2009/2010
Research Progress Report

*Tribology Group*

Year XIX

30th Annual
Turbomachinery Research Consortium Meeting

May 2010

Luis San Andrés
Leader
In late July 2009, Professor Luis San Andrés initiated a Faculty Development Leave in Asia. He witnessed and learned first hand where the future is made today!

Luis spent five months at the National University of Singapore (NUS) where he taught his Modern Lubrication Course and developed a course entitled Principles of Modern Engineering. The class, tailored to young engineering students, teaches those skills needed to succeed in a global engineering world: communication and business practices across cultures, managing a career and engineering management practices, focuses on the practice of innovation, and instills the work attributes and attitudes to keep a job: how to do more with less and how to do things right the first time. The course was extremely successful and will be offered at TAMU as an elective course in Spring 2011.

While in Singapore, Dr. San Andrés visited Malaysia, Vietnam, Indonesia, Thailand, Cambodia, Japan and China. He lectured at Chiang Mai University in Thailand, Xi’an Jiatong University in China, and attended the World Tribology Conference in Kyoto, Japan.

On January 2010, Dr. San Andrés initiated research work at the Energy Mechanics Center of the Korea Institute of Science and Technology (KIST). While spending three months in cold Korea, Dr. San Andrés visited numerous heavy machinery industries, lectured at Seoul National University, Korea University. He also traveled to Beijing (China) where he lectured at Tsinghua University. While at KIST, Dr. San Andrés taught seminars on rotordynamics and foil bearings and also his Modern Engineering Practices focusing on graduate student needs.

The sabbatical leave was most rewarding for Dr. San Andrés learning Asian culture, history and engineering practices. The fast pace development in Singapore and Korea towards knowledge-based societies is amazing! US scientists, academicians and engineers do not realize how far behind we are in novel technologies and applications. Dr. San Andrés enjoyed the food and music everywhere, got used to live in metropolitan cities where interconnectivity (transport and telecommunications) is far ahead of those in Texas. In Asia, government and industrial funding of university research is at least one order of magnitude larger than in the USA.

Dr. San Andrés resumed work at TAMU on April 1. His sabbatical leave was short two months because an industrial sponsor withdrew its support for his work in Shanghai, China. Currently, Dr. San Andrés is developing a bulk-flow code for annular seals operating with gas in liquid mixtures applicable in oil&gas pumps and compressors. He thanks Dr. Childs, Director of the Turbomachinery Laboratory, for granting him the means to conduct the work.

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<th>Published Journal papers (peer reviewed)</th>
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<tr>
<td>Conference Proceedings (not reviewed) &amp; Magazine</td>
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Total | 15 | 15 |

In 2009/10, students and Dr. San Andrés published thirty technical papers (13 journal and 17 conference). The productivity of the research group continues to exceed normal expectations in a world class research & education institution.

While in Asia, Dr. San Andrés reduced his research involvement and student mentoring activities at Texas
A&M University. Lack of funding dictated the outcome. In spite of the difficult economic times, Professor San Andrés and students continued to perform research of the utmost quality, doing more with less! Two TRC proposals were funded; however, Dr. San Andrés declined the work in lieu of current TRC project guidelines. Remnant funds from prior TRC funded projects were used to continue research work in foil bearings: bump-type and metal-mesh type. TRC members clearly benefit from more work without additional funding. Please note that any meaningful research project must tap into various funding sources and combine resources to deliver more and exceed expectations.

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

- **Squeeze Film Damper – operation of test rig for high frequency & high load measurements**
  
  **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 SFD with central groove. Effect of fluid inertia found to dominate SFD forced response.
  
  **SPONSOR:** PRATT & WHITNEY, **$331,000**
  
  Student: Sanjeev Seshagiri (M.S.), Paola Mahecha (M.S.), James Law (UG)

- **Foil Gas Bearings for Oil-Free Turbomachinery**
  
  **OBJECTIVE:** To quantify the performance of bump-type foil gas bearings for micro gas turbines
  
  **STATUS:** Completed computational analysis model for thermal management of foil bearings. Measurements of foil bearing performance at high temperatures (max 300 C) currently under way.
  
  **SPONSORS:** TRC REMNANT FUNDS USED IN 2009-2010. Cooperation with KIST
  
  Student: Keun Ryu (Ph.D.)

- **Metal Mesh Foil Bearings for Microturbomachinery**
  
  **OBJECTIVE:** Identify metal mesh foil bearings rotodynamic force coefficients
  
  **STATUS:** High speed (60 krpm) test rig with two orthogonal shaker load excitations constructed and operational. Identification of performance and force coefficients in progress.
  
  **SPONSOR:** TRC REMNANT FUNDS USED IN 2009-2010
  
  Student: Thomas Chirathadam (Ph.D.)

- **Research Experiences for Undergraduates: Development of Microturbomachinery**
  
  **OBJECTIVE:** The REU Summer Program funds 30 junior-level students to conduct hand-on training and research in mechanical, manufacturing, industrial, or materials engineering topics related to technological advances in microturbomachinery.
  
  **STATUS:** Thirteen selected UG students participated in Summer 2009: two students worked with Tribology Group students. In Summer 2010, two High School teachers will undertake educational research in micro manufacturing.
  
  **SPONSOR:** NATIONAL SCIENCE FOUNDATION (2006-2010), **$279,249**
  
  Investigators: PI: Wayne Hung (Engineering Technology), co-PI: Luis San Andrés

I thank the students for their hard work and progress while I was away. Without their support and patience I could not have enjoyed (and endured) a most rewarding sabbatical leave

[Signature]

Luis San Andrés, Leader
## Team Members 2009/2010

<table>
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<tr>
<th>Name</th>
<th>Research Project</th>
<th>Degree</th>
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<tr>
<td>Keun Ryu</td>
<td>Bump-type Foil Bearings: Measurements of High Temperature Performance</td>
<td>Ph.D.</td>
<td>August 2010</td>
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<tr>
<td>Katherine Janica*</td>
<td>Nonlinear Force Response of Foil Bearings</td>
<td>B.S.</td>
<td>December 2010</td>
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<tr>
<td>Sanjeev Seshaghiri</td>
<td>SFD Test Rig &amp; Measurements: Pratt &amp; Whitney</td>
<td>M.S.</td>
<td>December 2010</td>
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<tr>
<td>Paola Mahecha+</td>
<td></td>
<td>M.S.</td>
<td>May 2011</td>
</tr>
<tr>
<td>James Law</td>
<td></td>
<td>B.S.</td>
<td>May 2011</td>
</tr>
</tbody>
</table>

(*) undergraduate student, (+) minority student (female, Hispanic, Asian, African-American)
Seminars abroad 2009/2010

During his sabbatical leave, Professor San Andrés presented the following lectures and seminars. In most places, he introduced the Turbomachinery Laboratory research and continuing education activities. He also explained the structure of the Turbomachinery Research Consortium, its objectives and its members and currently funded research work.

**Seoul National University, Seoul, South Korea**, “High Temperature Leakage Measurements in Three Types of Gas Seals,” March 24, 2010

**Doosan Heavy Industries, Pusan, South Korea**, “Comparison of Leakage Performance for Three Gas Seal Types Operating at High Temperature,” March 17, 2010

**Tsinghua University, Beijing, China**, “Gas Bearings for Microturbomachinery – an Overview,” March 15, 2010

**Korea University, Seoul, South Korea**, “How to Get the Work Done,” March 10, 2010

**KAES, Co., Gyeongju, South Korea**, “The Turbomachinery Laboratory at TAMU – Overview of Research Capabilities,” March 9, 2010


**Korea Institute of Science and Technology, Seoul, Korea**

Seminars Series on Practices of Modern Engineering tailored to international graduate students

1. Introduction to Modern Engineering Practices – January 21, 2010
3. The Complete Engineer, February 4, 2010
4. How to get the (graduate) Work Done, February 11, 2010
5. Writing and Reviewing Papers, February 25, 2010
6. Honesty and Integrity, March 4, 2010
7. Ethics in the Workplace, March 11, 2010
8. Intellectual Property and Innovation, March 18, 2010

**National University of Singapore, Singapore**

Development of Freshman Seminar on Modern Engineering Practices, December 29, 2009

Advances in sealing technology for power & oil & gas turbomachinery: Comparison of leakage performance for three gas seal types operating at high temperature, November 6, 2009

How to Get the Work Done, October 5, 2009

**Chiang Mai University, Chiang Mai, Thailand**

Advances in Metal Mesh Foil Bearings for Oil-Free Turbomachinery, November 20, 2009

**NASA Glenn Research Center, Cleveland, (delivered from Singapore vie web)**

Final Presentation: Thermohydrodynamic Analysis of Bump Type Gas Foil Bearings: A Model Anchored to Test Data,” NASA SSRW2-1.3 Oil Free Engine Technology Program, August 26, 2009

**Escuela Politécnica Nacional, Quito, Ecuador**

Metal Mesh Foil Bearings for Oil-Free Turbomachinery, July 22, 2009
2010 RESEARCH PROGRESS REPORTS

More on Metal Mesh Foil Bearings: Effect of Excitation Frequency on Dynamic Force Coefficients
TRC-B&C-01-10
Luis San Andrés, Thomas Chirathadam

2010-2011 RESEARCH PROPOSALS

<table>
<thead>
<tr>
<th>Project Description</th>
<th># years</th>
<th>Cost Y1</th>
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<td>THRUST FOIL BEARINGS FOR OIL-FREE MICROTURBOMACHINERY</td>
<td>3</td>
<td>$44,463</td>
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<tr>
<td>METAL MESH FOIL BEARINGS: PREDICTED &amp; EXPERIMENTAL ROTORDYNAMIC FORCE COEFFICIENTS</td>
<td>2</td>
<td>$38,863</td>
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<td>MEASUREMENT OF LEAKAGE IN A NOVEL ALL METAL NON-CONTACTING ANNULAR SEAL AT HIGH TEMPERATURES</td>
<td>2</td>
<td>$39,863</td>
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<tr>
<td>AUTOMATED ANALYSIS OF TIME TRANSIENT RESPONSES IN NONLINEAR ROTOR BEARING SYSTEMS</td>
<td>2</td>
<td>$34,863</td>
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<tr>
<td>COMPUTATIONAL MODEL FOR TILTING PAD JOURNAL BEARINGS</td>
<td>2</td>
<td>$34,863</td>
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</table>
THRUST FOIL BEARINGS FOR OIL-FREE MICROTURBOMACHINERY

The widespread deployment of oil-free microturbomachinery (MTM) supported on gas foil bearings (GFB), radial and axial, relies on overcoming intermittent contact and damaging wear at rotor start up and shut down, temporary rubs during normal operating conditions; and most importantly, with engineered thermal management to ensure GFB performance in high temperature environments. Although, gains have been made in specific loading; high-temperature material limits, coating endurance and stability, and adequate thermal management still restrict application of GFBs into high power density gas turbines. Poor thermal management, eminently empirical and costly, due to inefficient cooling techniques and/or inadequate coatings can lead to catastrophic failure of the entire rotor-bearing system.

An ongoing research program at Texas A&M University, funded by NSF, NASA GRC, turbomachinery manufacturers and end users, has been instrumental in developing engineering design tools, experimentally validated, for prediction of radial GFB performance. The next step is to undertake similar research in thrust foil bearings (TFBs). A three-year research program, analytical and experimental, is proposed to the TRC.

The tasks are:

- Development of a computational model for prediction of TFB forced performance, static and dynamic.
- Measurements of TFB forced performance in a revamped high speed test rig for code validation. Tests will evaluate rotor lift and break away torque, touchdown speed and stall torque, TFB axial load versus minimum film thickness and drag power losses, and identification of axial force coefficients (stiffness and damping) over a range of speeds and excitation frequencies.

The products of the research, codes and test data, will enable the reliable application of gas foil bearings into high temperature turbomachinery. The research will educate mechanical engineering students applying gas bearing technology to oil-free turbomachinery.

TRC members will benefit from an existing water lubricated thrust bearing test rig ($220,876 in capital equipment) to conduct (gas) thrust bearing load capacity tests at high speeds (30 krpm).

MESH FOIL BEARINGS: PREDICTED & EXPERIMENTAL ROTORDYNAMIC FORCE COEFFICIENTS

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 footprint when compared to oil-lubricated bearing systems.

The main objective of the MMFB research at TAMU is to develop low cost and reliable gas bearings using commercially available metal meshes. In the next two years, 2010-12, the research tasks include:

a) Measurement of MMFB forced response due to shaker-load excitations and identification of rotordynamic force coefficients for increasing rotational speeds to 70 krpm.

b) Similar measurements conducted on a bump-type foil bearing, first generation. Comparison of static and dynamic load performances.

c) Development of FORTRAN program and EXCEL GUI for prediction of MMFB rotordynamic force coefficients, ready for integration into XLTRC. Predictions will be benchmarked against test data.

1 A comprehensive proposal with same objective is pending support from National Science Foundation. As in past instances, Dr. San Andrés will combine TRC and federal funds to complete the work.
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.

**MEASUREMENT OF LEAKAGE IN A NOVEL ALL METAL NON-CONTACTING ANNULAR SEAL AT HIGH TEMPERATURES**

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.

The HALO™ seal [Hydrostatic Advanced Low Leakage] is an all metal compliant seal engineered to close its clearance as pressure differentials increase. Laboratory measurements show an impressive reduction in leakage, 33% of that in a hybrid brush seal and 14% of the flow in a labyrinth seal! Industries seeking to increase efficiency by reducing (parasitic) secondary leakage losses will benefit greatly from a change in seal technology.

A two-year research program is proposed with the following tasks:

a) Revamp test rig for operation at higher rotor speeds to reach a tip surface speed of 120 m/s (15 krpm). Modifications include replacing the drive motor, stiffening the rotor and implementing gas bearings. Sealing of the bearing compartments at high temperature will be particularly difficult.

b) Perform clearance and leakage measurements with a three teeth labyrinth seal and the HALO™ seal operating with pressure ratios as high as 5 bar, temperatures to 300ºC, and tip surface speeds to 120 m/s.

c) 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 product—a reliable leakage data base—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.

TRC members will readily benefit from an existing high temperature seal test rig fully instrumented ($75,000 cost in capital equipment) to conduct (short seal) seal leakage measurements up to 300ºC. Labyrinth seals are an outdated technology.

**AUTOMATED ANALYSIS OF TIME TRANSIENT RESPONSES IN NONLINEAR ROTOR BEARING SYSTEMS**

XLTRC²© is a comprehensive GUI tool for the prediction of the dynamic response of realistic rotor-bearing systems (RBS). The tool includes linear analyses such as generation of critical speed maps, prediction of eigenvalues (critical speeds and damping ratios) and imbalance response, rotor static and synchronous motion deflected shapes, and generation of reports as per API 610 requirements. The nonlinear tool, presently incorporating a few simple nonlinearities that include the short length journal bearing model, integrates the equations of motion of the rotor-bearing system and calculates the RBS time response for a variety of loads: mass imbalance, maneuver and User specified. XLTRC²© outputs the predictions in tabular form and graphs depicting the rotor motion, at specified stations, versus time. The amount of data generated in a transient time response case is exceedingly large, i.e. tens of thousands of data points revealing little of the desired features expected when performing a nonlinear analysis. These
features include the frequency content of the rotor motions and the mode shapes at selected frequencies. Furthermore, XLTRC²©is constrained to single speed (range) operation which forestalls its use as an analysis tool generating waterfall plots, for example.

A two year project is proposed to develop GUIs integrated into XLTRC² nonlinear analysis feature to perform automated (point & click)
a) Multiple case rotor speed transient RBS responses with efficient data storage.
b) **Post-processing:** worksheet for FFT analysis of predicted RBS motions with generation of waterfall graphs and display of rotor motion amplitudes versus whirl frequency and rotor speed(s) (see Fig. 2)
c) Generation of 3D rotor operating deflected shapes within specified frequency ranges to verify modal conditions and strain energy distribution.
d) Upgrading XLTRC² Finite Element code XL_PressDam_TH®, released in 2009, into an impedance model for prediction of instantaneous bearing reaction forces as a function of journal center position \((X,Y)\) and velocities \((V_x,V_y)\). XL_PressDam_TH® models radial bearings with multiple pads (offset and preload) and pressure dam bearings. A squeeze film damper option, i.e. without journal or bearing rotation, will be built into the updated code. This feature will enable modeling semi-floating ring bearings.

The products of the research will enable TRC members to use efficiently XLTRC² for frequency domain analysis of the time response of nonlinear RBS. The research is of immediate applicability into high speed RBS such as turbochargers, for example.

TRC members will benefit from the vast experience accumulated during nine years of work funded by a major TM OEM.

**COMPUTATIONAL MODEL FOR TILTING PAD JOURNAL BEARINGS**

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. XLTRC² software suite includes a computational code for prediction of tilting pad bearings static operation and frequency reduced stiffness and damping force coefficients.

Childs and students have conducted measurements of rotordynamic force coefficients for a number of industrial type tilting pad journal bearings, including a flexure pivot configuration. In general, predicted force coefficients, 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. Rationale for the significant discrepancies lies on the model not accounting for the bearing’ pads pivot stiffness. The model assumes an ideal pivot configuration without friction and infinitely rigid along the radial direction. Furthermore, the computational model does not calculate the effective film clearance, which is affected by both mechanical and thermal deformations under heavy loaded conditions.

A two-year project is proposed 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 addition, the model will include simple formulations for estimation of the operating clearance as a function of local thermal expansion and mechanical deformation.

The upgraded computational program will enable 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.
# Tribology Group - Funded Research 2009-2010

## External NEW funds (09-10) $153,509+$20,000

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<tr>
<th>Sponsor</th>
<th>Project #</th>
<th>Amount</th>
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<td>PRATT &amp; WHITNEY</td>
<td></td>
<td>$185,577+ $153,509</td>
<td>Squeeze Film Damper – design of test rig for high frequency &amp; high load operation</td>
<td>07/01/08 – 12/31/10 (2)</td>
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<td>National Science Foundation</td>
<td>32525/35430/ME</td>
<td>$259,249+$20,000</td>
<td>Research Experiences for Undergraduates: Development of Microturbomachinery</td>
<td>2 HS teachers 2010</td>
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## Internal, $0.0 (TRC) - funding for projects declined and used remnant funds from past years

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<th>Sponsor</th>
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<td>SFD – Multiple Frequency Excitation</td>
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<td>TRC 32514/1519C4/ME</td>
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<td>Rotordynamic Performance of Foil Gas Bearings: High Temperature Tests and Analysis</td>
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## Research Expenditures Fiscal Year 2009: ~$459,736

Source: TEES portal 01/02/2010
Tribology Group Publications 2009/2010

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<th>Published Journal papers (peer reviewed)</th>
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+ 7 in print journal papers (2010)

2010

Journal publications (peer reviewed)


Peer reviewed Conference publications


Journal publications (peer reviewed)

Peer reviewed Conference publications

ASME Turbo Expo 2009, June 2009, Orlando, FLA

Conference Proceedings - Not Peer Reviewed

**Extended Abstracts**


**Student Poster presentations**

Two student posters prepared by NSF—Microturbomachinery REU Summer 2009 Program
Students: Jose Camero (UTSA), Shane Muller (Calvin College)

**PUBLICATIONS OF BOOKS OR AUTHORITATIVE REFERENCES**

**Modern Lubrication Theory** (2009) L. San Andrés 
(set of 14 lecture notes + predictive codes)

Open Source: [http://rotorlab.tamu.edu/ME626](http://rotorlab.tamu.edu/ME626)

**In print (**) 2010**


**Accepted**

Luis San Andrés, 2010

http://rotorlab.tamu.edu