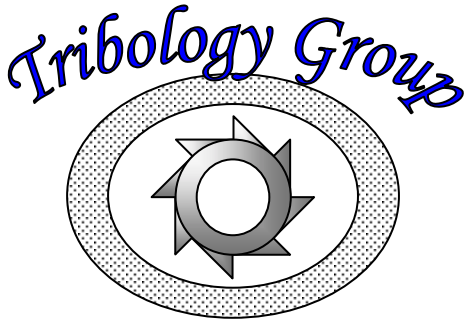
Mechanical Engineering Department
Texas A&M University

2002/2003
Research Progress Report
Tribology Group

Year XII

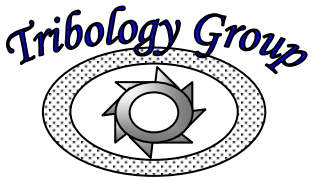
23th Annual
Turbomachinery Research Consortium Meeting



May 2003

Luis San Andrés

Professor



Tribology Group

Rotordynamics Laboratory

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FOREWORD

Milestones in our research program in 2002/2003 follow. First things first, though. Our group has seen changes with students graduating and joining the work force and new students arriving to pursue their engineering research. Deborah Wilde is with Honeywell in LA and works in foil bearings. Oscar de Santiago works at Dresser Rand, his exceptional skills adding to a fine team of former Aggies. Jason Kerth joined Exxon-Mobil Research in Houston and is learning quickly to master magnetic bearings.

Former and current students received the following distinctions:

Name	Society	Distinction	Contribution
Sergio Diaz	ASME Tribology Division	2003 B. Newkirk Young Investigator Award	Air Entrainment in SFDs
Deborah Wilde	STLE	2003 Best Paper Award	Wear in Seals – work conducted as undergraduate
Balantrapu Kishore	STLE	2003 Graduate Fellowship	Recognition of potential research ($5,000)
Nicholas Rouge	TAMU – Engineering Program	2003 Undergraduate Summer Research Grant	Opportunity to conduct research ($3,500)

Honeywell Foundation awarded the Tribology Group an unrestricted cash gift of $25,000 in recognition of our outstanding research assisting to their needs. We also recognize Active Power (Mr. Chris Holt) for donating a $100,000 high-speed floating ring bearing test rig that will be revamped for gas foil bearing testing.

Last September, Dr. Luis San Andrés was appointed Leader of the Systems and Controls Division of our Mechanical Engineering Department (MEEN). Luis is in charge of planning course curriculum and class schedules and must deal with a multitude of daily administrative emergencies. Times are hectic at Texas A&M University. There is a welcoming atmosphere promoting diversity and globalization. There are few resources to achieve the desired goals and less interest in actually changing things though. Luis assisted MEEN in developing a Strategic Plan and a reinvestment Plan. Dr. San Andrés is actively involved in A&M Professional Hispanic Network and working towards the establishment of the Mexican-American U.S. Latino Research Center to address the needs of the increasingly large Hispanic population in Texas.

In 203, the students and Dr. San Andrés co-authored eight technical papers to be presented at professional meetings and for publication in prestigious journals.

- Deborah Wilde will present two papers at the ASME Turbo-Expo'03 Conference (Atlanta, 06/03) and describing her test results and predictions for inexpensive gas bearings.
- Oscar de Santiago will be at the same conference to deliver two papers on his unique in-situ methods for bearing support parameter identification.

- Chris Holt and engineers from Honeywell will deliver to technical papers on turbocharger nonlinear rotordynamics, tests and analysis, at the *Symposium* on Nonlinear Dynamics and Control for Rotor Systems, 19th Biennial Conference on Mechanical Vibration and Noise, (Chicago, 09/03)
- Oscar de Santiago and Deborah Wilde prepared each one paper for presentation at the ASME/STLE International Tribology Conference in October. Oscar discusses the effects of air entrainment on SFD force coefficients, and Deborah details the benefits of low friction coatings at start up of a test rotor supported on gas bearings.
- In July, Dr. San Andrés will travel to Lima (Perú) to attend the 3rd Bolivarian Congress in Mechanical Engineering. He will also visit universities in Ecuador and Bolivia and recruit qualified graduate students.
- Currently, students are preparing papers for presentation at the 10th Congreso Latinoamericano de Turbomaquinaria to be held in Veracruz (Mexico) next October.

The current status on the various research efforts, the students involved in them and the sources of funding follow. The numerous archival publications and technical progress reports demonstrate the high quality and sustained productivity of our Tribology Group. Summaries for the TRC Research Progress Reports and new Proposals are also included. We hope to count on with your continued interest and support.

- **On site techniques for identification of bearing support parameters in flexible rotor systems**
  OBJECTIVE: Develop procedures for practical on site reliable parameter identification techniques
  STATUS: Method extended to handle realistic rotor configurations, namely flexible rotors. Imbalance responses at planes near bearings obtained from flexible rotor supported on hydrodynamic bearings. The identification method models the whole rotor structure, implements measured imbalance responses, and identifies support force coefficients agreeing well with analytical predictions. Further work needed to fine-tune the procedure since measurement planes, in practice, are away from bearing supports centerlines.
  SPONSOR: TRC, STLE Fellowship
  Students: Oscar de Santiago (Ph.D), Kishore Balantrapu (M.S.).

- **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: The turbocharger (TC) test rig continues to provide reliable data for floating ring speeds and shaft vibration. Processing software reveals multiple sub synchronous instability regions. Numerical predictions based on XLTRC^2 and bearing nonlinear models shows excellent correlation with the test data. Measurements with the compressor housing clocked at various angles aim to reveal aerodynamic loads affecting the TC rotordynamic response. A new TC incorporating semi-floating ring bearings will be installed and tested soon.
  SPONSOR: Garrett Engine Boosting Systems, $25k gift from Honeywell Foundation for oil-free turbochargers.
  Students: Jason Kerth (M.S.), Nick Rouge (UGS), Erick Jimenez (MS), Dan Braz (UG)

- **Gas Bearings for Oil-Free Turbomachinery**
  OBJECTIVE: To advance the technology of inexpensive gas bearings for micro gas turbines and micro power systems
  STATUS: Small 100 krpm test rig continues to provide superb data. Run up and coast down imbalance responses from 90 krpm recorded for flexure pivot hydrostatic pad gas bearings demonstrate their unsurpassed stability. Synchronous force coefficients extracted from recorded loads and rotor displacements agree well with predictions. Rayleigh-step type gas bearings with Argonne's NFC (near frictionless carbon – coating) currently being tested.
  SPONSORS: TRC. Industrial partners: Meruit, Argonne's National Laboratory.
  Students: Suzan Zhu (M.S.), Gautam Gupta (MS).

- **Foil Gas Bearings for Oil-Free Turbomachinery**
  OBJECTIVE: To quantify the physical parameters of bump foil gas bearings for micro turbine applications
  STATUS: Measurements of foil bearing structural stiffness for increasing loads and various angular orientations completed. Tests reveal nonlinear (hardening) stiffness, hysteresis, and dry-friction mechanism for energy dissi-

pation. Simple model for estimation of radial bearing stiffness forwards predictions comparing favorably to measurements. Active power donated high-speed (50 krpm) test rig to be revamped for foil bearing testing.
SPONSORS: TRC. Industrial partners: Meruit, Argonne National Laboratory.
Students: Dario Rubio (UGS, M.S.), Jeremy Williamson (UG).

- **Analysis of lift off speed and force coefficients for reversed rotation brush seals**
  OBJECTIVE: Advance computational models for prediction of the dynamic forced performance of shoed brush seals.
  STATUS: Analysis and software complete. Effect of dry-friction in bristle bed is paramount to generate enough damping enhancing rotordynamic stability of multiple-shoed brush seals. Simple leakage model and brush-seal stiffness model validated against laboratory measurements. Dynamic force measurements show dry-friction effects. The physical parameter characterization using nonlinear methods is in progress.
  SPONSOR: (ATS) ADVANCED TURBOMACHINERY SOLUTIONS (US NAVY SBIR II).
  Students: Heber Lemmon (M.S.), Adolfo Delgado (UGS, MS).

- **Upgrade of HYDRO codes for dynamic performance of cryogenic fluid film bearings**
  OBJECTIVE: Develop Graphical User Interfaces (GUI) for HYDROJET and HYDROTHRUST PC FORTRAN
  STATUS: Interface for radial bearing program **XLHYDROJET** completed. Licenses to Exxon-Mobil RC and Odegaard MS, Qualiseal, Inc., and MIT awarded. Interface for thrust bearing program in progress.
  SPONSORS: NASA MARSHALL SPACE FLIGHT CENTER

Not all is work! Dr. San Andrés found again love in music. He plays bass for Roca Azul, a Latin A&M faculty Rock & Blues Band. Roca Azul is currently completing its World Tour around the local bars in North Gate, across the university. The band members traveled last summer to Cuzco (Perú) and performed with other Latin musicians at a Rock Concert in Urubamba, the Incas Sacred Valley. In late July 2003, Roca Azul journeys to La Paz (Bolivia) to perform in the mystical ruins of Tiahuanaco.

That is all folks!

Luis San Andrés, Leader
Tribology Group
May 2003

Tribology Group

Team Members 2002/2003

Dr. Luis San Andrés, Leader

Name	Research project	Graduation date
Kishore Balantrapu	**Identification of support force coefficients in flexible rotor-bearing systems**	August 2003
Jason Kerth **Erick Jimenez** **Nicholas Rouge ***	**Dynamic Response of Turbocharger Rotors Supported on Floating Ring Journal Bearings**	June 2003 December 2004
Suzan Xhu[+] **Gautam Gupta**	**Experimental response of gas hybrid bearings for high speed oil-free turbomachinery**	May 2004
Dario Rubio[+] **Jeremy Williamson ***	**Gas Foil bearings**	December 2004
Adolfo Delgado[+]	**Analysis of Reverse Rotation Brush Seals**	December 2004
Daniel Braz *[+]	**Oil-Free Turbocharger**	
Clinton Adams * **Anthony Pruske ***	**Identification of Force Coefficients in Bearings with High Dynamic Loading**	

(*) undergraduate student, (+) minority student (female, Hispanic, etc)

Undergraduate student projects

	Grad date	Project
Nicholas Rouge	12/03	Effects of compressor housing clocking on turbocharger rotor-dynamics
Anthony Pruske	12/03	Identification of journal bearing force coefficients
Julene Agirrezabala	12/02	Effects of solid lubricants on gas bearing performance
Dario Rubio	08/02	Identification of foil bearing structural parameters
Alfonso Delgado	08/02	Identification of shoed-brush seal structural parameters

Tribology Group/Rotordynamics Laboratory

2003 RESEARCH PROGRESS REPORTS
A METHOD FOR IDENTIFICATION OF FORCE COEFFICIENTS IN FLEXIBLE ROTOR-BEARING SYSTEMS Luis San Andrés TRC-B&C-2-03
JOURNAL BEARING FORCE COEFFICIENTS UNDER HIGH DYNAMIC LOADING – EXPERIMENTAL RESULTS Luis San Andrés TRC-B&C-3-03
EXPERIMENTAL RESPONSE OF A ROTOR SUPPORTED ON FLEXURE PIVOT HYDROSTATIC PAD GAS BEARINGS Luis San Andrés and Suzan Zhu TRC-B&C-4-03
BUMP TYPE FOIL BEARING STRUCTURAL STIFFNESS: EXPERIMENTS AND PREDICTIONS Dario Rubio and Luis San Andrés TRC-B&C-5-03

2003 RESEARCH PROPOSALS
IDENTIFICATION OF FORCE COEFFICIENTS IN FLEXIBLE ROTOR-BEARING SYSTEMS (CONTINUATION)
EXPERIMENTAL FORCE COEFFICIENTS FOR A SEALED SQUEEZE FILM DAMPER (CONTINUATION)
GAS BEARINGS FOR OIL FREE TURBOMACHINERY (CONTINUATION)
IDENTIFICATION OF STIFFNESS AND DAMPING COEFFICIENTS IN FOIL GAS BEARINGS (CONTINUATION)

PROGRESS REPORTS – EXECUTIVE SUMMARIES

TRC-B&C-2-03: A METHOD FOR IDENTIFICATION OF FORCE COEFFICIENTS IN FLEXIBLE ROTOR-BEARING SYSTEMS

Field identification of bearing support parameters is important for adequate interpretation of rotating machinery performance and necessary to calibrate predictions from restrictive physical models. Field identification is also promising for condition monitoring and troubleshooting, and in the near future for self-adapting rotor-bearing systems.

A simple method for estimation of (bearing) support force coefficients in flexible rotor-bearing systems is detailed. The method requires of two independent tests with known mass imbalance distributions and the measurement of the rotor motion (amplitude and phase) at locations close to the supports. The procedure relies on the modeling of the rotor structure and finds the bearing transmitted forces as a function of observable quantities. Solving a simple set of algebraic equations identifies synchronous stiffness and damping force coefficients. Numerical simulations demonstrate perfect parameter identification for a model rotor-bearing system.

Imbalance response measurements conducted with a two-disk flexible rotor supported on two-lobe fluid film bearings allow validation of the identification method estimations. Predicted (linearized) bearing force coefficients agree reasonably well with the parameters derived from the test data. Note that the rotor motions at the support locations are of large magnitude, close to the fluid film bearing radial clearance. Thus, the estimated test coefficients do not correspond with conventional linearized force coefficients.

The method advanced does not add mathematical complexity nor requires of additional instrumentation than that already available in most high performance turbomachinery.

TRC-B&C-3-03: RESPONSE JOURNAL BEARING FORCE COEFFICIENTS UNDER HIGH DYNAMIC LOADING – EXPERIMENTAL RESULTS

Lightly damped rotor bearing systems experience large amplitudes of vibration when traversing critical speeds. Traditional fluid film bearing rotordynamic force coefficients, strictly valid for minute motions about an equilibrium position, may not provide reliable predictions for design or trouble shooting in rotordynamics analyses. Experiments assessing the dynamic forced response of a plain journal bearing undergoing large orbital motions due to single-frequency excitation forces were conducted in a test rig. The short test bearing of slenderness ratio L/D=0.25 has a nominal radial clearance of 0.127 mm (5 mils). Tests were conducted at three rotor speeds (900, 1800 and 2700 rpm), three feed pressures (1, 3 and 6 psig), and three excitation frequencies (15, 30 and 45 Hz). Baseline bearing motions due to shaft run-out are recorded and subtracted in the parameter identification procedure. The forces exerted on the bearing induce large orbital motions with peak amplitudes exceeding 50% of the nominal bearing clearance. Analytical direct damping and cross-coupled stiffness coefficients agree favorably with the experimental coefficients, thus demonstrating that linearized force coefficients do fairly well in predicting bearing motions of large amplitude. The bearing whirl frequency ratio approaches the typical 50% value at the highest speed tested. Excitation frequency has a marked influence of the test direct dynamic stiffness coefficients with added mass coefficients at least twice as large as predicted values.

PROGRESS REPORTS – EXECUTIVE SUMMARIES (CONTINUED)

TRC-B&C-4-03: EXPERIMENTAL RESPONSE OF A ROTOR SUPPORTED ON FLEXURE PIVOT HYDROSTATIC PAD GAS BEARINGS

Micro-turbomachinery demands gas bearings to ensure compactness, lightweight and extreme temperature operation. Gas bearings with large stiffness and damping, and preferably of low cost, will enable successful commercial applications. Presently, tests conducted on a small rotor supported on flexure pivot – hydrostatic pad gas bearings (FPTPBs) demonstrate stable rotordynamic responses up to 99,000 rpm (limit of drive motor). Experimental rotor responses show that feed pressure increases the bearings' direct stiffness and critical speed while the viscous damping ratio decreases. Predictions correlate favorably with experimentally identified synchronous direct stiffness, though test damping force coefficients are smaller. Tests without feed pressure show the rotor becomes unstable at ~ 81 krpm with a whirl frequency ratio of 20%. The instability caused the rotor to rub and burn its protective Teflon coating.

The dynamic performance of the FPTPBs is superior to that of simple hydrostatic three-lobed bearings (tested in 2002), which showed severe subsynchronous instabilities, and whose threshold speed increased with feed pressure.

FPTPBs are mechanically complex and more expensive than cylindrical plain bearings. However, their enhanced stability characteristics and predictable rotordynamic performance makes them desirable for the envisioned oil-free applications in high speed micro turbomachinery.

TRC-B&C-5-03: BUMP TYPE FOIL BEARING STRUCTURAL STIFFNESS: EXPERIMENTS AND PREDICTIONS

Foil gas bearings (FB) satisfy many of the requirements noted for novel oil-free turbomachinery. However, FB design remains largely empirical, in spite of successful commercial applications. Four bump-type foil bearings were acquired in 2002. The bearings, 1.50 in length and diameter, contain a single foil (0.004 in), Teflon coated, supported on 25 bumps, height and pitch equal to 0.015 in and 0.18 in, respectively. The nominal radial clearance is 1.4 mils for a 1.5 in journal. A simple test set up was assembled to measure the FB deflections resulting from static loads. The tests were conducted with three shafts, one of 1.5 in diameter; and the other two with +1 mil and –1 mil larger (smaller) diameters. The larger diameter shaft induces a degree of preload into the FB structure.

Static measurements show nonlinear FB deflections and varying with the orientation of the load relative to the foil spot weld. Loading and unloading tests evidence a hysteresis effect. The FB structural stiffness increases as the bumps-foil radial deflection increases (hardening effect). The estimated structural stiffnesses obtained from two bearings, identical in construction, also differ. The assembly preload results in notable stiffness changes, in particular for small radial loads.

A simple physical model assembles individual bump stiffnesses and renders predictions for the FB structural stiffness as a function of the bump geometry and material, dry-friction coefficient, load orientation, clearance and preload. The model predicts well the test data, including the hardening effect. The uncertainty in actual clearance (gap) upon assembly of a shaft into a FB affects most the predictions.

2003 Research Proposals to Turbomachinery Research Consortium

PROPOSAL SUMMARIES

IDENTIFICATION OF FORCE COEFFICIENTS IN FLEXIBLE ROTOR-BEARING SYSTEMS – (CONTINUATION)

Experimental identification of fluid film bearing parameters is critical for adequate interpretation of rotating machinery performance and necessary to validate or calibrate predictions from (often) restrictive computational fluid film bearing models. Parameter identification in the field is also promising for condition monitoring and trouble-shooting, and in the near future for self-adapting rotor/bearing control systems.

Further research is proposed to advance the on site procedures for experimental estimation of speed dependent and frequency dependent force coefficients of supports in flexible rotor-bearing systems. The planned tasks are:

a) To extend the imbalance response identification procedure by including other internal rotor support elements, seals for example.
b) To modify the flexible rotor rig and include a gas seal for parameter identification
c) To conduct measurements of rotor synchronous response to imbalances and identify force coefficients from the bearing supports and gas seal element.
d) Advance methods to identify nonlinear parameters (dry-friction, nonlinear stiffness) from complex supports (foil bearings, brush seals). Frequency domain methods will be investigated to characterize non-linear stiffness and damping coefficients.
e) The mechanical energy method will be explored to derive equivalent (linearized) damping coefficients representing the energy dissipated during a period of fundamental rotor motion.

The research continues to advance practical and reliable methods for identification of bearing support parameters in turbomachinery.

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

Rotating machinery operation at high speeds induces severe dynamic loading with large amplitude journal motions at the bearing supports. At these conditions, oil lubricated dampers with low levels of external pressurization are prone to air ingestion leading to an inhomogeneous lubricant film with large striations of entrapped gas. This pervasive phenomenon affects greatly the dynamic force capability and reduces the reliability of the rotor-bearing system.

The objective is to identify the damping and inertia force coefficients in an end sealed squeeze film damper. An existing test rig will be modified to accommodate an end fed-end sealed SFD, with a configuration replicating closely an industrial application. A new journal and bearing housing will be manufactured with provisions for an end seal ring with a wave spring and (optional) O-ring, a lubricant recirculation annulus and orifice discharge ports. The total cost of the modifications is ~ $ 12,000 with TRC covering 50%. The test rig will be revamped in the first year, with experiments being performed in the second year. With a fully operational, the major tasks will be:

a) Conduct static and dynamic tests under “dry conditions to determine the structure stiffness and test section natural frequencies. Develop identification technique and model to characterize end-seal friction (equivalent damping).
b) Measure pressure drop and leakage to determine the end seal coefficient as a function of pressure, lubricant temperature (viscosity), wave spring preload, journal centering, and orifice size.
c) Perform dynamic load tests (shakers) with lubricated SFD for increasing oil temperatures and feed pressures.
d) Develop test and DAQ procedures. Perform analysis of test data using frequency domain identification techniques to extract SFD force coefficients (damping and inertia). Forward estimated parameters as a function of excitation frequency and amplitude of whirl, lubricant flow rate, feed temperature and pressure, sealing conditions, etc.

The proposed research is of interest for applications such as squeeze film dampers in gas turbines, floating ring bearings in turbochargers, hydrodynamic bearings in compressors, etc.

PROPOSAL SUMMARIES (CONTINUED)

GAS BEARINGS FOR OIL FREE TURBOMACHINERY

(CONTINUATION)

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 ready application. The present investigation advances the analysis and experimental validation of simple gas bearing configurations 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 desired operating speeds.

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 in 2003/4 are:

a) Conduct experiments to measure the synchronous response and stability of the test rotor on Rayleigh step (Meruit type[1]) gas bearings. Stiffness and damping coefficients and stability margins will be determined from measured frequency domain transfer functions.
b) Assess effect of DLC[2] (solid lubricant) on rotor lift-off and touchdown speeds, and evaluate friction and wear on rotor and bearing surfaces.
c) Enhance predictive code and include effect of hydrostatic pressure on static and dynamic forced performance of externally pressurized gas bearings.

IDENTIFICATION OF STRUCTURAL STIFFNESS AND DAMPING IN FOIL BEARINGS

(CONTINUATION)

Recent deployment of successful micro power engines brings to focus 30 years of concerted developments in air bearing/oil-free turbomachinery. Most concepts employ gas foil bearings offering clear advantages over rolling element bearings: higher temperature and rotor speed operation, low maintenance and tolerance to debris and rotor misalignment. Although gains have been made in unit loading, the limitations in damping severely restrict application of gas foil bearings to supercritical flexible-rotor systems, essential for light, high-power density gas turbines. The lack of predictability has also been a key limiting factor since current analyses are unable to accurately predict rotor-bearing dynamic performance, resulting in extensive empirical developments for each application. The analytical difficulties are largely due to the lack of proper modeling and limited empirical evidence. Since the operating parameters are not well quantified, each bearing is a custom piece of hardware, with large variability even in seemingly identical units, and limited scalability.

Active Power donated a fully instrumented, high speed floating ring bearing test rig. The cost of the rig is ~ $100,000. The motor and rotor bearing system are installed within a one-inch steel containment cylinder. A DC motor drives a 2 inch diameter – 1.5 feet long shaft supported on two bearings to a top speed of 50 krpm.

The main research objective is to characterize quantitatively (gas) foil bearing rotordynamic performance, reliability and durability. The tasks to be performed are:

d) Revamp Active-Power test rig to house foil bearings and measure rotordynamic response of test rotor
e) Perform dynamic load tests to fully assess variations of equivalent damping coefficients versus frequency of excitation and amplitude of shaft motion.
f) Develop reliable methods for identification of stiffness and equivalent (viscous) damping force coefficients in foil gas bearings.

Turbomachinery users and manufacturers will benefit from a planned research effort to characterize foil bearings thus increasing their confidence on the deployment of gas foil bearings in their commercial products.

[1] DOE selected bearing type for a particular type of fuel cell – micro power engine.
[2] Agreement with Argonne National Laboratory to evaluate its Diamond Like Coating (DLC) -Near Frictionless Coating (NFC) on Meruit's Rayleigh step gas bearing.

Tribology Group - Funded Research **2002-2003**

GIFT

Honeywell Foundation	$25,000 TAMU 510319	Oil-Free Turbocharger Development	08/01/02

Principal Investigator	Sponsor Project #	Amount	Project	Dates (GS support)
L. San Andrés 32525/6865A//ME	Honeywell Turbocharging	$102,475	Computational Analysis of Floating Ring Journal Bearings and Experimental Validation in a Turbocharger Test Rig – Phase II	01/15/03-06/15/04 (1)
L. San Andrés 32513/1519 C3	TRC	$20,000	Experimental Response of a Hydrodynamic Bearing under High Dynamic Loading	06/01/02 - 05/31/03 (1)
L. San Andrés 32513/1519 SA7	TRC	$20,000	Identification of Force Coefficients in Flexible Rotor-Bearing Systems	06/01/02 - 05/31/03 (1)
L. San Andrés 32513/1519 B2	TRC	$20,000	Identification of Structural Stiffness and Damping in Foil Gas Bearings	06/01/02 - 05/31/03 (1)
L. San Andrés 32513/1519 B1	TRC	$20,000	Gas Bearings for Oil Free Turbomachinery	06/01/02 - 05/31/03 (1)

CONTINUING FROM 2001

Principal Investigator(s)	Sponsor Project #	Amount	Project	Dates (GS support)
L. San Andrés 32525/61570/ME	Honeywell Turbocharging	$129,000	Computational Analysis of Floating Ring Journal Bearings and Experimental Validation in a Turbocharger Test Rig	05/01/00-08/31/02 (1)
L. San Andrés	**NASA MSFC** 32525/66500/ME	$ 37,282	Software Upgrade for Cryogenic Fluid Film Bearings	12/01/01-07/31/03 (1)
L. San Andrés	**ATS** 32525/66260/ME	$ 79,580	Computational Analysis of Reverse Rotation Brush Seals	10/15/01-03/31/03 (1)

Support for equipment 2002/2003

Source	Amount	Purpose	Date
Turbomachinery Laboratory	$ 2,000	Cost sharing for upgrade of electrical connection in cells at Turbomachinery Laboratory ($6,000 total)	10/02
Active Power	$ ~ 100,000	Donation – Floating Ring Bearing Test Rig (50 krpm)	03/03

Tribology Group Publications 2002/2003

2003

Holt, C., L. San Andrés, S. Sahay, P. Tang, G. LaRue, and K. Gjika, 2003, "Test Response of a Turbocharger Supported on Floating Ring Bearings – Part I: Assessment of Subsynchronous Motions," to be presented at *Symposium* on Nonlinear Dynamics and Control for Rotor Systems, 19th Biennial Conference on Mechanical Vibration and Noise," Chicago (IL), September, ASME Paper DETC 2003/VIB-48418

Holt, C., L. San Andrés, S. Sahay, P. Tang, G. LaRue, and K. Gjika, 2003, "Test Response of a Turbocharger Supported on Floating Ring Bearings – Part II: Comparisons to Nonlinear Rotordynamic Predictions," to be presented at *Symposium* on Nonlinear Dynamics and Control for Rotor Systems, 19th Biennial Conference on Mechanical Vibration and Noise," Chicago (IL), September, ASME Paper DETC 2003/VIB-48419

Wilde, D.A., L. San Andrés, and J. Aguirrezabala, 2003, "Expermental Lift Off Characteristics and the Effect of a Low Friction Coating on the Startup Response of Simple Gas Hybrid Bearings for Oil-Free Turbomachinery," submitted for review at ASME Journal of Tribology and presentation at 2003 ASME/STLE International Tribology Conference.

De Santiago, O., and L. San Andrés, 2003, "Forced response of a Squeeze Film Damper and Identification of Force Coefficients from Large Orbital Motions," submitted for review at ASME Journal of Tribology and presentation at 2003 ASME/STLE International Tribology Conference.

Wilde, D.A., and San Andrés, L., 2003, "Comparison of Rotordynamic Analysis Predictions with the Test Response of Simple Gas Hybrid Bearings for Oil Free Turbomachinery," ASME Paper No. GT2003-38859, ASME Turbo-Expo 2003 Conference, Atlanta, GA, June (accepted for publication at ASME Journal of Gas Turbines and Power).

Wilde, D.A., and San Andrés, L., 2003, "Experimental Response of Simple Gas Hybrid Bearings for Oil-Free Turbomachinery," ASME Paper GT 2003-38833, ASME Turbo-Expo 2003 Conference, Atlanta, GA, June (accepted for publication at ASME Journal of Gas Turbines and Power).

De Santiago, O., and L., San Andrés, 2003, "Field Methods For Identification of Bearing Support Parameters. Part I-Identification from Transient Rotor Dynamic Response Due to Impacts", ASME Paper GT 2003-38583, ASME Turbo-Expo 2003 Conference, Atlanta, GA, June (accepted for publication at ASME Journal of Gas Turbines and Power)

De Santiago, O., and L., San Andrés, 2003, "Field Methods For Identification of Bearing Support Parameters. Part I-Identification from Rotordynamic Response due to Imbalances", ASME Paper GT 2003-38585, ASME Turbo-Expo 2003 Conference, Atlanta, GA, June (accepted for publication at ASME Journal of Gas Turbines and Power).

San Andrés, L., and S. Diaz, 2003, "Flow Visualization and Forces from a Squeeze Film Damper with Natural Air Entrainment," ASME Journal of Tribology, Vol. 125, 2, pp. 325-333 (ASME Paper 2002-TRIB-81).

Soulas, T., and L. San Andrés, 2003, "Performance of Damaged Hydrostatic Bearings: Predictions vs. Experiments," ASME Journal of Tribology, Vol. 125, 2, pp. 451-457 (ASME Paper 2002-TRIB-17).

2002

San Andrés, L., and T. Soulas, 2002, "A Bulk Flow Model for Off-Centered Honeycomb Gas Seals," accepted for publication at ASME Journal of Gas Turbines and Power (ASME Paper 2002-GT-30286).

San Andrés, L., T. Soulas, and F. Challier, 2002, "A Bulk Flow Model of Angled Injection Lomakin Bearing," accepted for publication at ASME Journal of Gas Turbines and Power (ASME Paper 2002-GT-30287).

San Andrés, L., and O. de Santiago, 2002, "Dynamic Response of Squeeze Film Dampers Operating with Bubbly Mixtures," accepted for publication at ASME Journal of Gas Turbines and Power (ASME Paper 2002-GT-30317).

San Andrés, L., 2002, "Force and Moment Coefficients for Misaligned Hybrid Thrust Bearings," ASME Journal of Tribology, Vol. 124 (1), pp. 212-219 (ASME Paper 2001-TRIB-119).

Diaz, S., and L. San Andrés, 2002, "Pressure Measurements and Flow Visualization in a Squeeze Film Damper Operating with a Bubbly Mixture," ASME Journal of Tribology, Vol. 124, 4, pp. 346-350 (ASME Paper 2001-TRIB-118).

Technical Reports to sponsors and TEES Turbomachinery Research Consortium

San Andrés, L., Analysis of Performance and Rotordynamic Force Coefficients of Brush Seals with Reverse Rotation Ability," Final Report to Advanced Turbomachinery Solutions (ATS), March 2003.

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