: Highlights in Bearing Analysis and Experimental Validation,” Paper CELT06-76, Memorias del IX Congreso y Exposición Latinoamericana de Turbomaquinaria, Boca del Río Veracruz, Mexico, June 22-23, 2006, ISBN 968-6114-20-3

1 San Andrés, L., and **A. Delgado**, 2006, “Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical End Seal,” Paper CELT06-74, Memorias del IX Congreso y Exposición Latinoamericana de Turbomaquinaria, Boca del Río Veracruz, Mexico, June 22-23, 2006, ISBN 968-6114-20-3

C Extended Abstracts

ASME/STLE International Joint Tribology Conference, San Antonio, TX, October 2006

Baker, J., A. Delgado, and L. San Andrés, 2006, “Measurements of Leakage and Identification of Structural Parameters in a Hybrid Brush Seal,” Paper IJTC 2006-12375

Ryu, K., and L. San Andrés, 2006, “Measurements of of Rotordynamic Response of a Rotor Supported on Hybrid Flexure Pivot Tilting Pad Gas Bearings” Paper IJTC 2006-12371

Student Poster presentations

ASME/STLE International Joint Tribology Conference, San Antonio, TX, October 2006

Baker, J., A. Delgado, and L. San Andrés, 2006, “Measurements of Leakage and Identification of Structural Parameters in a Hybrid Brush Seal,” Paper IJTC 2006-12375

Ryu, K., and L. San Andrés, 2006, “Measurements of of Rotordynamic Response of a Rotor Supported on Hybrid Flexure Pivot Tilting Pad Gas Bearings” Paper IJTC 2006-12371

Technical Reports to sponsors and TEES Turbomachinery Research Consortium

Monthly progress reports to Honeywell International and Northrop Grumman. Annual progress report to NSF, Siemens-Westinghouse.

San Andrés, L., Editor, “Research on Fluid Film Bearings, Tribology Group,” Year XV, 2005/2006, June 2006.

San Andrés, L., and Kim, T-H, “Computational Analysis of Gas Foil Bearings Integrating 1D and 2D Finite Element Models for Top Foil,” TRC-B&C-1-06

San Andrés, L., and Kim, T-H, “Further Imbalance Response Measurements of Rotor Supported on Bump-Type Gas Foil Bearings – Operation to 50 krpm,” TRC-B&C-2-06

San Andrés, L., and Delgado, D., "Squeeze Film Damper with Mechanical Seal: Identification of Force Coefficients from Circular Centered Orbit Tests,” TRC-SFD-1-06

San Andrés, L., and Ryu, K., **“**Test Results for Load-On-Pad and Load-Between-Pad Hybrid Flexure Pivot Tilting Pad Gas Bearings**,** TL-B&C-1-06