Mechanical Engineering Department
Texas A&M University

2001/2002
Research Progress Report
Tribology Group

Year XI

22th Annual
Turbomachinery Research Consortium Meeting

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Professor

http://www.mengr.tamu.edu:70/mechanics-systems/lsanandres/rotorlab.htm

Tribology Group

Rotordynamics Laboratory

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FOREWORD

Milestones in our research program in 2001/02 follow. The current status on the various research efforts, the students involved in them and the sources of funding are highlighted. 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.

? **Effect of air entrainment on the dynamic forced performance of squeeze film dampers**

OBJECTIVE: To assess quantitatively the severity of air ingestion on the forced response of squeeze film dampers and hydrodynamic journal bearings.
STATUS: Project completed. CD with digital videos correlating flow fields to dynamic film pressures and journal motions available to TRC members. Measurements of journal motions to periodic forced excitations in a vertical test rig completed for TRC. The identification of parameters show test damping coefficients more linear than theoretical formula predict, and experimental inertia coefficients consistently larger. The results evidence once again the peculiar phenomena due to sustained air ingestion into the fluid film.
SPONSORS: NSF and TRC.

? **Identification of bearing support parameters using on site techniques on a rotor supported on series tilting pad bearings and integral squeeze film dampers.**

OBJECTIVE: Develop procedures for practical on site reliable parameter identification techniques
STATUS: Imbalance response and impact load measurements conducted on TRC-NSF rig. Identified bearing parameters correlate well with predictions and validate the identification methods over a range of excitation frequencies and operating rotor speeds. Further work needed to fine-tune the procedures and their applicability to flexible rotor-bearing systems.
SPONSOR: TRC.

? **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 GT 37 turbocharger test rig provided amazing test data to 100 krpm with successful measurement of floating ring speeds using fiber optics sensors. PC FORTRAN FE model and EXCEL® interface worksheets predict FRB static and dynamic force performance characteristics including thermal phenomena and lubricant shear thinning effects. Aerodynamically induced loads arising from compressor operation off-BEP are under scrutiny to assess their effect on rotor-FRB stability. Interface of predictive tools with XLTRC^2 nonlinear rotordynamics program delayed indefinitely: Don't ever trust anyone who promises to deliver today something due yesterday!
SPONSOR: Honeywell Turbocharging Systems, ends August 2002.

? **Feasibility Study of Gas Bearings for Oil-Free Automotive Turbochargers**

OBJECTIVE: Assess state of the art and rank bearing technologies for ready deployment and commercialization to oil-free automotive turbochargers.
STATUS: Completed comprehensive study reviewing preformed thermoplastic bushings, ceramic ball bearings, gas rigid/tilting pad/foil bearings, magnetic bearings and solid lubricants (coatings). Inexpensive Diamond-Like

Coatings (low friction/high hardness/high temperatures) are already revolutionizing the tribology of non-lubricated contacts in the near future. We urge TRC members to look into low friction hard material coatings for many advanced applications in the near future.
SPONSOR: Garrett Boosting Systems, ended October 2001.

? **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 fully operational. Coast down imbalance responses from 90 krpm recorded for externally pressurized three lobe bearings, pressure dam bearings and Graphalloy tilting pad bearings. Effects of EMRALON© coating on early rotor lift off speed and reduction of friction and wear during start-up and shut-down transients fully assessed. Gas foil bearings and KMC flexure pivot bearings acquired for independent evaluation at TAMU. Many interested parties and promises for engineering consulting!
SPONSORS: Texas Energy Resources Program, TRC.

? **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 in progress. Measurements on a brush seal show severe stick-slip (dry friction) nonlinearities. The reverse rotation brush seal is unique due to its bi-directional operation and non-contact operation preventing wear!
SPONSOR: (ATS) ADVANCED TURBOMACHINERY SOLUTIONS (US NAVY SBIR II).

? **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: Original codes developed for NASA LRC (1996) and NASA MSFC (2000) are being upgraded to take advantage of fast computing algorithms and processors with GUIs for easy access and seamless interface to rotordynamic analysis programs. Further integration with SRS comprehensive cryogenic turbo pump analysis software proposed. Modernizing the predictive tools became an urgent need; searching for qualified students able to program is desperate!
SPONSORS: NASA MARSHALL SPACE FLIGHT CENTER

? **Bulk flow analysis of Lomakin Bearings/Seals for Cryogenic Turbomachinery**.
OBJECTIVE: To develop a computational model for prediction of rotordynamic force coefficients in Lomakin liquid seals with anti-swirl injection.
STATUS: Analysis completed and PC FORTRAN code released to SNECMA. Enhanced program for prediction of rotordynamic force and moment coefficients in off-centered gas honeycomb also completed. TRC members may license programs.
SPONSORS: SNECMA (SEP) FRANCE supporting a graduate student.

The curriculum in our undergraduate Mechanical Engineering program has changed dramatically. Our faculty has started to deliver comprehensive education that not only provides engineering content but also prepares the young engineers to be team players, long life learners, and includes instructional material to develop the students writing and oral presentation skills. The success of the program will be assessed in 2004 when ABET will officially evaluate our performance satisfying the Engineering Criteria 2000. The challenge is immense! We have had to give away important curriculum content in order to deliver the educational material in less credit hours and with more non-engineering content. Currently, few students learn and practice the methods for computational programming, and even less have enough mathematical skills that will enable them to confront and resolve efficiently complex engineering issues.

We acknowledge the support and active participation of the following engineers and team works in industry:

Sunil Sahay, Gerry La Rue, Peter Tang and Kostandin Gjika at Honeywell, Gerry LaRue and Russell Stoddart at Garrett, John Justak at ATS, Tim Jett at NASA MSFC, Jim Moore at SRS, Daniel Lubell at Capstone MicroTurbines, David Ransom at TurboCare. Many of the engineers above have graciously assisted in the education of the graduate and undergraduate student workers.

Thanks to Capstone Micro Turbines (Mr. Daniel Lubell) for the donation of our first foil air bearing rig demonstrator and to Dr. Ming Chen at Foster-Miller Technologies who made possible the acquisition (below cost) of four bump-foil bearings. We acknowledge Dr. Dara Childs for cost sharing funds to acquire the foil bearings.

In the course of our experimental work we have also developed superb virtual instruments (data acquisition) for dedicated rotordynamic testing and extremely powerful MATHCAD worksheets for comprehensive analysis of test data and identification of bearing/seal force coefficients.

The students' outstanding efforts bring forward the quality of our research. I thank them for their hard work and dedication. The students graduating this past year have been: Thomas Soulas (M.S., 12/01) currently at Dresser Rand, Deborah Wilde (M.S. 05/02) soon to join Honeywell, and Oscar de Santiago (Ph.D., 05/02) who will also work for Dresser. Best wishes in their professional engineering careers.

Luis San Andrés, Leader
Tribology Group
May 2002

Tribology Group

Team Members 2001/2002

Dr. Luis San Andrés, Leader

Name	Research project	Graduation date
Oscar De Santiago	**Identification of bearing supports' force coefficients from rotor responses due to imbalances and impact loads**	May 2002
Jason Kerth **Chris Holt**	**Dynamic Response of Turbocharger Rotors Supported on Floating Ring Journal Bearings**	December 2002 December 2003
Deborah Wilde	**Experimental response of gas hybrid bearings for high speed oil-free turbomachinery**	May 2002
Thomas Soulas SNECMA-SEP (France)	**Bulk-Flow Analysis of Lomakin Bearing for Cryogenic Applications**	December 2002
Heber Lemmon	**Analysis of Reverse Rotation Brush Seals**	May 2003
Jason Preuss	**Identification of Force Coefficients in SFDs with High Dynamic Loading**	

Undergraduate student workers

	Grad date	Project
Albert Atkins	12/01	Measurements and characterization of turbocharger response
Fernando Romero	12/01	Identification of bearing parameters in vertical bearing rig
Chris Roth Nicholas Rouge	12/01 12/03	Assistance in rig preparation and experiments on TC rig
Brian Doud	06/02	Assistance in rig preparation and experiments on NSF-SFD rig
Jack Charles	12/02	PC HYDROJET software development and SFD flow videos
Julene Agirrezabala	12/02	Effects of solid lubricants on gas bearing performance
Dario Rubio	12/02	Identification of foil bearing structural parameters
Alfonso Delgado	12/02	Identification of shoed-brush seal structural parameters

Dr. Sergio Diaz from Universidad Simon Bolivar (Venezuela) spent part of the Summer 2001 at TAMU. He was hired to develop LABVIEW© DAQ programs for the Laboratory.

Tribology Group/Rotordynamics Laboratory

2002 RESEARCH PROGRESS REPORTS
IDENTIFICATION OF BEARING SUPPORTS' FORCE COEFFICIENTS FROM ROTOR RESPONSES DUE TO IMBALANCES AND IMPACT LOADS Oscar de Santiago TRC-RD-1-02
RESPONSE OF A SQUEEZE FILM DAMPER UNDER HIGH DYNAMIC LOADING AND IDENTIFICATION OF DAMPING AND INERTIA COEFFICIENTS Luis San Andrés TRC-SFD-1-02
EXPERIMENTAL RESPONSE OF GAS HYBRID BEARINGS FOR HIGH SPEED OIL-FREE TURBO-MACHINERY Deborah Wilde TRC-B&C-2-02

2002 RESEARCH PROPOSALS
IDENTIFICATION OF FORCE COEFFICIENTS IN FLEXIBLE ROTOR-BEARING SYSTEMS (CONTINUATION)
EXPERIMENTAL RESPONSE OF A HYDRODYNAMIC BEARING UNDER HIGH DYNAMIC LOADING (CONTINUATION)
GAS BEARINGS FOR OIL FREE TURBOMACHINERY (CONTINUATION)
IDENTIFICATION OF STRUCTURAL STIFFNESS AND DAMPING IN FOIL GAS BEARINGS (NEW)

2002 TURBOMACHINERY RESEARCH CONSORTIUM

PROGRESS REPORTS – EXECUTIVE SUMMARIES

TRC-RD-1-02: IDENTIFICATION OF BEARING SUPPORTS' FORCE COEFFICIENTS FROM ROTOR RESPONSES DUE TO IMBALANCES AND IMPACT LOADS

Experimental identification of fluid film bearing parameters is critical for adequate interpretation of rotating machinery performance and necessary to validate or calibrate predictions from restrictive computational fluid film bearing models. Parameter identification in the field is also promising for condition monitoring and troubleshooting, and in the near future for self-adapting rotor-bearing control systems. Two procedures for bearing supports parameter identification with potential for in-situ implementation follow.

The analytical bases for the identification of bearing support coefficients derived from measurements of rotor responses to impact loads and due to calibrated imbalances in characteristic planes are thoroughly discussed. Subsequent implementation of the procedures to measurements performed in a (nearly) rigid massive rotor traversing two critical speeds forward force coefficients for a novel bearing support comprising a tilting pad bearing (*TPJB*) in series with an integral squeeze film damper (*SFD).* Compared to conventional bearing configurations, the novel support has the advantage of compactness, integral construction and lightweight; and most importantly, it offers increased rotordynamic stability, control of critical positioning, and reduced force transmissibility.

At a constant rotor speed, the first method requires impacts loads exerted along two lateral planes for identification of frequency-dependent force coefficients. Simulation numerical examples show the method is reliable with a reduced sensitivity to noise as the number of impacts increases (frequency averaging). In the experiments, an ad-hoc fixture delivers impacts to the rotor middle disk at speeds of 2,000 and 4,000 rpm, just below and above the system first critical speed (~3,000 rpm). The experimentally identified force coefficients are in close agreement with predicted coefficients for the series support *TPJB-SFD*. In particular, damping coefficients are best identified around the system first natural frequency (~ 52 Hz). Bearing stiffness are correctly identified in the low frequency range (below 30 Hz), but show a marked reduction at higher frequencies apparently due to inertial effects not accounted for in the model (test rig base resonance).

Measurements of rotor response to calibrated imbalances allow identification of speed-dependent force coefficients. The procedure requires a minimum of two different imbalance distributions for identification of force coefficients from the two bearing supports. The rotor responses show minimal cross-coupling effects, as also predicted by the computational analysis. Presently, the identification procedure disregards cross-coupled force coefficients thereby reducing the effect of false cross-correlations that cause ill conditioning of the identification matrix and pollute the end results. The procedure renders satisfactory force coefficients in the speed range between 1,500 and 3,500 rpm, enclosing the first critical speed. The identified direct force coefficients are in accordance with those derived from the impact load excitations.

The second method identifying bearing support parameters from imbalance response measurements is simpler since it does not rely on direct application (and measurement) of external forces or transmitted bearing reaction forces. However, its adequate implementation requires of accurate measurement of phase angles, which are difficult to assess if the amplitude of rotor response is not large enough (instrumentation and software constraints).

TRC-B&C-2-02: EXPERIMENTAL RESPONSE OF GAS HYBRID BEARINGS FOR HIGH SPEED OIL-FREE TURBOMACHINERY

Gas film bearings offer unique advantages enabling successful deployment of high-speed micro-turbomachinery. Current applications encompass micro power generators, air cycle machines and turbo expanders. Mechanically complex gas foil bearings are in use; however, their excessive cost and lack of calibrated predictive tools deter their application to mass-produced oil-free turbochargers, for example. The present investigation advances the analysis and experimental validation of 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 the operating speed.

Comprehensive experiments and analysis are conducted on a small rotor supported on three lobed hybrid (hydrostatic/hydrodynamic) rigid gas bearings. The rigid bearings comprise preloaded 120? lobes with minute feedholes for external pressurization; bleed off from a turbocharger compressor outlet, for example. The bearing nominal clearance and dimensionless preload are 66 microns and 0.33, respectively. The test rotor, weighing 827 grams, integrates a DC motor and can achieve speeds as large as 100,000 rpm. Without rotor spinning, feed pressure lifts the test rotor at 1.36 bar (5 psig). For various imbalance conditions, coasts down tests from 60,000 rpm characterize the rotor response on its bearings. As the supply pressure rises, the rotor response shows an increase in critical speed and a noticeable reduction in damping ratio. Threshold speeds of instability also increase with increasing supply pressures, and whirl frequency ratios range from nearly 50% of rotor speed for a purely hydrodynamic condition to 25 % for a pressure supply five times ambient conditions. A rotor/gas bearing dynamics analysis forwards natural frequencies in agreement with measurements, and sub synchronous instability whirl frequency ratios around 50% of rotor speed.

Similar imbalance response measurements are conducted with the test rotor supported on pressurized pressure dam bearings and on HyPad? tilting pad bearings. Feed orifice repositioning into the film lands eliminates severe pneumatic hammer instability initially exhibited by the pressure dam bearings. The rotor supported on the pressure dam bearings shows adequate damping and a much lower threshold speed of instability than the rotor supported on the three-lobe bearings. The HyPad? bearings show good damping coefficients without rotordynamic instability for rotor speeds as large as 90,000 rpm. At high speeds, feed pressure can be removed to the HyPad? bearings since the rotor rides safely on the hydrodynamic gas film.

Experiments to determine breakaway friction and rotor lift off speed are conducted on a coated and uncoated rotor starting from rest. The coating is a commercial (PTFE) solid lubricant applied at room temperature. The transient response measurements vividly reveal rotor lift off and reduced friction with the coated rotor.

TRC-SFD-1-02: RESPONSE OF A SQUEEZE FILM DAMPER UNDER HIGH DYNAMIC LOADING AND IDENTIFICATION OF DAMPING AND INERTIA COEFFICIENTS

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. At these conditions, oil lubricated dampers and journal bearings 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 of the support fluid film bearings and reduces the reliability of the rotor-bearing system.

Forced response experiments on a test squeeze film damper for various dynamic load conditions are reported. Shakers exert single frequency loads and induce circular orbits and elliptical orbits of increasing. Measurements of the applied loads, bearing displacements and accelerations permit identification of damping and inertia force coefficients for operation at three whirl frequencies (40, 50 and 60 Hz) and increasing lubricant temperatures. Measurements of film pressures reveal an early onset of air ingestion.

Identified damping force coefficients agree well with predictions based on a well-known bearing model if an effective length is used. This length ranges from 82% to 78% of the actual length as the whirl excitation frequency increases. Justifications for the reduced length or effective viscosity follow from the small through flow rate, not large enough to offset the dynamic volume changes. The measurements and analysis thus show the pervasiveness of air entrainment, whose effect increases with the amplitude and frequency of the dynamic journal motions. Identified inertia coefficients are at least two times larger than predictions.

Further experiments are planned to assess the effect of air ingestion in dynamically loaded hydrodynamic bearings, to identify rotordynamic force coefficients, and to advance predictive (semi-empirical) formulae validating the measurements.

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 troubleshooting, and in the near future for self-adapting rotor/bearing control systems.

The analytical bases for the identification of bearing coefficients derived from measurements of rotor responses to impact loads and due to calibrated imbalances were advanced in 2001. Subsequent implementation of the procedures to measurements performed on a rigid rotor traversing two critical speeds forward force coefficients for a complex bearing support comprising a tilting pad bearing in series with a squeeze film damper. The results of the identification are excellent for tests conducted with impact loads; and less impressive for tests with calibrated imbalances. Rotor flexibility must be accounted for in actual applications though. Incidentally, reliable measurements of vibration phase angles are needed for accurate parameter estimation from rotor imbalance responses.

Further research will advance the on site procedures for experimental estimation of speed dependent and frequency dependent force coefficients of rigid and flexible rotors supported on gas- and oil-lubricated fluid film bearing, respectively. The work will extend the imbalance response identification procedure to include shaft and bearing support flexibilities. Experiments on a flexible rotor supported on two lobe oil-film bearings will include passage through the first bending mode. Enhancements on data acquisition for reliable phase angle measurement will be implemented, with algorithms for real-time estimation of transfer functions in a test rotor supported on (hybrid) tilting pad gas bearings. Bearing loads and rotor displacements are measured in the current test rig, and thus frequency dependent force coefficients at fixed rotor speed could be readily estimated. Comparisons of estimated force coefficients to predictions would validate and calibrate computational software for hybrid gas bearing analysis.

EXPERIMENTAL RESPONSE OF A HYDRODYNAMIC BEARING UNDER HIGH DYNAMIC LOADING (CONTINUATION)

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. At these conditions, oil lubricated dampers and journal bearings 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 of the support fluid film bearings and reduces the reliability of the rotor-bearing system.

Forced response experiments on a test squeeze film damper for various dynamic load conditions were performed in 2001/02. Measurements of film pressures reveal an early onset of air ingestion. Identified damping force coefficients agree well with predictions if an effective bearing length is used. This length ranges from 82% to 78% of the actual length as the whirl excitation frequency increases. The measurements thus show the pervasiveness of air entrainment, whose effect increases with the amplitude and frequency of the dynamic journal motions. Air entrainment models developed in past years allow quick calibration for ready prediction of the measured response, with good results for small amplitude motions.

Further experiments are planned to assess the effect of air ingestion in dynamically loaded hydrodynamic bearings, to identify rotordynamic force coefficients, and to advance predictive (semi-empirical) formulae validating the measurements. The ultimate goal is to advance guidelines to avoid bearing performance degradation under such stringent operating conditions. The experiments will concentrate on dynamic loading for a range of frequencies to 100 Hz and a top rotor speed of 3,600 rpm. The measurements of shaker loads, bearing dynamic displacements and accelerations will allow estimation of the system transfer functions and the identification of four bearing mechanical impedances using a frequency domain method.

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.

Comprehensive experiments and analysis have been conducted on a small rotor supported on three-lobed, pressure dam, and HYPAD® tilting pads hybrid gas bearings. The three-lobed bearings show the largest damping ratio albeit becoming unstable at threshold rotor speeds proportional to the feed pressure. Tilting pad bearings are free of hydrodynamic instability yet with little damping at critical speeds. If improperly designed, pressure dam bearings show pneumatic hammer instability.

The technology of (inexpensive) gas film bearings will be advanced by conducting experiments to measure the synchronous response and stability of the test rotor on flexure pivot hybrid bearings and Rayleigh step gas bearings (both already manufactured). Stiffness and damping coefficients and stability margins will be determined. The effects of a Diamond Like Coating on rotor lift-off and touchdown speeds, star-up and shut-down friction and wear will also be investigated.

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.

The Turbomachinery Laboratory purchased four bump-foil bearings from Foster Miller Technologies with no restrictions on test procedures and results dissemination. Capstone Micro Turbines also donated an air-bearing demonstrator with a top steep of 25 krpm. Turbomachinery users and manufacturers will benefit from a planned effort to characterize foil bearings.

The main research objective is to characterize quantitatively (gas) foil bearing rotordynamic performance, reliability and durability. Measurements of structural load and stiffness of the foil bearings for various angular orientations and at least two interference shaft/bearing diameters will be performed with a (stationary) test rotor. Dynamic load tests will follow to fully assess variations of equivalent damping coefficients versus frequency of excitation and amplitude of shaft motion. The Capstone air-demo rig will be revamped to include a bearing housing for ready measurement of gas foil bearing displacements along with a procedure for identification of stiffness and equivalent damping force coefficients.

Tribology Group - Funded Research **2001-2003**

Principal Investigator(s)	Sponsor Project #	Amount	Project	Dates (GS support)
L. San Andrés	**NASA MSFC** 32525/66500/ME	$ 37,282	Software Upgrade for Cryogenic Fluid Film Bearings	12/01/01-12/31/02 (1)
L. San Andrés	**ATS** 32525/66260/ME	$ 79,580	Computational Analysis of Reverse Rotation Brush Seals	10/15/01-03/31/03 (1)
L. San Andrés J. M. Vance,	Garrett Boosting Systems 32525/62780/ME	$ 44,000	Feasibility Study on Alternative Oil-Less Bearing Technologies for Automotive Turbochargers	05/01/01-10/31/01 (2)
L. San Andrés 32513/1519 C3	TRC	$20,000	Identification of Equivalent Force Coefficients for a Rotor Supported on Series Tilting Pad Bearings and Integral Dampers	06/01/01 - 05/31/02 (1)
L. San Andrés 32513/1519 SA7	TRC	$20,000	Experimental Response of a Hydrodynamic Bearing under High Dynamic Loading	06/01/01 - 05/31/02 (1)
L. San Andrés 32513/1519 B1	TRC	$20,000	Gas Bearings for Oil Free Turbomachinery	09/01/01 - 08/31/02 (1)
CONTINUING FROM 2001				
J. M. Vance, L. San Andrés 32525/62780/ME	GE Transportation Systems	$173,514	Turbocharger Rotordynamics	11/01/00-08/15/01
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 32525/58130/ME	NSF	$172,079	Dynamic Forced Performance of Fluid Film Bearings Operating with Air Entrainment	05/01/99-04/30/02 (2)
L. San Andrés TAMU 155290	Energy Resources Program	$25,000	Gas Bearings for Oil Free Gas Turbines	06/01/00 - 05/31/02 (1)

Support for equipment 2001/2002

Source	Amount	Purpose	Date
Turbomachinery Laboratory	$ 3,000	Cost sharing for acquisition of four foil bearings – Total $5,000	11/01
Capstone Micro-Turbines	$ ~ 12,000	Donation – Gas Foil Bearing Tester (25 krpm)	03/02

Tribology Group Publications 2001/2002

2002

San Andrés, L., and S. Diaz, "Flow Visualization and Forces from a Squeeze Film Damper with Natural Air entrainment," accepted for presentation at ASME/STLE International Tribology Conference, Cancún, MX, October 2002.

Soulas, T., and L. San Andrés, "Performance of Damaged Hydrostatic Bearings: Predictions vs. Experiments," accepted for presentation at ASME/STLE International Tribology Conference, Cancún, MX, October 2002.

San Andrés, L., and O. de Santiago, "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., and T. Soulas, "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, "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 D. Wilde, "Finite Element Analysis of Gas Bearings for Oil-Free Turbomachinery," Revue Européenne des Eléments Finis, Vol. 10 (6/7), pp. 769-790, 2001

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

Diaz, S., and L. San Andrés, "Pressure Measurements and Flow Visualization in a Squeeze Film Damper Operating with a Bubbly Mixture," ASME Journal of Tribology, Vol. 124 (2), pp. 346-350, 2002 (ASME Paper 2001-TRIB-118).

2001

De Santiago, O., and L. San Andrés, "Imbalance Response of a Rotor Supported on Flexure Pivot Tilting Pad Journal Bearings in Series with Integral Squeeze Film Dampers," accepted for publication at ASME Journal of Gas Turbines and Power (ASME Paper 2001-GT-257).

San Andrés, L., "A Hybrid Bearing with Improved Rotordynamic Stability," Paper 2006, 1st International Conference in Rotordynamics of Machinery (ISCORMA1), Lake Tahoe, NV, August 2001. (CD only).

Naranjo, J., C. Holt, and L. San Andrés, "Dynamic Response of a Rotor Supported in a Floating Ring Bearing," Paper 2005, International Conference in Rotordynamics of Machinery (ISCORMA1), Lake Tahoe, NV, August 2001. (CD only).

San Andrés, L., S. Diaz, and L. Rodriguez, "Sine Sweep Load Versus Impact Excitations and their Influence on the Damping Coefficients of a Bubbly Oil Squeeze Film Damper," Tribology Transactions, Vol. 44, 4, pp. 692-698, 2001.

Diaz, S. and L. San Andrés, L., A Model for Squeeze Film Dampers Operating with Air Entrainment and Validation with Experiments," ASME Journal of Tribology, Vol. 123, 1, pp. 125-133, 2001.

Diaz, S., and L. San Andrés, "Air Entrainment Versus Lubricant Vaporization in Squeeze Film Dampers: An Experimental Assessment of their Fundamental Differences," ASME Journal of Gas Turbines and Power, Vol. 123 (4), pp. 871-877, 2001.

<u>Technical Reports to sponsors and TEES Turbomachinery Research Consortium</u>

San Andrés, L., and J.M. Vance, "Feasibility Study on Alternative Oil-Less Bearing Technologies for Automotive Turbochargers," Final Report to Garrett Boosting Systems, October 2001.

San Andrés, L., "Measurements of Vibration and Instability on T2 Turbocharger," Progress Report to Honeywell Turbocharging Systems, August 2001.

San Andrés, L., "Dynamic Forced Performance of Fluid Film Bearings Operating with Air Entrainment," Annual Progress Report to NSF, May 2001.

San Andrés, L., Editor, "Research on Fluid Film Bearings, Tribology Group," Year X, 2000/2001, May 2001.

San Andrés, L., "Parameter Identification of Series Bearing Supports from Imbalance Response and Impact Excitations", TRC-RD-1-01.

San Andrés, L., "Flow Visualization and Forces from a Squeeze Film Damper Operating with Natural Air Entrainment", TRC-SFD-1-01.

Technical Reports to sponsors and TEES Turbomachinery Research Consortium

San Andrés, L., and J.M. Vance, "Feasibility Study on Alternative Oil-Less Bearing Technologies for Automotive Turbochargers," Final Report to Garrett Boosting Systems, October 2001.

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San Andrés, L., "Dynamic Forced Performance of Fluid Film Bearings Operating with Air Entrainment," Annual Progress Report to NSF, May 2001.

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San Andrés, L., "Parameter Identification of Series Bearing Supports from Imbalance Response and Impact Excitations", TRC-RD-1-01.

San Andrés, L., "Flow Visualization and Forces from a Squeeze Film Damper Operating with Natural Air Entrainment", TRC-SFD-1-01.