Mechanical Engineering Department
Texas A&M University

2010/2011 Research Progress Report

Tribology Group

Year XX

31th Annual Turbomachinery Research Consortium Meeting

May 2011

Luis San Andrés
Mast-Childs Tribology Professor
Leader
FOREWORD

This past year (June 2010-May 2011), Luis San Andrés spent time chasing funds for continuing the research program on gas bearings for high speed micro-turbomachinery; in particular towards the experimental verification of thrust foil gas bearings and to develop a predictive tool (to be) benchmarked by test data. NSF (National Science Foundation) rejected twice a crafted comprehensive proposal with a strong recommendation to search for industrial funding in a well established area of engineering. Other potential sponsors such as NASA and TRC members also showed no interest on the proposed work. This engineering research area is now pursued efficiently in other nations with foreign TM OEMS taking the lead on gas bearing technology.

In addition, students and Dr. San Andrés worked feverishly to satisfy the demands of a fast-paced project on testing and re-testing squeeze film dampers. Alas the sponsor leadership changed frequently and the project ended in a muddle without resources to support the graduating students. Nonetheless, the test results obtained and model developed advance significantly the state of the art in damper technology. The SFD test rig constructed is a highly engineered system for ready use to verify the forced response of SFDs operating with high static loads (off-centered) and high dynamic loads with frequencies to 400 Hz.

As per teaching, years 2010/11 are the most rewarding in Dr. San Andrés academic career. UG students taking the Junior Dynamics & Vibrations course in Fall 2010 performed better (50% more A’s) than thirteen prior classes (2004-2009) taking the same class. The students showed a genuine interest in the topic and excelled in the projects and exams. In addition, in Spring 2011, Dr. San Andrés prepared and taught a new course, a technical elective without technical content. This class entitled Practices of Modern Engineering gives the undergraduate students the (soft) skills necessary to succeed in a global engineering world: fluent oral and written communication skills including the elevator speech; business and management practices across cultures; managing one’s career and engineering one’s management practices; the practice of innovation and a solid foundation on intellectual property; and how to interview and how to keep a job; how to do more with less; and, how to do things right the first time. Students’ interest drove the content that included technical presentations on green engineering and sustainability as well as the 21th century Grand Challenges for Engineering. Please browse http://rotorlab.tamu.edu/me489 to know more about a course that teaches to learn how to learn, the lectures and student presentations, as well as sound advice from young engineers and experienced engineers who graciously donated their time and exchanged their experience with the engineering UG students.

The Turbomachinery Research Consortium (TRC) funded three projects out of four proposals submitted last May 2010. Details follow, not all projects started on September 1, 2010.

- Measurement of leakage in a novel all-metal non-contacting annular seal at high temperature
  - OBJECTIVE: revamp high temperature gas seal test rig for high speed measurements and measure leakage for a labyrinth seal and a HALO™ seal
  - STATUS: Measurements of leakage in labyrinth seal and HALO seal completed; no rotor spinning. Revamping of test rig in progress. Project started September 1, 2010 (2 years).
  - SPONSOR: TURBOMACHINERY RESEARCH CONSORTIUM, $39,863
  - Student: Alain Anderson (M.S.), James Law (U.G.)

- Computational Model for Tilting Pad Journal Bearings
  - OBJECTIVE: Develop code for prediction of tilting pad bearings forced response accounting for thermal effects and including pivot radial and transverse flexibility.
STATUS: Code for ideal rigid-pivot bearings operational. Mathematical model to include pivot stiffness shows progress. Project started September 1, 2010 (2 years).
**Sponsor**: Turbomachinery Research Consortium, **$34,863**
Student: Yujiao Tao (M.S.)

- **Automated Analysis of XLTRC² Time Transient Responses in Nonlinear Rotor Bearing Systems**
  **Objective**: Modeling of NL rotor-bearing systems and GUIs for data handling of XLTRC² nonlinear transient rotor response output data.
  **Status**: Project started May 2011 (1 year).
  **Sponsor**: Turbomachinery Research Consortium, **$34,863**
  Student: Qing Liu (Ph.D.)

Other funded/unfund projects include:

- **Squeeze Film Damper – Identification of force coefficients from tests with high frequency & high loads**
  **Objective**: To assess novel SFD designs for aircraft applications.
  **Status**: Test rig operational (500 lbf dynamic force). Measurements and force coefficients identification completed in a 5 inch diameter open and sealed ends SFDs with central groove. Effect of fluid inertia dominates SFD forced response. Contract ended December 31, 2010
  **Sponsor**: Pratt & Whitney, **$339,086**
  Students: Sanjeev Seshagiri (M.S.), Paola Mahecha (M.S.), Sarabeth Froneberger (UG)

- **Thermal Energy Transport Analysis for (Semi) Floating Ring Bearings in Turbochargers**
  **Objective**: Integrate thermal energy transport for prediction of forced response in turbocharger bearings
  **Status**: Completed theoretical analysis and development of computational code in progress. Project started October 1, 2010 (2 years).
  **Sponsor**: Honeywell Turbocharging Technologies, **$208,340**
  Student: Feng Yu (M.S.)

- **Computational Model for Textured Surface Gas Face Seals**
  **Objective**: Develop code for prediction of leakage and forced response in novel gas face seals for steam turbines.
  **Status**: Code SpiralG under extensions for novel groove geometries.
  **Sponsor**: CIATEQ A.C. (MX),
  Student: Jose Hernandez (M.S. sponsored student)

- **Gas foil bearings for high speed turbomachinery**
  **Objective**: Continue to advance gas bearing technology for high temperature, high speed microturbomachinery applications (power < 400 kW).
  **Status**: Compare dynamic forced performance between a MMFB (metal mesh foil bearing) and first-generation bump-type foil bearing. Computational analysis of radial MMFBs in progress.
  **Sponsor**: NONE. Funds from licensing software support one student
  Student: Thomas Chirathadam (Ph.D.)

In spite of the difficulties in securing significant funding, the Tribology Group students continue to excel in the quality of their research products as evidenced by the number of technical papers published. See the inset for the statistics in 2010-2011 (May).

Enjoy the 31st TRC Annual Meeting. We hope to count with your continued support in 2011-2012. As per other news, do listen to some original music recordings at http://www.ies3.com/ElSanto I do have a life after all.

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# Tribology Group

## Team Members 2010-2011

<table>
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<tr>
<th>Name</th>
<th>Research Project</th>
<th>Degree</th>
<th>Graduation date</th>
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</table>
| Keun Ryu  
*Borg-Warner TCs* | Bump-type Foil Bearings: Measurements of High Temperature Performance | Ph.D. | August 2011 |
| Thomas Chirathadam | Metal Mesh and Bump-type Foil Bearings: Identification of Rotordynamic Force Coefficients | Ph.D. | December 2011 |
| Alain Anderson  
*James Law(*)* | Measurement of leakage in a novel all metal non contacting annular seal at high temperatures | M.S.  
B.S. | May 2012  
May 2011 |
| Sanjeev Seshaghiri  
Paola Mahecha  
Sarabeth Froneberger(*) | SFD Test Rig & Measurements: Pratt & Whitney | M.S.  
M.S.  
B.S. | May 2011  
August 2011  
May 2011 |
| Feng Yu | Turbocharger Bearing Code Development | M.S. | May 2012 |
| YuJiao Tao(*) | Computational Model for Tilting Pad Journal Bearings | M.S. | May 2012 |
| Qing Liu(*) | Nonlinear Dynamics of Rotor-Bearing Systems | Ph.D. | May 2013 |

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

(Keun Ryu not pictured. He is out in the real world making a difference!)
2011 Research Progress Reports

Comparison of Leakage Between a Labyrinth Seal and an All-Metal Compliant Gas Seal at High Temperature
TRC-Seal-XX-11
Luis San Andrés

2011 Research Proposals

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<td>Computational Model for Tilting Pad Journal Bearings</td>
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<td>Linear-Nonlinear Force Coefficients for Squeeze Film Dampers</td>
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<tr>
<td>Metal Mesh Foil Bearings: Operation at High Temperature</td>
<td>1</td>
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MEASUREMENT OF LEAKAGE IN A NOVEL ALL METAL NON-CONTACTING ANNULAR SEAL AT HIGH TEMPERATURES (YEAR II)

Parasitic secondary flows (seals leakage) in centrifugal compressors and gas and steam turbines represent a substantial loss in efficiency and power delivery with an increase in specific fuel consumption. Labyrinth seals (LBS) are the most common and inexpensive means of reducing secondary leakage, albeit wearing out with operation and thereby penalizing performance and even affecting rotordynamic stability. Presently, there are other seal types that can perform better in terms of leakage reduction and low drag power losses.

In July 2010, TRC funded a two-year program to (a) conduct non-proprietary leakage tests with a HALO™ seal and, for comparison, a three tooth labyrinth seal; and (b) to revamp the test rig for operation at higher rotor speeds to reach a tip surface speed of 120 m/s (15 krpm), thus replicating tip speeds found in land-based power generation gas and steam turbines. The HALO™ seal [Hydrostatic Advanced Low Leakage] is an all metal compliant seal engineered to close its clearance as pressure differentials increase.

The following tasks will be completed during the second year of the research program (2011-2012):

a) Complete revamping test rig for operation at a high rotor speed (15 krpm) to reach a tip surface speed of 120 m/s.

b) Perform clearance and leakage measurements with a three tooth labyrinth seal and the HALO™ seal operating with large pressure ratios, 8 max., air inlet temperatures to 300ºC, and tip surface speeds to 120 m/s.

c) To compare the labyrinth seal measured leakage with XLLABY® predictions at high temperatures. The benchmarking is essential to trust, modify or discard current predictive models.

The research products –a reliable leakage data base and technical report (M.S. thesis)- will enable the application of state of the art sealing technology that increases system efficiency by reducing leakage and that extends maintenance intervals by eliminating wear of components

COMPUTATIONAL MODEL FOR TILTING PAD JOURNAL BEARINGS (YEAR II)

Accurate prediction of the static and dynamic forced performance of tilting pad journal bearings is necessary to design, troubleshoot and predict the dynamic response and stability of rotor-bearing systems. XLTRC® software suite includes a computational code for prediction of tilting pad bearings static operation and frequency reduced stiffness and damping force coefficients. Since 2006, Childs and students have conducted measurements of rotordynamic force coefficients for a number of industrial type tilting pad journal bearings. In general, predicted bearing stiffness and damping correlate well with the measurements for small to moderate specific loads (up to 150 psi [10 bar]). The measurements evidence the bearing stiffness force coefficients to be strongly frequency dependent, best represented with a K-M model. Damping coefficients are adequately represented with magnitudes not depending on frequency. In a heavily loaded condition, poor correlation of predictions to measured force coefficients is evident.

TRC funded a two-year project to enhance an existing computational tool for accurate prediction of tilting pad bearing force coefficients for heavily loaded operating conditions. The upgraded model will include pivot flexibility, typically nonlinear, for a number of pivot type configurations, with specification of sliding or rolling contact conditions. In 2011, the student working in the project read the extensive literature on experimental identification of tilting pad bearing force coefficients, understood the differences in physical behavior for the various types of pivots, and the paramount effect of pad flexibility and pivot...
flexibility on reducing (or increasing) TPJBs (reduced frequency) stiffness and damping force coefficients; as well as current issues on rotordynamic stability criteria for rotors supported on tilting pad bearings. The student took XL PRESDAM_TH® code, beginning modifications and enhancements towards making it into a tilting pad bearing code. Presently, the code predicts reduced frequency force coefficients for ideal tilting pad bearings, i.e., those with infinite pivot stiffness, radial and lateral. Predictions from the modified code are in agreement with those published in Someya’s Bearing Handbook as well as with results obtained with XL TFPBRG® code, the tool presently available in the XLTRC² software suite.

In the second year, the student will complete the computational program enabling TRC members to model accurately realistic tilting pad configurations. The computer code will be integrated into XLTRC² for ready use. A technical report detailing the model enhancements as well as comparisons to the test data of Childs et al. will be delivered at the end of the project. The GUI will be revamped for more expedite computational predictions with physically reasonable starting initial guesses to reduce the burden on the unseasoned user.

New

**METAL MESH FOIL BEARINGS: OPERATION AT HIGH TEMPERATURES**

Metal Mesh Foil Bearings (MMFBs) are simple and inexpensive gas bearings that provide low friction, long operating life, and material damping for mechanical energy dissipation into high speed rotor bearing systems. Engineered MMFBs will aid to improve system efficiency, raise power density, and lower carbon foot-print when compared to oil-lubricated bearing systems.

The main objective of the proposed work is to demonstrate the reliable operation of MMFBs at elevated temperatures (max 200°C) and their ability to survive harsh environments with an adequate thermal management. A high temperature rotor-bearing test rig constructed with NASA funds for evaluation of bump type foil bearings is available. In the rig, an electric heater cartridge inside the hollow rotor warms the rotor to high temperature (max 300°C). The tasks for 2011/12 are:

a) Construct two MMFBs fitting the existing bearing casing and shaft diameter, install the MMFBs in the test rig, align and balance the test rotor, and calibrate the high temperature instrumentation.

b) Conduct experiments with rotor OD surface temperatures to 200°C and to a top rotor speed of 50 krpm. Measure bearing temperatures as the rotor (slowly) heats up and while providing increasing cooling streams. Assess the effectiveness of the cooling flow rates on managing the bearing and rotor temperatures. Rotor speed up and coast-down measurements will show rotor lift-off and touch down speeds, and the amplitude of motion data will serve to identify system damping ratios and effective bearing stiffnesses.

c) Compare the thermal performance of the MMFBs with that recorded for generation I, bump-foil bearings.

The results of the research will characterize, both qualitatively and quantitatively, a novel (non-proprietary) gas bearing technology of low cost, simple in construction, and suitable for operation at high and low temperatures.

New

**LINEAR-NONLINEAR FORCE COEFFICIENTS FOR SQUEEZE FILM DAMPERS**

High performance turbomachinery demands high shaft speeds, increased rotor flexibility, tighter clearances in the flow passages, advanced materials, and increased tolerance to imbalances. Operation at high speeds induces severe dynamic loading with large amplitude journal motions at the bearing supports. Squeeze Film dampers (SFD) aid to reduce rotor vibrations due to imbalance and other sources and also serve to isolate the rotor(s) from the engine frame or casing. Energy efficient and reliable rotordynamic operation of aircraft engines calls for detailed understanding of SFD forced performance. Predictions derived from classical SFD analyses fail to accurately predict the force coefficients for SFDs.
Pratt & Whitney engines sponsored a two-year test program (2008-2010) to investigate novel SFD configurations operating at typical conditions encountered in aircraft jet engines. The project provided reliable SFD forced performance data and benchmarked predictions from a new computational program. The existing test rig permits the excitation of the BC with large amplitude whirl motions of arbitrary shape. In practice this is a normal occurrence. However, predicted (linear) SFD force coefficients may not represent with fidelity the actual forced response of a SFD, in particular for off-centered journal motions. Recall that rotodynamic force coefficients are strictly valid for infinitesimally small amplitude motion about an equilibrium condition. Both requirements, an equilibrium state and small whirl amplitude motions, are often violated in SFD operation. Work is proposed to:

(a) Test the short length open ends damper with dynamic loads (20-300 Hz) inducing off-centered elliptical orbital motions with amplitude ratios as large as 5:1 to reach 80% of the bearing clearance (see inset).

(b) Extract SFD force coefficients from test impedances obtained over a frequency range and correlate coefficients with predictions of linear force coefficients and experimental coefficients for smallest whirl amplitudes (5%).

(c) Perform computational model numerical experiments, similar to the physical tests, to also extract linearized SFD force coefficients from the nonlinear forces and valid within a frequency range. Determine goodness of linear-nonlinear representation from the equivalence in mechanical energy dissipation with the work performed from the actual nonlinear forces (experimental and numerical).

The TAMU SFD research program is the most renown in the world. The proposed research is of interest for SFD applications in gas turbines, semi-floating ring bearings in turbochargers, hydrodynamic bearings in compressors, etc. Since 1990, TRC sponsors the SFD research program with many practical advances derived from planned experiments and computational analysis.
# Tribology Group - Funded Research 2011

## External NEW funds (2010) $208,340

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<th>Amount</th>
<th>Project</th>
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<td>HONEYWELL TURBOCHARGING TECHNOLOGIES</td>
<td>$208,340</td>
<td>Turbocharger Bearing Code Development</td>
<td>09/01/10 – 08/31/12</td>
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<td>L. San Andrés</td>
<td>PRATT &amp; WHITNEY</td>
<td>$339,086</td>
<td>Squeeze Film Damper – design of test rig for high frequency &amp; high load operation</td>
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## Internal: $109,589 (TRC)

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<td>$34,863</td>
<td>Automated Modeling XLTRC2 RBS</td>
<td>03/01/11</td>
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<td>Modeling of Tilting pad Bearings</td>
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## Software licensing through TEES, $44,500 project 32271/84390

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<td>Knight Hawk Eng</td>
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<td>Borg-Warner</td>
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Source: TEES portal 05/06/2011
**Tribology Group Publications 2010/2011**

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Dr. San Andrés lecture notes on *Modern Lubrication Theory* have a permanent (perpetual), stable indexed URL address at Texas A & M University Digital Libraries, [http://repository.tamu.edu/handle/1969.1/93197](http://repository.tamu.edu/handle/1969.1/93197) below **bold face**=student co-author

**Journal publications (peer reviewed)**

2011


San Andrés, L., and **Kim, T.H.**, 2010, “Thermohydrodynamic Analysis of Bump Type Gas Foil Bearings:


Peer reviewed Conference publications

2011


8th IFToMM International Conference on Rotordynamics, September 12-15, Seoul, Korea


ASME Turbo Expo 2010, June 2010, Glasgow, Scotland


Conference Proceedings - Not Peer Reviewed

2010


STLE Tribology Transactions: Handbook of Tribology: Chapter on Gas Lubrication (2010)

Accepted for journal & in print (*) 2011
