Mechanical Engineering Department
Texas A&M University

2005/2006
Research Progress Report
Tribology Group

Year XV

26th Annual
Turbomachinery Research Consortium Meeting

June 2006

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
Mast-Childs Professor
Leader

LSanAndres@mengr.tamu.edu

FOREWORD

2005/6 has been one the busiest years ever with many new students and new projects, many trips and distinctions, and service to the professional societies and to the Hispanic organizations. We continue to excel in our work advancing the state of art in high speed turbomachinery with novel applications

MILESTONES

The TAMU Mechanical Engineering Department awarded Luis San Andrés the Mast-Childs Tribology Professorship in recognition of his outstanding research contributions. Luis also became a Fellow of the American Society of Mechanical Engineers (ASME) and the Society of Tribologists and Lubrication Engineers (STLE).

In March 2006, The Von Karman Institute invited Luis San Andrés to deliver three lectures on rotordynamics of high speed pumps. In May, Luis completed his term as Chair of the IGTI Structures and Dynamics Committee and Chair of the Council of Chairs. Luis, member of the ASME Tribology Division Executive Committee, is the incoming Chair of the Research Committee in Tribology (RCT).

Luis San Andrés continues to actively participate in developing policies towards the advancement of Hispanic students and professionals at Texas A&M. He is currently on the Academic Advisory Board of the Mexican-American US Latino Research Center recently established at A&M. Luis is featured as an outstanding faculty in *!Siempre! Hispanics at Texas A&M, Celebrating 130 years* (TAMU Cushing Memorial Library and Archives, April 2006).

Wayne Hung from the Engineering Technology Department and Luis San Andrés prepared proposals to National Science Foundation (NSF) towards the establishment of a Microturbomachinery Research Center at Texas A&M. NSF funded only the portion related to Summer Research Undergraduate Experiences (REU). Read more below. This program will train 10 undergraduate students per year in emerging technology areas related to microturbomachinery. We will recruit the best students nationwide. TRC support is needed for program to succeed!

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 and without external pressurization. Software predictions validated by rotordynamics tests (ASME TRIB-05-1089, TRC-B&C-1-05, TL-B&C-1-06)

GasFoilBear: MS Excel® GUI to Fortran codes for prediction of static and dynamic forced performance of bump-foil gas bearings, including preloaded configurations (shimmed)

XL2DFEFOILBEAR® implements a 2D anisotropic shell FE model for a top foil supported on bump strip layers.

XL1DFEFOILBEAR® implements a 1D thin beam FE model for the top foil supported on bump strip layers. The 1D model is preferred due to its low computational cost.

BEST feature: FE analyses of top foil and bumps is conducted off-line and prior to computations coupling structure to gas film.

Publications and travel

In the past year, the students and Dr. San Andrés co-authored twenty-three technical papers (four journal publications and 19 conference papers – nine peer reviewed), one technical article in a trade magazine, and one student conference poster presentation. Dr. San Andrés also prepared three extended lectures for presentation at the Seminar on Design and Analysis of High Speed Pumps organized by the Von Karman Institute.

Dr. San Andrés and students attended:

- ASME Turbo-Expo'05 Conference, June, Reno, NV
- ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, September, Long Beach, California

- Word tribology Conference, October, Washington, D.C.
- ASME Turbo-Expo'06 Conference, May, Barcelona, Spain
- ASME Regional Student Conference, April 6-8, University of Arkansas – Fayetteville, AR

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

- **New: 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. This program is part of a larger scale multidisciplinary research project at TAMU to develop microturbines to enhance defense, homeland security, transportation, and aerospace applications. **Activities** include a series of informative seminars, field trips and social events to complement the research activities while enhancing the group cohesiveness. Students will also sharpen their communication skills through the writing of a research report and presenting their research work to industry (TRC).
  STATUS: Grant awarded in 04/06. Program guidelines are being established and nationwide advertisement is in progress. Support from TRC members sought in the form of mentorship and hardware for Summer Experiences.
  SPONSOR: NATIONAL SCIENCE FOUNDATION (3 YEARS)
  Investigators: PI: Wayne Hung (Engineering Technology), co-PI: Luis San Andrés

- **CLIN 004 - 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.
  (a): To develop hydrostatic bearing tool with capability for modeling the non-linear forced response of fluid film bearing, i.e. bearing reaction forces (impedance models) as a function of instantaneous journal position, velocity and acceleration
  (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) in progress, (c) design of test rig completed, motor and quill shaft procured, in preparation bids for manufacturing and instrumentation.
  SPONSOR: NORTHROP GRUMMAN
  Personnel: Luis San Andrés,Steve Phillips (Research Engineer), Student: Nicholas Tydlacka (M.S.), Juan Carlos Valles (M.S.), Michael Forsberg (M.S.), April Acosta (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) is a production tool at Honeywell. Research continues to model compressor and turbine aerodynamic forces and more complex bearing geometries. Advice on foundation model to Jiatong University (China).
  SPONSOR: HONEYWELL TURBOTECHNOLOGIES
  Student: Ash Maruyama (MS)

- **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: Further measurements for load on pad and load between pad conditions and correlation to computational model predictions successful. Demonstrated controlled pressurization avoids excitation of critical speeds with smooth operation over extended speed zones. Computational program and GUI available to TRC members.

SPONSORS: None. Further TRC support sought.
Personnel: 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: Extensions to computational analysis include models for the top foil (1D and 2D). Code and GUI available to TRC members. Codes have unsurpassed speed of execution since foil structure is modeled prior to integration with gas film analysis. Test rig modified with AC motor running to 50 krpm and with centrifugal clutch and DC motor for start up. Tests for structural parameter identification conducted at high temperatures (250 F) using a heater.
  SPONSORS: NATIONAL SCIENCE FOUNDATION, P.I. INCENTIVE FUNDS, TRC
  Students: Tae-Ho Kim (PhD), Anthony Breedlove (M.S.), and Christy Petter (UG.)

- **Identification of Structural parameters in shoed brush seals**

  OBJECTIVE: Assess mechanical parameters from improved 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 being revamped for tests with rotor speed. Shaker load tests at various frequencies conducted to identify the stiffness and equivalent damping coefficients of shoed brush seal. Leakage vs. supply pressure tests completed.
  SPONSOR: SIEMENS-WESTINGHOUSE. HARDWARE FROM ADVANCED TURBOMACHINERY SOLUTIONS (ATS)
  Student: Adolfo Delgado (Ph.D.), Jose Baker (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. Seal design most successful to avoid air ingestion and entrapment. Structural, dry-friction parameter of mechanical seal and squeeze film damper damping and inertia coefficients identified from single frequency load tests forcing unidirectional and circular centered orbits. Predicted SFD force coefficients agree well with measured ones.
  SPONSOR: TRC
  Students: Adolfo Delgado (Ph.D.), Jeffrey Hunt (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. Seal design most successful to avoid air ingestion and entrapment. Structural, dry-friction parameter of mechanical seal and squeeze film damper damping and inertia coefficients identified from single frequency load tests forcing unidirectional and circular centered orbits. Predicted SFD force coefficients agree well with measured ones.
  SPONSOR: TRC
  Students: Adolfo Delgado (Ph.D.), Jeffrey Hunt (UG)

Graduated students

Dario Rubio, Adolfo Delgado and Juan Carlos Rivadeneira graduated with M.S. degrees in the Fall 05 and Spring 06. Dario Rubio conducted rotordynamic measurements on gas foil bearings that evidenced imbalance as a source of nonlinear forced response with severe subsynchronous motions within confined shaft speed zones. Dario published three ASME papers, one being awarded a Best Rotordynamics Paper distinction from IGTI in 2004. Dario is presently working at Bechtel Corp. in Houston.

Juan Carlos Rivadeneira assisted in performing numerous computational analyses predicting the linear and nonlinear rotordynamic response of automotive turbochargers. The computer codes also known as a Virtual Tool for Turbocharger Design and Prototyping have become production tools at Honeywell. Juan has published two ASME papers and one WTC extended abstract. Juan Carlos is presently working at KBR Halliburton in Houston.

Adolfo Delgado has been working on the identification of parameters in a SFD with a mechanical seal. The rigorous procedure identifies first the contact force at the seal interface and then extracts the SFD parameters from the lubricated test system force coefficients. The sealed SFD is best to avoid air ingestion and entrapment, known to reduce the damping ability at high frequencies and high amplitudes of motion. Adolfo also directs a M.S. student performing identification of structural parameters in shoed brush seals. Adolfo has published two ASME technical papers on brush seals and one paper on sealed squeeze film dampers. Adolfo stayed as a Ph.D. student to continue his research work in SFDs.

OTHER

Roca Azul rocks! (phn.tamu.edu/Roca_Azul) gigs included fund raisers for the Katrina Hurricane Relief Fund (10/05) and the Brazos Valley Progressive Organizations *Forward Fest* (03/06), and two other gigs in Fitzwilly's Bar (09/05, 04/06). We also performed a mini-concert in Barranquilla, Colombia (05/06)

Luis turns 50 in 2006. Cheers! Luis is healthy for a change, inspired by music and surrounded by family and friends. Half a century! What a ride, yet miles and miles to walk.

IJTC Microturbomachinery (MTM) Sessions

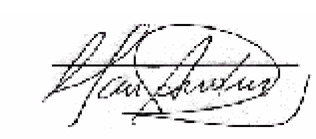
Luis is organizing technical paper sessions on MTM for the upcoming ASME/STLE International Joint Tribology Conference-IJTC (San Antonio, TX, 10/06). He invites TRC members to participate in a panel discussion session with other representatives from industry. Topics of discussion may include: state of the art and projected role of MTM, manufacturing issues, rotordynamic issues, thermal management, coatings and sealing and bearing technologies, etc. Contact Luis should you have an interest in participating.

CONCERNS

The cost of supporting graduate students increased suddenly in September 2005. The State currently mandates the payment of tuition for teaching and research assistants. Without overhead (45%), the increase in cost is approximately $2,500/semester ($7,500/year). The added cost is ~ 50% larger than in the prior year, for example. The unexpected increase was not budgeted in existing contracts and P.I.'s had to use/beg for other funds. New contracts must include tuition support. With overhead, the extra cost is $ 10,875/year per student.

Many graduate students, foreign and domestic, show grave deficiencies in written and oral communication skills and lack sound knowledge in mathematics and physics. They are superb in tackling the physics by computer, even for the simplest problem! Design is merely computer generated graphics, without regard for manufacturability, tolerances and functionality.

A successful 21st century engineer must work and network with good communication skills, work and network as a team player, and work and network in the new multi-cultural and multi-national environment. The education in our Tribology Group focuses on making the students long life learners. The students do not merely learn to "test" a mechanical element or to "run" a computer program. They develop competence in their field of work as demonstrated by peer reviewed technical publications and presentations, for example.



Luis San Andrés, Leader
Tribology Group
June 2006

Tribology Group

Team Members 2005/2006

Luis San Andrés, Leader

Name	Research project	Graduation date
Ash Maruyama	**Dynamic Response of Turbocharger Rotors Supported on Floating Ring Journal Bearings**	May 2007
Tae-Ho Kim, **Anthony Breedlove**+**,** **Christy Petter***+	**Gas Foil Bearings – Computational Analysis & Test Rig Development and Identification of System Parameters**	December 2006 May 2007 December 2006
Keun Ryu	**Flexure Pivot Gas Bearings for Oil Free TM**	December 2008
José Baker+	**Reverse Rotation Brush Seals - Testing**	December 2007
Adolfo Delgado+ **Jeffrey Hunt ***	**Identification of Force Coefficients in Sealed SFD**	May 2008
Nicholas Tydlacka*	**Mixed Lubrication Lift off Model for Hydro-static Bearings (USET program)**	May 2007
Michael Forsberg, **Juan Carlos Valles,** **April Acosta***+	**Design and Construction of Hydrostatic Thrust Bearing Test Rig (USET program)**	August 2007 August 2007 December 2006

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

L to R: Keun Ryu, Nick Tydlacka, Carlos Valles, Mike Forsberg, Ash Maruyama, José Baker, Anthony Breedlove, Tae Ho Kim. Missing: Adolfo Delgado, April Acosta, Christy Petter

Tribology Group/Rotordynamics Laboratory

2006 RESEARCH PROGRESS REPORTS
COMPUTATIONAL ANALYSIS OF GAS FOIL BEARINGS INTEGRATING 1D AND 2D FINITE ELEMENT MODELS FOR TOP FOIL Luis San Andrés and Tae-Ho Kim TRC-B&C-1-06
FURTHER IMBALANCE RESPONSE MEASUREMENTS OF ROTOR SUPPORTED ON BUMP-TYPE GAS FOIL BEARINGS – OPERATION TO 50 KRPM Luis San Andrés and Tae-Ho Kim TRC-B&C-2-06
SQUEEZE FILM DAMPER WITH MECHANICAL SEAL: IDENTIFICATION OF FORCE COEFFICIENTS FROM CIRCULAR CENTERED ORBIT TESTS Luis San Andrés and Adolfo Delgado TRC-SFD-1-06
TEST RESULTS FOR LOAD-ON-PAD AND LOAD-BETWEEN-PAD HYBRID FLEXURE PIVOT TILTING PAD GAS BEARINGS Luis San Andrés and Keun Ryu TL-B&C-1-06

2006-2007 RESEARCH PROPOSALS
EXPERIMENTAL FORCE COEFFICIENTS FOR A SEALED SQUEEZE FILM DAMPER (CONTINUATION III)
ROTORDYNAMIC PERFORMANCE OF FOIL GAS BEARINGS: TESTS AND ANALYSIS (TRC MATCHING TO NSF FUNDED PROJECT) (CONTINUATION II)
GAS BEARINGS FOR OIL-FREE TURBOMACHINERY – CONTROLLED EXTERNAL PRESSURIZATION TO ELIMINATE CRITICAL SPEEDS (CONTINUATION FROM 2003)

PROGRESS REPORTS – EXECUTIVE SUMMARIES

TRC-B&C-1-06 Computational Analysis of Gas Foil Bearings Integrating 1D and 2D Finite Element Models for Top Foil

Gas foil bearings (GFBs) are finding widespread usage in oil-free turbo expanders, APUs and micro gas turbines for distributed power due to their low drag friction and ability to tolerate high level vibrations, including transient rubs and severe misalignment, static and dynamic. The static load capacity and dynamic forced performance of GFBs depends largely on the material properties of the support elastic structure, i.e. a smooth foil on top of bump strip layers. Conventional models include only the bumps as an equivalent stiffness uniformly distributed around the bearing circumference. More complex models couple directly the elastic deformations of the top foil to the bump underlying structure as well as to the hydrodynamics of the gas film. This report details two FE models for the top foil supported on bump strips, one considers a 2D shell anisotropic structure and the other a 1D beam-like structure. The decomposition of the stiffness matrix representing the top foil and bump strips into upper and lower triangular parts is performed off-line and prior to computations coupling it to the gas film analysis governed by Reynolds equation. The procedure greatly enhances the computational efficiency of the numerical scheme.

Predictions of load capacity, attitude angle, and minimum film thickness versus journal speed are obtained for a GFB tested decades ago. 2D FE model predictions overestimate the minimum film thickness at the bearing centerline, but underestimate it at the bearing edges. Predictions from the 1D FE model compare best to the limited tests data; reproducing closely the experimental circumferential profile of minimum film thickness. The 1D top foil model is to be preferred due to its low computational cost. Predicted stiffness and damping coefficients versus excitation frequency show that the two FE top foil structural models result in slightly lower direct stiffness and damping coefficients than those from the simple elastic foundation model.

A three lobe GFB with mechanical preloads, introduced by inserting shims underneath the bump strips, is analyzed using the 1D FE structural model. Predictions show the mechanical preload enhances the load capacity of the gas foil bearing for operation at low loads and low shaft speeds. Energy dissipation, a measure of the bearing ability to ameliorate vibrations, is not affected by the preload induced. The mechanical preload has no effect on the static and dynamic forced performance of GFBs supporting large static loads.

TRC-B&C-2-06: Further Imbalance Response Measurements of Rotor Supported on Bump-Type Gas Foil Bearings: Operation to 50 krpm

A 2005 TRC report presents imbalance response measurements of a hollow test rotor supported on bump-type gas foil bearings. The top speed of the tests is 25 krpm, the limit of the drive router motor. The 2005 measurements show the gas foil bearings are prone to subsynchronous whirl with amplitudes of motion exacerbated by the imbalance condition of the rotor, i.e. a forced nonlinearity. Presently, a 0.75 kW (1 HP) motor with maximum speed of 50 krpm drives the rotor through a flexible coupling. However, at start up the AC motor does not have enough torque to overcome the dry-friction from the foil bearings contacting the rotor. Hence, the original DC router motor, 1.49 kW (2.0 HP), is installed on the free end of the motor with a centrifugal clutch that engages the test rotor, overcomes the friction in the bearings and accelerates the rotor towards high speeds. The router motor is turned off and the main drive motor spins the test rotor to a top speed of 50 krpm. The rotor is balanced first in a commercial machine and then in-place; the maximum motion amplitudes are less than 12 μm, ~ 27 % of the nominal bearing clearance (c = 45 μm), in the speed range from 2 to 25 krpm.

Coast down rotor responses from 50 krpm to rest are recorded only for the baseline imbalance condition and with side pressurization into the bearings set at 0.34 bar (5 psig). The test data show significant subsynchronous motions from 50 krpm to 27 krpm with a main whirl frequency ranging from 20 % to 27% of rotor speed. At lower rotor speeds, subsynchronous motions are negligible. The rotor speed decay curve versus time is linear from 50 krpm to 30 krpm, and from 5 krpm to rest, thus implying rotor rubbing. From 30 krpm towards 5 krpm, the speed decay is exponential showing operation with a gas film in the foil bearings.

Measurements of rotor motion are obtained for increasing imbalance masses, in-phase and out-of-phase, in coast down tests from 25 krpm where no subsynchronous vibrations exist. The amplitudes of synchronous motion show passage through a critical speed that decreases from 13 krpm to 9 krpm as the imbalance mass increases. The peak amplitudes of motion appear to increase proportionally with the imbalance, thus giving some assurance into the linearity of the test rotor-gas foil bearing system. A rotordynamic analysis to predict the measurements is presently being conducted. In spite of the large motions recorded for speeds above 26 krpm when subsynchronous whirl sets in, the gas foil bearings tolerated without damage a persistent rubbing condition. Thus, the experimental results confirm gas foil bearings are more rugged and reliable than other types of gas bearings operating under similar test conditions.

TRC-SFD-1-06 Squeeze Film Damper with Mechanical Seal: Identification of Force Coefficients from Circular Centered Orbit Tests

Air ingestion and entrapment reduce significantly the damping capability of squeeze film dampers. This phenomenon is pervasive in squeeze film dampers with open ends or poor end seals. This report extends the experimental study of a SFD featuring a mechanical seal that effectively eliminates lubricant side leakage. The test damper reproduces an aircraft application intended to contain the lubricant in the film lands for extended periods of time. The test damper journal is 2.54 cm in length and 12.7 cm in diameter, with a nominal clearance of 0.127 mm. The SFD feed end is flooded with oil, while the discharge end contains a recirculation groove and four orifice discharge ports. In a prior 2005 TRC report, single frequency - unidirectional load excitation tests were conducted, without and with lubricant in the squeeze film lands, to determine the seal dry-friction force and viscous damping force coefficients. Presently, tests with single frequency excitation loads rendering circular centered orbits excitations are conducted to identify the test system and SFD force coefficients. The tests include two sets of flow restrictors with orifice sizes equal to 2.8 mm and 1.1 mm in diameter.The flow restrictors regulate the discharge flow area, and thus control the oil flow through the squeeze film damper land. Magnitudes of dynamic pressures in the squeeze film land are similar for both sets of flow restrictors. The measurements also show dynamic pressures in the discharge groove, and with magnitudes more pronounced for small amplitude orbits when compared to the squeeze film land pressures. The identified parameters include the test system damping and the individual contributions from the squeeze film, dry friction in the mechanical seal and structure remnant damping. The identified system damping coefficients are frequency and motion amplitude dependent due to the dry friction interaction at the mechanical seal interface. Identified squeeze film force coefficients, damping and added mass, are in agreement with predictions based on the full film, short length open ends damper model. The experimental squeeze film damper force coefficients are nearly identical for both flow restrictor sizes and for the largest orbit amplitude tested (50 μm).

TL-B&C-1-06 Test Results for Load-On-Pad and Load-Between-Pad Hybrid Flexure Pivot Tilting Pad Gas Bearings

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. Rotordynamic measurements on a test rotor, 0.825 kg and 28.6 mm diameter, supported on hybrid (hydrostatic/hydrodynamic) flexure pivot tilting pad gas bearings are performed for various imbalances, increasing supply pressures, and under load-on-pad (LOP) and load-between-pad (LBP) configurations. From prior testing, the bearing pads have uneven wear and thus dissimilar clearances which affect the dynamics of the rotor-bearing system. In coast down rotor responses from 50 krpm, the rotor traverses critical speeds corresponding to rigid body modes. There are no noticeable differences in rotor response for the LOP and LBP configurations due to the light-weight rotor, i.e. small static load acting on each bearing. External pressurization into the bearings increases their direct stiffnesses and reduces their damping, while raising the system critical speed and evidencing a reduction in viscous damping ratios. External pressurization into the bearings determines large times for rotor deceleration, thus demonstrating the little viscous drag typical of gas bearings. Rotor deceleration tests with manually controlled supply pressures eliminate the passage through critical speeds, thus showing a path for rotordynamic performance without large amplitude motions over extended regions of shaft speed. Predicted bearing force coefficients for the LOP and LBP cases are nearly identical within the test speed range. The rotordynamic analysis shows critical speeds and peak amplitudes of motion agreeing very well with the measurements. The synchronous rotor responses for increasing imbalances demonstrate the test system linearity. Pressurized flexure pivot gas bearings are mechanically complex and costly, but their superior stability and predictable performance can further their implementation in high performance oil-free microturbomachinery.

2006 TRC PROPOSAL SUMMARIES

EXPERIMENTAL FORCE COEFFICIENTS FOR A SEALED SQUEEZE FILM DAMPER (CONTINUATION III)

The test facility integrates a SFD and mechanical seal in parallel. The damper journal is 1” length, 5” diameter, and nominal clearance of 5 mils (0.127 mm). The top end of the SFD is open to a flooded plenum, while the bottom end has a deep circular groove and four discharge orifice ports. A wave-spring pushes a ring in contact with the bottom surface of the damper journal, thus sealing the discharge end to prevent air ingestion. Proper installation of the seal ring is crucial. 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 contact area and the damper forced performance deteriorates due to air ingestion.

In 2004/5, single frequency - unidirectional load excitation tests were conducted to determine the seal dry-friction force and viscous damping force coefficients. In 2005/6, tests with single frequency excitation loads rendering circular centered orbits excitations were conducted to identify the test system and SFD force coefficients. The tests include two sets of discharge orifices, 2.8 mm and 1.1 mm in diameter. The flow restrictors regulate the discharge flow area, and thus control the oil flow through the squeeze film land. Magnitudes of dynamic pressures in the squeeze film land are similar for both sets of orifices. The measurements also show dynamic pressures in the discharge groove, and with magnitudes more pronounced for small amplitude orbits when compared to the squeeze film land pressures.

The identified system damping coefficients are frequency and motion amplitude dependent due to the dry friction interaction at the mechanical seal interface. Identified squeeze film force coefficients, damping and added mass, are in agreement with predictions based on the full film, short length open ends damper model. The experimental squeeze film force coefficients are nearly identical for both flow restrictor sizes and for the largest orbit size tested.

In 2006/7 the following tasks will be completed:

a) Validation of analytical models to improve the prediction of inertia coefficients in SFDs and annular seals. Available predictive methods do not account for appropriate boundary conditions (in/out).
b) Test the damper with closed outlet ports to amplify its damping and find motion limits for onset of oil cavitation and air ingestion. The no thru-flow condition is of interest for UAV applications.
c) Implementation of a non-linear parameter identification method to determine simultaneously the dry-friction force and squeeze film force coefficients. Provide estimated parameters as a function of excitation frequency and motion amplitude, feed pressure and lubricant temperature, various orifice diameters, 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. To date, the research has advanced:

- Extended computational tools (and GUIs) with two FE models for the top foil supported on bump strip layers. Predictions for load capacity and minimum film thickness have been validated to the only known reliable test data available in the open literature.
- Coast down rotor response measurements from 50 krpm conducted on a hollow rigid rotor supported on the foil bearings. The tests show persistent and severe subsynchronous motions from 50 to 27 krpm. The whirl frequency ranges from 20% to 27% of rotor speed and coincides with the system natural frequency. At lower rotor speeds, subsynchronous motions are negligible. Measurements are obtained for increasing imbalance masses in coast down tests from 25 krpm where no subsynchronous vibrations exist. The peak amplitudes of motion are proportional to the mass imbalance. The bearings tolerated without damage a persistent rubbing condition!

In 2006/7 the following tasks will be completed:

a) To analyze the extensive test data collected and to identify the bearings’ synchronous stiffness and damping force coefficients;
b) To conduct more rotordynamic tests with the foil bearings modified with shims inserted underneath the bump strips and in contact with the bearing housing. The shims will preload the bearings to increase their direct stiff-

nesses, thus raising the test system natural frequency and delaying the onset of subsynchronous whirl motions to higher shaft speeds;

c) To extend the computational models and include the conduction of thermal energy through the foil bearing structure and casing; and
d) To validate predictions from the computational model with test identified gas foil bearing force coefficients.

TRC members will benefit from independent research characterizing quantitatively gas foil bearing rotordynamic performance, reliability and durability.

GAS BEARINGS FOR OIL-FREE TURBOMACHINERY – CONTROLLED EXTERNAL PRESSURIZATION TO ELIMINATE CRITICAL SPEEDS

(CONTINUATION FROM 2003)

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. The bearings comprise four pivoted pads, offset 60%, with 1 mm feed holes for external pressurization, and nominal clearance and preload equal to 0.040 mm and 20%, respectively. The test rotor, (0.825 kg, 28.6 mm diameter) integrates an AC motor with top speed of 100 krpm. For various imbalance conditions, coasts down tests from 60 krpm characterize the rotor response on its bearings. The experimental results show that external pressurization stiffens the bearings, increasing the system critical speed while reducing the modal damping. Most importantly, the measurements evidence that external pressurization is not needed for super critical speed operation. In practice, the feed pressure could be shut off at high speeds with substantial savings in machine efficiency, unless thermal management is an issue. In addition, controlling the feed pressure while the rotor passes through speed zones of critical speed generation could eliminate high amplitude motions because of lack of damping. Fig. 2 depicts the measurements of rotor motion during a speed coast down while controlling manually the supply pressure. The results are remarkable, i.e. elimination of critical speeds with smooth operation at all rotor speeds! In the test, the feed pressure is 1.5 bar while the rotor decelerates to ~ 17 krpm. Over the speed range from 17 krpm to 10 krpm, the pressure is manually increased in steps towards 5 bar. For lower rotor speeds until rest, the pressure is kept at 5 bar to ensure rotor lift off and avoidance of hard landing (rub).

The main objective is to advance the technology of gas film bearings for applications to oil-free turbomachinery by demonstrating their rotordynamic performance, reliability and durability. The tasks to be performed are:

e) The bearings pd surfaces and rotor are worn and must be re-machined and re-coated, respectively
f) Design, build and program a simple controller linking feed pressure delivery to shaft speed. Speed of pressure control is not a major issue since the time constant of the rotor-air bearing system is large.
g) Conduct measurements of rotor response for increasing imbalances and compare to predictions from computational models. ..
h) Acquire larger electrical relay to deliver larger impact loads into test rig. Identify from transient response measurements modal damping and stiffness of rotor-bearing system. Assess reliability of gas bearings to withstand shock loads without damage.

TRC members will benefit from an independent research program characterizing quantitatively the most appropriate gas bearing technology in terms of rotordynamic performance, reliability and durability. Note that available computational models for flexure pivot-tilting pad bearings are readily available. Most importantly, bearing and rotordynamic predictions compare very well with the measurements. The assertion cannot be stated for foil bearings, for example.

Tribology Group - Funded Research **2005-2006**

External New funds $ 1,400,384

Principal Investigator(s)	Sponsor Project #	Amount	Project	Dates (GS support)
W. Hung (ENT), L. San Andrés	National Science Foundation	**$259,249**	Research Experiences for Undergraduates: Development of Microturbomachinery	30 UG / 3 years 06/01/06
L. San Andrés	Siemens - Westinghouse 32525/34650	**$ 50,000**	Brush Seals with Reverse Rotation	01/01/06-12/31/06 (1)
L. San Andrés	Northrop Grumman 32525/2433B/ME	**$787,277**	Thrust Bearing Rig for validation of liquid hydrogen TP bearings	09/01/05 – 09/30/08 (3)
L. San Andrés D. Childs	Northrop Grumman 32525/24330/ME	**$224,529**	Mixed Lubrication Model for Start Up of Cryo Turbopumps	02/01/05 – 06/30/06 (1)
L. San Andrés	NSF 32525/53900//ME	$255,475	Gas Foil Bearings for Oil-Free Rotating Machinery – Analysis Anchored to Experiments	06/15/03-05/31/07(2)
L. San Andrés	Honeywell Turbocharging 32525/6865A//ME	$211,314 +$79,529 $ 290,843	Computational Analysis of Floating Ring Journal Bearings and Experimental Validation in a Turbocharger Test Rig – Phase III	01/15/03-12/31/06 (1)

Internal, $ 44,000 (TRC)

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	07/01/05-06/30/06
L. San Andrés	TRC 32514/1519/S7	$22,000	Experimental Force Coefficients for a Sealed Squeeze Film Damper	07/01/05-06/30/06

Research Expenditures 2005/6: ~ $ 420,920

Tribology Group Publications 2005/2006

4 journal publications + 9 peer reviewed conference papers + 10 not peer reviewed conference papers + 1 technical magazine article + 1 student poster + 3 invited lectures

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

2006

von Karman Institute - RTO Lecture Series, RTO-MP-AVT-143,
DESIGN AND ANALYSIS OF HIGH SPEED PUMPS, *20-23 March 2006, Belgium,*
L. San Andrés
Introduction to Pump Rotordynamics (26 p.),
Hydrodynamic fluid film bearings and their effect on the stability of rotating machinery (35 p.),
Annular pressure seals and hydrostatic bearings (36 p.)

Accepted for Journal publications

Kim, T.H., and L. San Andrés, 2006, "Limits for High Speed Operation of Gas Foil bearings," TRIB-05-1042, accepted for publication at ASME Journal of Tribology (in production)

San Andrés, L., 2006, "Hybrid Flexure Pivot-Tilting Pad Gas Bearings: Analysis and Experimental Validation," TRIB-05-1089, accepted for publication at ASME Journal of Tribology (in production)

Peer reviewed Conference publications

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

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 Gas Turbines and Power)

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 Gas Turbines and Power)

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

STLE Annual Meeting, Calgary, Canada, May 2006

De Santiago, O., and San Andrés, L., 2006, "Experimental Identification of Bearing Dynamic Force Coefficients in a Flexible Rotor – Further Developments"

Conference Proceedings Not Peer Reviewed

IX Congreso y Exposición Latinoamericana de Turbomaquinaria,
Boca del Río Veracruz, Mexico, June 22-23, 2006

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."

San Andrés, L., and **A. Delgado**, 2006, "Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical End Seal."

Poster presentation

Petter, C., 2o06, "Analysis of Gas Foil Bearings and Test Data Predictions," ASME Regional Student Conference, District E – Eastern Area (2006 Spring Student Conference, April 6-8, University of Arkansas – Fayetteville, AR

2005

Articles

San Andrés, L., **A. Delgado**, and J. Justak, 2005, "Measurements of leakage, structural stiffness and energy dissipation parameters in a shoed brush seal," *Sealing Technology,* December, (Elsevier Pubs) ISSN 1350-4789/05

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 Vibrations Conference, Sept 2005

Delgado, A., and L. San Andrés, 2005, "Identification of Structural Stiffness and Damping in a Shoed Brush Seal," Paper DETC 2005-84159, Proceedings of IDETC/CIE 2005, ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, September 24-28, Long Beach, California

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)

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)

Kim, T.H., and L. San Andrés, 2005, "Heavily Loaded Gas Foil Bearings: a Model Anchored to Test Data," ASME Paper GT 2005-68486

Zhu, X, and L. San Andrés, 2005, "Experimental Response of a Rotor Supported on Rayleigh Step Gas Bearings," ASME Paper GT 2005-68296

Conference publications Not Peer reviewed — 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

Conference Proceedings Not Peer Reviewed

Delgado, A., and **L.** San Andrés, 2005, "Measurements of Leakage, Structural Stiffness and Energy Dissipation Parameters in a Shoed Brush Seal," 4th EDF/LMS Poitiers Workshop *"Advanced Topics and Technical Solutions In Dynamic Sealing"* FUTUROSCOPE, France, October 6

San Andrés, L., 2005, "HYBRID GAS BEARINGS FOR OIL-FREE TURBOMACHINERY: Experiments and Model Validation," 1st International Conference on Experiments/Process/System Modeling / Simulation / Optimization, Athens, Greece, July 6-9

Rubio, D., and L. San Andrés, 2005, "Identification of Structural Parameters in a Bump-Type Foil Gas Bearing," DMI-NSF Grantees Conference, Prescott, Arizona, January

Technical Reports to sponsors and TEES Turbomachinery Research Consortium

Monthly progress reports to Honeywell International and Northrop Grumman. Annual progress report to NSF

San Andrés, L., Editor, "Research on Fluid Film Bearings, Tribology Group," Year XIV, 2004/2005, May 2005.

San Andrés, L., HYBRID TILTING PAD GAS BEARINGS: ANALYSIS & EXPERIMENTAL VALIDATION, TRC-B&C-1-05

Rubio, D., and L. San Andrés, Rotordynamic Performance of a Rotor Supported on Gas Foil Bearings, TRC-B&C-2-05

Delgado, A., and L. San Andrés, Identification of Force Coefficients in a Squeeze Film Damper with a Mechanical Seal, TRC-SFD-1-05

Delgado, A., and L. San Andrés, Identification of Structural Stiffness and Damping in a Shoed Brush Seal, TRC-SEAL-3-05