Mechanical Engineering Department
Texas A&M University

2004/2005
Research Progress Report
Tribology Group

Year XIV

25th Annual
Turbomachinery Research Consortium Meeting

May 2005

Luis San Andrés
Leader

Tribology Group
Turbomachinery Laboratory
Mechanical Engineering Department
Texas A&M University
College Station, TX 77843-3123
phone: 979 862-4744, fax: 979 845-1835

Luis San Andrés
Leader

LSanAndres@mengr.tamu.edu

FOREWORD

2004/5 has been a fruitful year with notable progress and advances in our engineering research work. We continue to strive at being the most productive research team at the Turbo Lab and delivering products of the highest quality. Not every student joining our research group is successful. However, those remaining demonstrate, day after day, their hard work and dedication to learning.

MILESTONES

Luis San Andrés reworked entirely the Tribology Group web site. Visit http://phn.tamu.edu/TRIBGroup We look forward to receiving your comments.

Distinctions

2004 Best Rotordynamics Paper Award (IGTI, Structures & Dynamics Committee)

Rubio, D., and L., San Andrés, 2004, "Bump-Type Foil Bearing Structural Stiffness: Experiments and Predictions", ASME Paper GT 2004-53611 (accepted for publication at ASME Journal of Gas Turbines and Power).

	Society	Distinction	Contribution
Luis San Andrés	Society of Tribologists and Lubrication Engineers	STLE Fellow	Research (05/05)
	TAMU – College of Engineering	Ruth and William Neely'52 Faculty Fellow	Research (04/05)
	TAMU – College of Engineering	E.D. Brockett Professorship	Scholarly Excellence (10/04)

Invited Seminars

"Turbocharger Rotordynamics," MEEN & NUE Dept., Pennsylvania State University, 2004-2005 Air Products Distinguished Lecture Series, April 26.

"Gas Bearings for Oil-Free Turbomachinery," MEEN Dept., University of Florida, Distinguished Lecture Series, March 24.

Visitors

Dr. Mihai Arghir, Professor from Universite de Poitiers (France) visited the Turbolab last Summer. Mihai spent four weeks working on gas bearing and seal analyses. He enjoyed the Texas country style of living while bravely enduring the heat.

Available software to TRC members

TiltPadHGB: MS Excel® GUI to Fortran code for prediction of static and dynamic forced performance of rigid surface and tilting pad gas bearings with(out) external pressurization

GasFoilBear: MS Excel® GUI to Fortran code for prediction of static and dynamic forced performance of bump-foil gas bearings

Graduating students

Dario Rubio, Adolfo Delgado and Juan Carlos Rivadeneira will graduate with M.S. degrees in the summer 05.

Dario Rubio constructed the foil bearing rotordynamics test rig and conducted measurements of rotor imbalance response that evidenced the gas foil bearings are prone to show severe subsynchronous instabilities within confined shaft speed zones. Dario published 2 ASME papers, one being awarded a Best Rotordynamics Paper distinction from IGTI in 2004.

Adolfo Delgado revamped the SFD test rig and installed a damper with a mechanical seal. He conducted measurements to identify the dry friction force and squeeze film damping coefficients from periodic shaker load tests. Adolfo also conducted measurements to identify structural parameters in shoed brush seals. Adolfo has distinguished himself as a very careful experimentalist. He has published 2 ASME technical papers in brush seals.

Juan Carlos Rivadeneira assisted in performing numerous computational analyses predicting the linear and nonlinear response of automotive turbochargers. The student has accumulated a vast amount of experience in conducting comprehensive rotordynamic analyses. Juan will present a technical paper at the upcoming Gas Turbine Conference.

I wish the students the very best in their professional lives. Their education in structural mechanics and vibrations, lubrication theory and rotordynamics is outstanding. I hope the most qualified students would stay to pursue Ph.D. degrees, yet it is difficult to compete with the allure of a real job in industry, getting real money! The technical needs of our country urgently call for engineers with advanced degrees; otherwise our major advantage over other first world countries will soon be lost.

Note that students graduating from our Group do not merely learn to "test" a mechanical element or to "run" a computer program. The students have complete competence in their field of work as demonstrated by their excellent technical publications and presentations.

Publications and travel

In 2004-05, the students and Dr. San Andrés co-authored twenty-one technical papers (4 journal and 17 conference) and (to be) presented at professional meetings and for publication in professional journals.

Dr. San Andrés and students attended:

- ASME Turbo-Expo'04 Conference (Vienna, June) to present 4 papers in foil and tilting pad gas bearings for oil-free turbomachinery, in-situ identification of bearing force coefficients, and shoed brush seals.
- ASME/STLE International Tribology Conference (Palm Beach, October) to present 1 paper on experimental identification of journal bearing force coefficients.

In June 2005, we will attend the ASME Turbo-Expo'05 Conference (Reno, NV) to present four papers in foil bearings – tests and analysis, turbocharger rotordynamics and Rayleigh-step gas bearings. In September, we will present five papers at the World Tribology Conference (Washington, D.C.) and one paper at the ASME Biannual Vibrations Conference (Palm Beach, Ca).

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

- **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) delivered to sponsor and already saving money and time in product qualification. The research continues to advance the software for modeling more realistic TC configurations.
  SPONSOR: HONEYWELL TURBOTECHNOLOGIES
  Student: Juan Carlos Rivadeneira (MS)

- **Gas Bearings for Oil-Free Turbomachinery**
  OBJECTIVE: To advance the technology of inexpensive gas bearings for micro gas turbines and micro power systems
  STATUS: Computational analysis for static and dynamic forced performance of tilting pad – hybrid gas bearings completed (Easy GUI interface available to TRC members). Correlation of predictions to test data recorded in 2003 is very good.

SPONSORS: TRC. Industrial partners: none.
Personnel: Luis San Andrés, Tae-Ho Kim (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 for static and dynamic forced performance of simple gas foil bearings completed (Easy GUI interface available to TRC members). Imbalance response measurements recorded in test rig demonstrate gas foil bearings are prone to show severe rotordynamic instabilities over certain ranges of rotor speed, typically around twice the critical speed of the rotor-bearings system. Computational analysis coupling the top foil (plate) structure to the gas film model is quite promising
  SPONSORS: NATIONAL SCIENCE FOUNDATION, P.I. INCENTIVE FUNDS, UNIVERSAL TECHNOLOGY CORPORATION
  Students: Dario Rubio (M.S.), Tae-Ho Kim (PhD), Anthony Breedlove (M.S.), and Bo-Hung Kim (M.S.)

- **Identification of Structural parameters in shoed brush seals**
  OBJECTIVE: Assess mechanical parameters from shoed brush seal and advance computational models for prediction of the dynamic forced performance of shoed brush seals.
  STATUS: Test rig for identification of stiffness and damping coefficients is operational. Shaker load tests at various frequencies conducted to identify the stiffness and equivalent damping coefficients of a 20 pad shoed brush seal.
  SPONSOR: TRC. HARDWARE FROM ADVANCED TURBOMACHINERY SOLUTIONS (ATS)
  Student: Adolfo Delgado (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: Properly designed end seals increase the damping capability of short length SFDs. Test rig fully operational accommodates an industrial end sealed SFD with a recirculation annulus, end ring and push wave spring. Structural and dry-friction parameter of mechanical seal identified. Single frequency load tests aid to identify the viscous damping coefficients of film alone. Dry friction effect of mechanical end seal fully accounted for.
  SPONSOR: TRC
  Students: Adolfo Delgado (MS).

- **New LH2 Turbopump USET Development**
  OBJECTIVE: Enhancements to computational models for prediction of dynamic forced performance of cryogenic liquid hydrostatic bearings - USAF Upper Stage Engine Technology Program.
  STATUS: Project started in February 2005. Main progress expected in Summer 2005. ITAR prevents disclosure of activities. Sorry!
  SPONSOR: NORTHROP GRUMMAN
  Personnel: Luis San Andrés, Student: Nicholas Tydlacka (UGS)

OBSERVATION

The science education and engineering competence of incoming domestic and foreign graduate students has deteriorated rapidly in the last few years. There are very few students able to conduct computational analysis and even less students with moderate mathematical skills. Incoming students, some even with professional experience, can not perform independent work and individual thinking. Students expect to find ready-to-punch software for all stages of research, not just for design of equipment and data acquisition, but also for data analysis and interpretation of results. What can we do to improve the students' conditions? How could you help us to enhance the education of our students?

OTHER

In July 2004, Luis San Andrés resigned as Leader of the MEEN Systems and Control Division, a time consuming service post with no rewards and less prestige. Time to move on!

Although recognized twice by the TAMU College of Engineering with research awards in 2004 & 2005, Luis failed to obtain a professorship from the MEEN Dept. The distinction recognizes outstanding and enduring contributions in research. The faculty committee in charge of the appointment conducted a rigorous selection process equivalent to a promotion beyond Full Professor. Luis could not fulfill the expectations of the selection committee. Is this a preamble to work harder to reach “the raising bar”? Nope, just time to move on!

The Band continues to make waves. We keep having fun at being irreverent! In July 2004, *Roca Azul* performed in Quito (Ecuador). Two other gigs followed in College Station (Times Square, 10/04, and Revolutions, 02/05). Visit our URL site at phn.tamu.edu/Roca_Azul

We rock!

Luis San Andrés, Leader
Tribology Group
May 2005

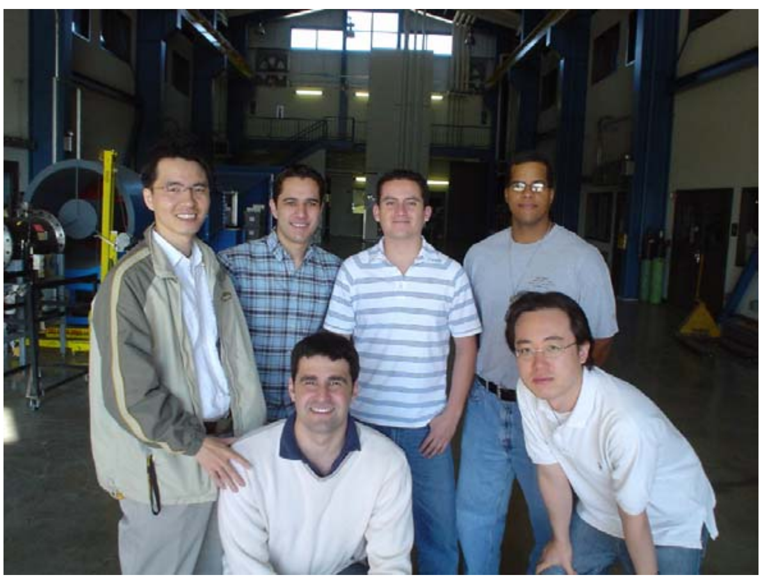
Tribology Group

Surviving Team Members 2004/2005

Luis San Andrés, Leader

Name	Research project	Graduation date
Juan Carlos Rivadeneira	**Dynamic Response of Turbocharger Rotors Supported on Floating Ring Journal Bearings**	August 2005
Dario Rubio+ **Jose Garcia** *+ **Anthony Breedlove***+	**Gas Foil Bearings – Test Rig Development and Identification of System Parameters**	August 2005
Tae-Ho Kim **Bo Hung Kim**	**Gas Foil Bearings – Computational Analysis**	December 2006 August 2005
Adolfo Delgado+	**Reverse Rotation Brush Seals - Testing**	December 2005
Adolfo Delgado+ **Jon Neff** *	**Identification of Force Coefficients in Sealed SFD**	December 2005
Nicholas Tydlacka*	**Lift off Model for Hydrostatic Bearings**	

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



Top (L to R): Tae Ho Kim, Dario Rubio, Juan Carlos Rivadeneira, Anthony Breedlove
Bottom: Adolfo Delgado, Bo Hung Kim

Tribology Group/Rotordynamics Laboratory

2005 RESEARCH PROGRESS REPORTS
HYBRID TILTING PAD GAS BEARINGS: ANALYSIS & EXPERIMENTAL VALIDATION Luis San Andrés TRC-B&C-1-05
ROTORDYNAMIC PERFORMANCE OF A ROTOR SUPPORTED ON GAS FOIL BEARINGS Dario Rubio Luis San Andrés TRC-B&C-2-05
IDENTIFICATION OF FORCE COEFFICIENTS IN A SQUEEZE FILM DAMPER WITH A MECHANICAL SEAL Adolfo Delgado and Luis San Andrés TRC-SFD-1-05
IDENTIFICATION OF STRUCTURAL STIFFNESS AND DAMPING IN A SHOED BRUSH SEAL Adolfo Delgado and Luis San Andrés TRC-SEAL-3-05

2005-2006 RESEARCH PROPOSALS
EXPERIMENTAL FORCE COEFFICIENTS FOR A SEALED SQUEEZE FILM DAMPER (CONTINUATION II)
ROTORDYNAMIC PERFORMANCE OF FOIL GAS BEARINGS: TESTS AND ANALYSIS (TRC MATCHING TO NSF FUNDED PROJECT) (CONTINUATION I)
STIFFNESS AND DAMPING COEFFICIENTS OF AN IMPROVED SHOED BRUSH SEAL (CONTINUATION)

PROGRESS REPORTS – EXECUTIVE SUMMARIES

TRC-B&C-1-05 HYBRID TILTING PAD GAS BEARINGS: ANALYSIS & EXPERIMENTAL VALIDATION

Gas film bearings offer unique advantages enabling successful deployment of high-speed micro-turbomachinery. Current applications encompass micro power generators, air cycle machines and turbo expanders. Mechanically complex gas foil bearings are in use; however, their excessive cost and lack of calibrated predictive tools deter their application to mass-produced oil-free turbochargers, for example. The present investigation advances the analysis and experimental validation of hybrid gas bearings with static and dynamic force characteristics desirable in high-speed turbomachinery. These characteristics are adequate load support, good stiffness and damping coefficients, low friction and wear during rotor startup and shutdown, and most importantly, enhanced rotordynamic stability at the operating speed.

Hybrid (hydrostatic/hydrodynamic) flexure pivot-tilting pad bearings (FPTPBs) demonstrate superior static and dynamic forced performance than other geometries as measured in a high speed rotor-bearing test rig operating to a top speed of 100 krpm. A computational model including the effects of external pressurization predicts the rotordynamic coefficients of the test bearings and shows good correlation with measured force coefficients, thus lending credence to the predictive model. In general, direct stiffnesses increase with operating speed and external pressurization; while damping coefficients show an opposite behavior. Predicted mass flow rates validate the inherent restrictor type orifice flow model for external pressurization. Measured coast down rotor speeds demonstrate very low-friction operation with system time constants on the order of 60 seconds. Estimated bearing drag torques validate indirectly the recorded system time constant.

TRC-SEAL-3-05: IDENTIFICATION OF STRUCTURAL STIFFNESS AND DAMPING IN A SHOED BRUSH SEAL

The multiple-shoe brush seal, a variation of a standard brush seal, accommodates arcuate pads at the bristles free ends. This novel design allows reverse shaft rotation operation, and reduces and even eliminates bristle wear, since the pads lift off due to the generation of a hydrodynamic film during rotor spinning. This type of seal, able to work at both cold and high temperatures, not only restricts secondary leakage but also acts as an effective vibration damper. The dynamic operation of the shoed-brush seals, along with the validation of reliable predictive tools, relies on the appropriate estimation of the seal structural stiffness and energy dissipation features. Single frequency external load tests conducted on a controlled motion test rig and without shaft rotation allow the identification of the structural stiffness and equivalent damping of a 20-pad brush seal, 153 mm in diameter. The seal energy dissipation mechanism, represented by a structural loss factor and a dry friction coefficient, characterizes the energy dissipated by the bristles and the dry friction interaction of the brush seal bristles rubbing against each other. The physical model used reproduces well the measured system motions, even for frequencies well above the identification range. Measurements of the leakage through the seal as the supply pressure increases (pressure ratio =3.4) show the seal unique performance characteristics, i.e. very small flow rate (laminar flow) which can be effectively represented as a "labyrinth seal" of very narrow clearance. Model predictions agree reasonably well with the flow measurements.

TRC-SFD-1-05 IDENTIFICATION OF FORCE COEFFICIENTS IN A SQUEEZE FILM DAMPER WITH A MECHANICAL SEAL

Squeeze film dampers (SFDs) with low levels of external pressurization and poor end sealing are prone to air entrapment, thus not generating enough damping capability. Predictive models are too restrictive and do very poorly. Single frequency, unidirectional load experiments were conducted on a recently completed sealed SFD test rig. The damper journal is 1" in length and 5" in diameter, with nominal clearance of 5 mils (0.127 mm). The SFD feed end is flooded with oil, while the exit end contains a recirculation groove and four orifice discharge ports to prevent air ingestion. The end is fully sealed with a wave-spring that pushes a seal ring into contact with the SFD journal.

The measurements conducted without and with lubricant in the squeeze film lands, along with a frequency domain identification procedure, render the mechanical seal dry-friction force and viscous damping force coefficients as functions of frequency and motion amplitude. The end seal arrangement is quite effective in eliminating side leakage and preventing air entrainment into the film lands. Importantly enough, the dry friction force, arising from the contact forces in relative motion, increases significantly the test element equivalent viscous damping coefficients. The identified system damping coefficients are thus frequency and amplitude of motion dependent, albeit decreasing rapidly as the motion parameters increase. Identified force coefficients, damping and added mass, for the squeeze film damper alone agree very well with predictions based on the full film classical lubrication model.

TRC-B&C-2-05 **ROTORDYNAMIC PERFORMANCE OF A ROTOR SUPPORTED ON GAS FOIL BEARINGS**

Foil gas bearings appear to satisfy most requirements for oil-free turbomachinery, i.e. relatively simple in construction, ensuring low drag friction and reliable high speed operation. However, gas foil bearings have a limited load capacity and minimal amounts of damping. A test rig for the rotordynamic evaluation of gas foil bearings was constructed. A DC router motor, 25 krpm max speed, drives a 2.2 lb hollow rotor supported on two bump-type foil gas bearings (L=D=1.5 “) . Measurements of the test rotor dynamic response were conducted for increasing mass imbalance conditions. Typical waterfalls of rotor coast down response from 25 krpm to rest evidence the onset and disappearance of severe subsynchronous motions with whirl frequencies at ~ 50% of rotor, roughly coinciding with the (rigid mode) natural frequencies of the rotor-bearing system. The amplitudes of motion, synch and subsynchronous, increase (non) linearly with respect to the imbalance displacement. The rotor motions are rather large; yet, the foil bearings, by virtue of their inherent flexibility, prevented the catastrophic failure of the test rotor. Tests at the top shaft speed, 25 krpm, did not excite subsynchronous motions; the unstable zone being well confined (12 to 22 krpm). Surprisingly enough, external air pressurization on one side of the foil bearings acted to reduce the amplitudes of motion while the rotor crossed its critical speeds and ameliorated the severity of the subsynchronous vibrations. An air-film hovering effect may enhance the sliding of the bumps thus increasing the bearings damping action. While coasting down, the rotor speed decreased rather rapidly, thus denoting a significant rotational drag due to operation with minute film gaps. Post-test inspection of the rotor evidenced sustained wear at the locations in contact with the bearings’ axial sides. However, the foil bearings are almost in pristine condition, except for transfer of shaft coating material to the top foils.

2005 TRC Proposal Summaries

Experimental Force Coefficients for a Sealed Squeeze Film Damper (Continuation II)

A sealed SFD test facility is fully operational. The damper consists of a journal, 1" in length and 5" in diameter, with a film of nominal radial clearance equal to 5 mils (0.127 mm). The SFD feed end is flooded with oil, while the exit end contains a recirculation annulus and four orifice discharge ports to prevent air ingestion. This end is fully sealed with a wave-spring that pushes a seal ring into contact with the SFD journal. Proper installation of the seal ring is crucial to ensure adequate SFD performance. If the ring is too tight, contact forces due to dry friction stiffen, even lock, the damper and no viscous damping action is possible. If the ring is too loose, then excessive leakage flows through the gap between the damper journal and seal ring and the damper forced performance deteriorates due to air ingestion.

Dynamic unidirectional load tests with a dry and a lubricated SFD system were conducted in 2005. A sound frequency domain procedure provides the mechanical seal dry-friction force and viscous damping force coefficients as functions of frequency and motion amplitude. The end seal effectively prevents side leakage though increases the effective damping coefficient, in particular at low frequencies.

In 2005/06, the objective is to continue identifying the damping and inertia force coefficients of the end sealed squeeze film damper. The major tasks are:

a) To measure pressure drop and lubricant leakage to determine the end seal coefficient as a function of discharge orifice size and wave spring preload, journal centering, etc.
b) To perform single-frequency dynamic load tests leading to circular orbits, centered and off centered, for increasing oil feed pressures.
c) To implement frequency domain identification techniques to extract SFD force coefficients (damping and inertia). Provide estimated parameters as a function of excitation frequency and amplitude of motion, lubricant flow rate, feed temperature and pressure, sealing conditions, etc.

The proposed research is of interest for SFD applications in gas turbines, semi-floating ring bearings in turbochargers, etc. The test SFD is designed to contain (seal) the lubricant for large periods of time (years) for applications into UAVs, for example.

Rotordynamic Performance of Foil Gas Bearings: Tests and Analysis
(Continuation II: TRC matching to NSF funded project)

In 2003, NSF funded a three-year research program, analytical and experimental, to advance the technology (design and operation) of gas foil bearings for oil-free turbomachinery. The research objectives are:

- Comprehensive modeling of gas foil bearing performance (static and dynamic) operating at high speeds.
- Exhaustive (independent) experimentation of foil bearings in a test rig to determine rotor lift and touch down speeds, load capacity and drag power losses, and identification of rotordynamic force coefficients.

A test rig for the rotordynamic evaluation of gas foil bearings was constructed in 2004. A DC router motor, 25 krpm max speed, drives a 2.2 lb hollow rotor supported on two foil gas bearings. Measurements of the test rotor dynamic response for increasing mass imbalance conditions were conducted in 2005. The test results evidence the onset and disappearance of severe subsynchronous motions with whirl frequencies at 50% of rotor. The amplitudes of motion, synch and subsynchronous, increase (non)linearly with the magnitude of the mass imbalances tested. The rotor motions are rather large; yet, the foil bearings, by virtue of their inherent flexibility, prevented the catastrophic failure of the test rig. A computational program for prediction of foil bearing rotor dynamic forced response is available to TRC members.

The main objective is to characterize <u>quantitatively</u> foil bearing rotordynamic performance, reliability and durability. The tasks for 2005/06 are:

a) To analyze the extensive test data collected and to identify the foil bearings' synchronous stiffness and damping force coefficients.
b) To acquire a higher speed rotor (75 krpm) and to conduct further imbalance response tests aiming to identify regions of stable and unstable rotordynamic response.
c) To validate predictions from the computational model with test identified FB force coefficients

The research program requires industry to cost-share expenses. TRC matching funds will support a graduate student conducting the experimental work. TRC members will benefit from an independent research program characterizing foil bearings and addressing to the bearings limited stability characteristics.

2005 TRC PROPOSAL SUMMARIES

STIFFNESS AND DAMPING COEFFICIENTS OF AN IMPROVED SHOED BRUSH SEAL
(CONTINUATION)

Labyrinth seals are the primary seal type used in gas turbines due to their simplicity, low cost and easy installation. However, leakage through a labyrinth seal increases with operation due to inevitable wear, thermal growth and rotor excursions. Furthermore, labyrinth seals are poor rotordynamic elements, often producing negative effective damping and leading to dangerous rotordynamic sub synchronous instabilities. Brush seals effectively control leakage in air breathing engines. However, their current state of the art limits their application to relatively low-pressure differentials. Multiple-shoed brush seals represent an alternative to resolve poor reliability resulting from bristle tip wear while also allowing for shaft reverse rotation. The novel brush seal incorporates pads contacting the shaft; and which under rotor spinning; lift off due to the generation of hydrodynamic pressure. The ensuing gas film prevents intermittent contact; thus lowering the operating temperature and thermal distortions, and even eliminating bristles wear.

The shoed-brush seal model relies on the physical characterization of the bristle bed structural stiffness and damping coefficients. This can only be achieved through exhaustive testing rather than complicated computational analyses. In 2004/5, single frequency external load tests were conducted on a controlled motion test rig to identify the structural stiffness and equivalent damping of a 20-pad brush seal, 153 mm in diameter. The seal energy dissipation mechanism, represented by a structural loss factor and a dry friction coefficient, characterizes the energy dissipated by the bristles and the dry friction interaction of the brush seal bristles rubbing against each other. The physical model used reproduces well the recorded system motions, even for frequencies well above the identification range. Measurements of the leakage through the seal as the supply pressure increases show the seal unique performance characteristics, i.e. a very small flow rate, effectively represented as a "labyrinth seal" of very narrow clearance (1.7 mil). Leakage model predictions agree reasonably well with the flow measurements.

ATS (Advanced Turbomachinery Solutions) recently donated an improved shoed brush seal. This seal, more rugged in construction, has its pads wire-EDM into the seal holder. The proposed tasks in 2005/6 are:

a) To perform dynamic load tests (shakers) for increasing supply gas pressures. Single and multiple frequency experiments are planned.
b) To measure the leakage through the seal for increasing feed pressures and to identify its equivalent clearance.
c) To continue developing reliable identification methods to determine the shoed-brush seal' structural stiffness and dry-friction (loss factor) as well as an equivalent (viscous) damping coefficient.

Seal force coefficients will be delivered as a function of excitation frequency and amplitude of staic load and whirl motion, supply pressure, and seal interference for three shaft diameters**.**

2005 PROPOSAL SUMMARIES (END)

Tribology Group - Funded Research 2004-2005

External New funds $ 227,339

Principal Investigator(s)	Sponsor Project #	Amount	Project	Dates (GS support)
L. San Andrés	Universal Technologies Corp	**$20,000**	Foil Bearings – Support for GS student	09/01/04-05/31/05
Dara Childs L. San Andrés 32525/20580/ME	Northrop Grummann	**$98,500**	CLIN 0001 of the AFRL – Support for USET	02/01/05-06/30/06 (1)
L. San Andrés 32525/53900//ME	**NSF**	$255,475	Gas Foil Bearings for Oil-Free Rotating Machinery – Analysis Anchored to Experiments	06/15/03-05/31/06 (2)
L. San Andrés 32525/61140//ME	Honeywell Turbocharging	$102,475 **+$108,839** $211,314	Computational Analysis of Floating Ring Journal Bearings and Experimental Validation in a Turbocharger Test Rig – Phase II	01/15/03-12/31/05 (1)

Internal, $ 88,000 (TRC) + $65,000 (TTI) = $ 153,000

Principal Investigator(s)	Sponsor	Amount	**Project**	Dates
L. San Andrés	TRC 32514/1519/C4	$22,000	Rotordynamic Performance of Foil Gas Bearings: Tests and Analysis	07/01/04-06/30/05
L. San Andrés	TRC 32514/1519/S4	$22,000	Stiffness and Damping Coefficients of Brush Seals with Reverse Rotation Ability	07/15/04-06/30/05
L. San Andrés	TRC 32514/1519/S7	$22,000	Experimental Force Coefficients for a Sealed Squeeze Film Damper	07/01/04-06/30/05
L. San Andrés	TRC 32514/1519/B2	$22,000	Hybrid Tilting Pad Gas Bearings: Analysis and Tests	07/01/04-06/30/05
H. Liang, L. San Andrés	TTI #405450	$65,000	Self-Repairing Railroad Track	02/01/05-01/31/06

Research Expenditures 2004/5: ~ $ 240,000

Tribology Group Publications 2004/2005

4 journal publications and 17 conference papers

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

2005

Journal publications

San Andrés, L., and O. De Santiago, 2005, "Identification of Journal Bearing Force Coefficients Under High Dynamic Loading," STLE Tribology Transactions, Vol. 48(1), pp. 9-18.

Holt, C., L. San Andrés, S. Sahay, P. Tang, G. LaRue, and K. Gjika, 2005, "Test Response and Nonlinear Analysis of a Turbocharger Supported on Floating Ring Bearings," ASME Journal of Vibrations and Acoustics, Vol. 127(2), pp. 107-212.

Peer reviewed Conference publications **ASME Turbo-Expo 2005, Reno, June 2005**

Rubio, D., and L. San Andrés, 2005, "Structural Stiffness, Dry-Friction coefficient and Equivalent Viscous Damping in a Bump-Type Foil Gas Bearing," ASME Paper GT 2005-68384 (accepted for publication at ASME Journal of Gas Turbines and Power)

Kim, T.H., and L. San Andrés, 2005, "Heavily Loaded Gas Foil Bearings: a Model Anchored to Test Data," ASME Paper GT 2005-68486 (accepted for publication at ASME Journal of Gas Turbines and Power)

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

Zhu, X, and L. San Andrés, 2005, "Experimental Response of a Rotor Supported on Rayleigh Step Gas Bearings," ASME Paper GT 2005-68296 (accepted for publication at ASME Journal of Gas Turbines and Power)

Peer reviewed Conference publications **World Tribology Conference, Washington D.C., September 2005**

San Andrés, L., **J.C. Rivadeneira,** K. Gjika, M. Chinta, and G. LaRue, 2005, "Advances in Nonlinear Rotordynamics of Passenger Vehicle Turbochargers: a Virtual Laboratory Anchored to Test data," Paper WTC 2005-64155

De Santiago, O., and L. San Andrés, 2005, "Identification of Bearing Force Coefficients in Flexible Rotors: Extensions to Method," Paper WTC 2005-63276

San Andrés, L., and **T.H**. **Kim,** 2005 "Gas Foil Bearings: Limits for High Speed Operation," Paper WTC 2005-63398

Kim, T.H., and L. San Andrés, 2005, "Analysis of Gas Foil Bearings with Piecewise Linear Elastic Supports," Paper WTC 2005-63397

Pan, C., and L. San Andrés, 2005, "The Narrow Groove Bearing Analysis Revisited," Paper WTC 2005-63803

Delgado, A., and L. San Andrés, 2005, "Identification of Structural Stiffness and Damping in a Shoed Brush Seal," Paper DETC 2005-84159, ASME 2005 Biannual Vibrations Conference, Palm Beach, September

Under review

Kim, T.H., and L. San Andrés, 2005, "Limits for High Speed Operation of Gas Foil bearings," ASME Journal of Tribology.

Kim, T.H., and L. San Andrés, 2005, "Analysis of Advanced Gas Foil Bearings with Series Elastic Supports," Tribology Transactions

2004

Journal publications

San Andrés, L. and **J. Kerth**, 2004, "Thermal Effects on the Performance of Floating Ring Bearings for Turbochargers", Journal of Engineering Tribology, Special Issue on Thermal Effects on Fluid Film Lubrication, IMechE Proceedings Part J, Vol. 218, 5, pp. 437-450.

De Santiago, O., and L. San Andrés, 2004, "Forced Response of a Squeeze Film Damper and Identification of Force Coefficients from Large Orbital Motions," ASME Journal of Tribology, Vol. 126, 2 , pp. 292-300 (ASME Paper 2003-TRIB-162)

Peer reviewed Conference publications

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