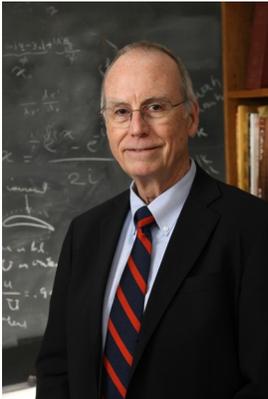


# ROTATING MACHINERY & CONTROLS LABORATORY

## ROMAC NEWSLETTER

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### To ROMAC Industrial Members,



Houston Wood  
Professor  
Mechanical & Aerospace Eng.  
Director of ROMAC

This fall semester we welcomed new students, second time around students and a new staff member. We also are happy to host many visiting scholars who have joined the ROMAC labs for appointments of several months to a year. This ROMAC team is looking forward to a future full of collegiality, insightful and productive research and fun along the way.

Some of you have had the opportunity to meet or speak with Lori Mohr Pedersen recently. Lori joined the team in late May, assisting with the final details and execution of the 2014 Annual Meeting. Lori's role with ROMAC is everything that is administrative, operational or planning related. Recently she has been updating the website which will continue to grow as an inclusive resource for ROMAC members and others interested in learning more about us. Please contact Lori Mohr Pedersen, ROMAC Office Assistant, for any ROMAC inquiry, need or concern.

## 2014 - New ROMAC Members

Our research efforts continue to expand to better serve our ROMAC member companies. The ROMAC industrial membership continues to grow rapidly. We are pleased to welcome Mitsubishi Heavy Industry as the newest member of the ROMAC Consortium. In 2014, the ROMAC Consortium has added six new members in total. These companies are listed below in alphabetical order:

- \* Brazilian Navy, Brazil
- \* BRG Machinery Consulting, LLC, USA
- \* Grant County PUD, USA
- \* Mitsubishi Heavy Industry, Japan
- \* Rodyn Vibration Analysis, Inc., USA
- \* Shanghai Electric Group, China

## ROMAC Graduate Students

There are quite a few ROMAC students who graduated or plan to graduate this year. In May 2014 Michael Branagan and Neal Morgan both finished their M.S, Mechanical & Aerospace and are now Ph.D. students with a May 2016 expected



### Fall 2014 Issue

Nov. 5, 2014

#### Special points of Interest:

- *New ROMAC Member Companies*
- *New Graduate Students*
- *2014 Annual Meeting Summary*
- *ROMAC Reports in 2014*
- *Results of Questionnaire*

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#### Inside this issue:

*Rotating Seal Test Rig*

*Stability Test Rig*

*Fluid Film Bearing Test Rig*

*Seals and Experimental Design*

*Brush Seal Modeling*

*Emulation of Energy Storage Flywheels*

*Fractional Order Control of AMBs*

## ROMAC Graduate Students (cont.)

graduation. Several students will graduate in December: Saeid Dousti, Ali Gerami, Brian Weaver and Zack Whitlow. Brian Weaver will continue to perform research in support of ROMAC as a Research Associate and Software Engineer.

In addition, ROMAC welcomed a total of 7 new graduate students. Thomas Gresham, Day Griffin and Benny Schwartz are M.S. degree students. Both Day and Benny come from industry. Gen Fu, Hanixian (Han) Jin and Cori Watson are Ph.D. students along with Major Ben Thomas, US Army, who are in their first semester with ROMAC.

We also have three undergraduate students working with ROMAC this semester: Justin Hsu and Chris Irion both in their 4<sup>th</sup> year of Computer Science and Scott Tepsuporn a 4<sup>th</sup> year in Computer Engineering and Computer Science. Please see the ROMAC Student page of the website for more details about each student.



## ROMAC Visiting Scholars

ROMAC is currently hosting several visiting scholars from various locations with appointments ranging from a few months to a year.

- \* **Emil Kurvinen**, Junior Researcher and Fulbright Scholar from Lappeenranta University of Technology Laboratory of Machine Design, Finland
- \* **Dr. Wei Wei**, Associate Professor from Beijing Institute of Technology, China
- \* **Dr. Qingliang Zhao**, Lecturer from Beijing University of Chemical Technology, China
- \* **Dr. Tianwei Lai**, Lecturer from Xi'an Jiaotong University Refrigeration & Cryogenic Engineering, School of Energy and Power Engineering, China
- \* **Dr. Heyun Bao**, Associate Professor from Nanjing University of Aeronautics and Astronautics, China



We expect six more scholars to join us before the end of this academic year. Please check the website for more information regarding our visiting scholars, their research interests and appointment dates.

## 2015 Rotordynamics Short course

A rotordynamics and magnetic bearings short course is planned for August 3-7, 2015. The course will cover topics in rotordynamics, bearing and seal dynamics, magnetic bearings, and applied dynamics for industrial rotors. The course will include presentations by University of Virginia faculty and graduate students. Case histories and examples from industry will also be presented by speakers from ROMAC industrial members.

ROMAC personnel are available to offer short courses on request throughout the year. Course topics can include Introduction to Advanced Rotordynamics and/or Magnetic Bearings. These courses can take place at the ROMAC labs at the University of Virginia, member locations, or other locations more convenient to attendees.

Please contact us at [romac@virginia.edu](mailto:romac@virginia.edu) for more information.

## 2014 Annual Meeting Summary

The 2014 Annual Meeting was held in late June in Charlottesville, the home of the University of Virginia, School of Engineering and Applied Science, Mechanical and Aerospace Engineering Department, and the ROMAC Laboratories. The meeting brought together over thirty industry members along with faculty, students and staff. We represented all the regions of the US, most coming from the northeast and the south; however we did have members from the mid-west and the west here as well as representation from five continents!

The week started with something new. Prior to the start of the annual meeting our faculty and students held a one-day

Short Course. We were very pleased with the participation and plan to offer this again in 2015. Monday evening, attendees met and mingled during our welcome reception. The following morning the meeting opened with remarks by Barry Johnson, Professor and Senior Associate Dean, SEAS, and Hossein Haj-Hariri, Professor and Chair, MAE, followed by an overview of the current state of ROMAC by Houston Wood. Over the next few days 39 talks were given, colleagues conversed, new members met long-time members, and new research ideas were presented and discussed.



The 2015 Annual Meeting will be held the first week of June. The planning is well underway. Be sure to check the ROMAC website for updated information. The member choice location for the meeting was overwhelmingly the Wintergreen Resort, located just 45 minutes from Charlottesville in Nelson County. The schedule of events is currently coming together with an expected highlight to be a tour of the Daikin-Applied plant in nearby Staunton.

Figure 1. 2014 ROMAC Annual Meeting Attendees

## Results of the Questionnaire

Companies at the annual meeting completed questionnaires detailing their desires for future research within ROMAC. The overall results are shown in the table below.

	Total Points	Percentage
Bearings and SFD	91	39.6%
Rotordynamics	58	25.2%
Seals	48	20.9%
Magnetic Bearings and Controls	19	8.3%
Optimization	13	5.7%
Other	1	0.4%

## ROMAC Reports

In 2014 ROMAC faculty and students submitted research papers to journals and also presented their work at major engineering conferences. A list of journal publications and conference papers published in 2014 is included below. These papers will be posted on our website soon as ROMAC reports.

Yoon SY, Anantachaisilp P and Lin Z, "An LMI approach to control of exponentially unstable systems subject to saturation and time-varying delay in the input", in *Recent Results on Nonlinear Delay Control Systems*, eds., I. Karafyllis, M. Malisoff, F. Mazenc and P. Pepe, Springer, 2014.

Morgan N, Untaroiu A, Migliorini PJ, Wood HG, "Design of Experiments to Investigate Geometric Effects on Fluid Leakage Rate in a Balance Drum Seal", *ASME Journal of Engineering for Gas Turbines and Power*, 2014, 137(3), 032501.

Untaroiu A, Liu C, Migliorini PJ, Wood HG, Untaroiu CD, "Hole-Pattern Seals Performance Evaluation using Computational Fluid Dynamics and Design of Experiment Techniques", *ASME J of Engineering for Gas Turbines and Power*, 2014, 136(10): 102501.

Migliorini PJ, Untaroiu A, Witt CW, Neal, NR, Wood HG, "Hybrid Analysis of Gas Annular Seals with Energy Equation", *ASME Journal of Tribology*, 2014, 136(3): 031704.

## ROMAC Reports (cont.)

Migliorini PJ, Untaroiu A, Wood HG, "A Numerical Study on the Influence of Hole-Depth on the Static and Dynamic Performance of Hole-Pattern Seals", ASME Journal of Tribology, 2014, in press.

Yoon SY, Lin Z and Allaire PE, "Experimental evaluation of a surge controller for an AMB supported compressor in the presence of piping acoustics," IEEE Transactions on Control Systems Technology, Vol. 22, No. 3, pp. 1215-1223, 2014.

Di L and Lin Z, "Control of a flexible rotor active magnetic bearing test rig: a characteristic model based all-coefficient adaptive control approach," Control Theory and Technology, Vol. 12, No. 1, pp. 1-12, 2014.

Yoon SY and Lin Z, "Predictor based control for linear systems with both state and input delays," Proceedings of the 2014 American Control Conference, pp. 4157-4162, Portland, Oregon, June 4-6, 2014.

Weaver BK, Dimond TW, Kaplan JA, Untaroiu A, Clarens AF, "Gas-Expanded Lubricant Performance and Effects on Rotor Stability in Turbomachinery", Proceedings of ASME Turbo Expo 2014: Power for Land, Sea and Air, GT2014, Paper no. GT2014-26980, June 16-20, 2014, Dusseldorf, Germany.

Morgan, NM, Untaroiu A, Migliorini PJ, Wood HG, "Design of Experiments to Investigate Geometric Effects on Fluid Leakage Rate in a Balance Drum Seal", Proceedings of ASME Turbo Expo 2014: Power for Land, Sea and Air, GT2014, Paper no. GT2014-27021, June 16-20, 2014, Dusseldorf, Germany.

Migliorini PJ, Untaroiu A, Wood HG, "A numerical Study on the Influence of Hole Aspect Ratio on the Performance Characteristics of a Hole-Pattern Seal", Proceedings of ASME Turbo Expo 2014: Power for Land, Sea and Air, GT2014, Paper no. GT2014-26581, June 16-20, 2014, Dusseldorf, Germany.

Whitlow Z, Fittro R, and Knospe C, "Segmented Magnetic Thrust Bearings: Analytic Models and Predictions of Significant Improvement in Dynamic Performance", Proceedings of the 14th International Conference on Magnetic Bearings, Linz, Austria, August, 2014.

Yoon SY and Lin Z, "Output regulation of linear systems with input and state delays," Proceedings of the 19th World Congress of the International Federation of Automatic Control (IFAC'14), pp. 9780-9785, Cape Town, South Africa, August 24-29, 2014.

Di L, Zhou J, Chen C and Lin Z, "Experimental verification of a rotor unbalance response based approach to the identification of magnetic bearing support parameters," Proceedings of the 14th International Symposium on Magnetic Bearings, pp. 581-586, Linz, Austria, August 11-14, 2014.

Lyu X., Di L, Yoon SY, Lin Z and Hu Y, "Emulation of an energy storage flywheel on a rotor-AMB test rig," Proceedings of the 14th International Symposium on Magnetic Bearings, pp. 326-331, Linz, Austria, August 11-14, 2014.

Gerami, A, Allaire, P, and Fittro, R, "Nonlinear Modeling and Control of a Magnetic Bearing with Material Saturation", Proceedings of the 14th International Conference on Magnetic Bearings, Linz, Austria, August 2014.

Morgan N, Wood HG, Migliorini PJ, Untaroiu A, "Groove Geometry Optimization of Balance Drum Labyrinth Seal to Minimize Leakage Rate by Experimental Design", 13<sup>th</sup> EDF/Pprime Workshop: Energy savings in seals, Futuroscope, Oct. 2, 2014, University of Poitiers, France.

Weaver BK, Zhang Y, Clarens A, Untaroiu A, "Nonlinear Analysis of Rub Impact in a Three-Disk Rotor and Correction via Bearing and Lubricant Adjustment", Proceedings of the ASME International Mechanical Engineering Congress and Exposition 2014, Paper no. IMECE2014-40055, November 8-13, 2014, Montreal, Canada.

Anatachaisilp P, Di L, Yoon SY and Lin Z, "Control of active magnetic bearing systems with input delay for applications in remotely controlled turbomachinery," to be presented at The 53rd IEEE Conference on Decision and Control, Los Angeles, CA, December 15-17, 2014.

## Summary of Research Projects

Below is a current list of projects being performed by ROMAC students, organized by the semester in which the students intend to graduate.

### An Extended Reynolds Equation Development with Applications to Fixed Geometry Bearings and Squeeze Film Dampers

**Student: Saeid Dousti**

**Expected Graduation Date: December 2014**

Water lubricated bearings and squeeze film dampers exhibit large lubricant inertia forces in the magnitude order of viscous forces. To model these bearings the traditional Reynolds equation is not adequate. An extended Reynolds equation is developed in this study which takes into account the turbulence and inertia effects: both convective and temporal. The most complete form of temporal inertia, which applies to the turbulent regime as well, is developed that consists of primary and secondary temporal inertia terms. The convective inertia model follows Constantinescu's approach. The turbulence model is also Constantinescu's which is tuned with CFD work.

#### SLEEVEBRG

To apply the proposed model to fixed geometry cylindrical water bearings, a computer code named SLEEVEBRG has been developed. This program is capable of satisfying the circumferential periodicity of the cylindrical bearings and is suitable for water bearings. SLEEVEBRG 1.0 is an isoviscous finite element code capable of handling full cylindrical fixed geometry sleeve bearings with *no* axial groove. This code solves an extended Reynolds equation in two dimensions, axial and circumferential directions, which makes it suitable for longer bearing with high L/D ratios. A sophisticated turbulence model and inertia effect modeling capabilities are embedded in the code which makes it applicable to low viscosity lubrication. This results in the prediction of the bearing added mass coefficients in addition to the corrected stiffness and damping coefficients. This code is also capable of modeling submerged bearings lubricated (with mainly water) in high subsea ambient pressures or in canned pumps.

SLEEVEBRG 1.0 takes advantage of an interactive, user friendly GUI which facilitates its application. This GUI allows the user to easily switch between different tabs and modify them. Also, both SI and U.S. customary systems are allowed in the code and switching between the two is conducted by proper unit conversions. SLEEVEBRG is capable of analyzing two types of operating conditions: load matching the eccentricity and displacement matching the external force. For each operating condition type, maximum number of seven cases are allowed to be analyzed in the same run. A useful entry check control flags probable entry mistakes.

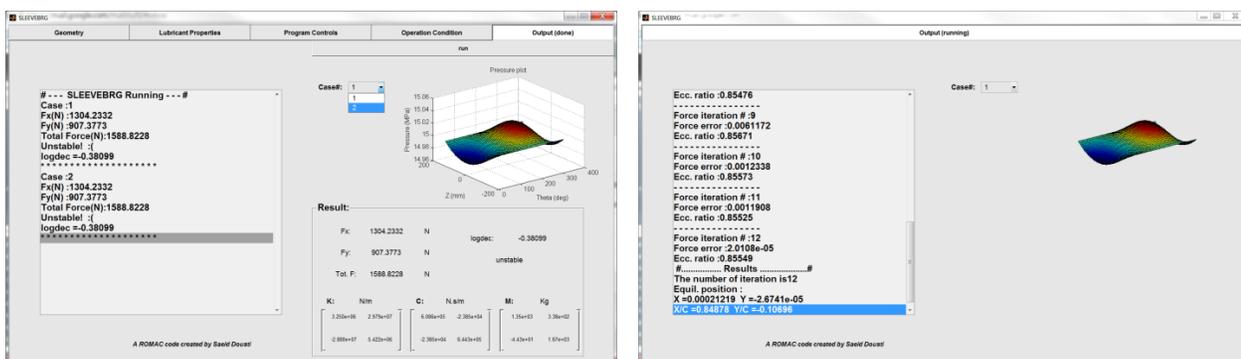


Figure 2. SLEEVEBRG user interface

The calculation process is reported in a console under the output tab. In this tab, the calculation process and results are displayed. The code is designed to be able to remove the inertia option to avoid divergence in the analysis. The results include the steady state operation values, pressure profile plot, and dynamic coefficients. These values can be interactively converted from SI to U.S. Customary and vice versa. Also in the same page, the results of different cases can be displayed and selected. To avoid confusion, once the code is running, the user is banned from making changes in the entry values.

## MAXSFD

Squeeze film dampers are designed in different configurations. Features like supply and discharge holes, end seals, and grooves contribute to the dynamic characteristics of squeeze film dampers. Grooves are proven, contrary to the old perception, to generate a considerable amount of dynamic pressure. To capture their effects an effective groove depth approach is adopted. Additionally, an applicable extended Reynolds equation including temporal inertia is developed which takes into account the contribution of holes as well. A computer code is developed accordingly.

MAXSFD 1.0 is a finite element code capable of modeling and analyzing squeeze film dampers (SFD). This code solves an extended Reynolds equation in two dimensions: the axial and circumferential directions. This code can capture the dynamic effects of grooves, holes and end seals. The code also takes advantage of a mesh refining algorithm that generates a finer mesh in hole and seal regions. These capabilities allow for a more accurate analysis. It is a well-known fact that the dynamics of the grooves are very complicated. MAXSFD uses an effective groove depth technique to capture this complicated dynamic effect. The output of the code consists of stiffness, damping and added mass coefficients calculated for an assumed circular centered orbit. Four different configurations are analyzed and results are compared against the experimentally attained data. It is found that in general two distinct effective groove depths are required to match the experimental added mass and damping values. This indicates that different amounts of lubricant trapped in the groove contribute into the added mass and damping characteristics of squeeze film dampers. In open end squeeze film dampers the ratio of the two effective grooves is almost three and in the sealed squeeze film dampers it is about one. The numerical observations prove that secondary temporal inertia plays a minor role in the determination of the added mass coefficients. The results from SQFDAMP, which is based on the old model, under predicts the damping values and lacks the added mass prediction capability.

## BUSHBRG

BUSHBRG 2.0 is a code capable of modeling and analyzing short length floating bush bearings used mainly in turbochargers. Bush bearings contain a bushing floated between the journal and bearing housing which splits the lubricant film to inner and outer films. In the 2.0 version, this code solves an extended Reynolds equation applicable to short bearings analytically for both lubricant films. Films interact with each other, which requires a coupled algorithm to find the unknowns of the steady state operation. The solution algorithm is robust and converges for all the load cases. One of the important unknowns is the bush rotational speed that can be readily calculated by this code. The dynamic coefficients calculated for the bearing are calculated by using a perturbation scheme. The code also calculates the power loss of the bearing, which shows significant reduction compared to regular bearings.

## Rotating Seal Test Rig

**Student: Brian Weaver**

**Expected Graduation Date: December 2014**

As increasingly powerful predictive analysis and design tools are being developed for turbomachinery seals, it is essential that these tools are validated for a wide range of designs and operating conditions. Recent work has focused on the development of a rotating seal test rig that will be used to study seal performance in a wide range of fluid conditions including low-pressure and high-pressure gases, liquids, and multi-phase mixtures (Figure 3). This test rig will provide ROMAC with an important validation tool as new seal codes such as DampSeal and HybridSeal are developed and improved over time.

This test rig has been designed to include a versatile test section in which interchangeable seals can be installed to test a variety of seal designs including plain cylindrical, hole pattern, and other types of annular seals at speeds up to 15,000 rpm and supply pressures up to 1,500 psi. The test section will also be equipped with instrumentation allowing

for the measurement of pressure and temperature profiles across the seals, seal leakage, and power loss. Though preliminary efforts will focus on using the seal rig to validate ROMAC's seal modeling capabilities, this test rig can also be used to study seal design optimization, the validity of seal PV ratings, the behavior of unique fluid mixtures such as gas-expanded lubricants, and other unique seal designs of interest to the ROMAC membership. Seal coefficient measurement capabilities may also be considered as a potential future upgrade. Interested members are encouraged to contact us with project requests.

Currently, a majority of the components for the seal test rig have been received and facilities work has commenced to allow for its installation and initial testing. In the coming months power will be connected to the necessary components, a base will be installed to place the test section on, and instrumentation and data acquisition systems will be installed. It is then planned to begin preliminary gas seal experiments with plain cylindrical and hole pattern seals in the spring and summer of the coming year.

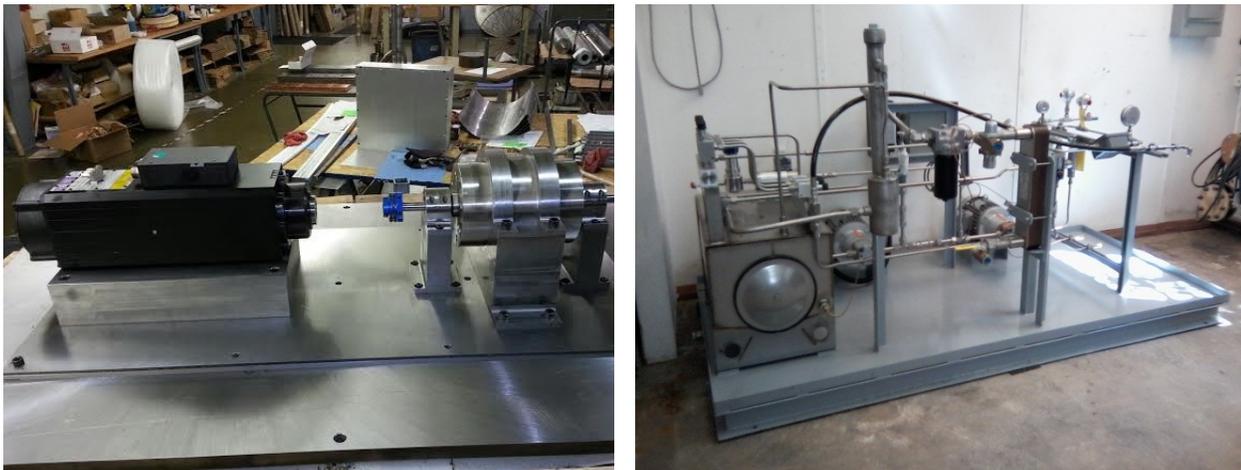


Figure 3. The seal test rig will enable a wide range of rotary seal experiments.

## Gas-Expanded Lubricants for Increased Energy Efficiency and Control in Rotating Machinery

**Student: Brian Weaver**

**Expected Graduation Date: December 2014**

Lubricants are necessary in rotating machinery to provide separation between solid surfaces and to enable efficient, long-term operation. However, they can also contribute to power loss and heat buildup as the fluid is subject to shear forces. Here, tunable binary mixtures called gas-expanded lubricants (GELs) were studied to overcome these limitations of conventional lubricants. GELs consist of a synthetic lubricant and dissolved carbon dioxide delivered at elevated pressure with properties, such as viscosity, that can be controlled dynamically in response to changing environmental or rotordynamic conditions. These tunable fluids enable operators to minimize bearing losses and operating temperatures as well as control rotordynamic performance via bearing stiffness and damping control. By lowering the pressure, the original properties of the lubricant can also be restored.

The properties of GELs were measured experimentally and the effects of these lubricants on bearing and rotordynamic performance were predicted analytically using a number of ROMAC codes including MAXBRG, ComboRotor, GearRotor, and RotorTran. Experimental results demonstrate the control of GEL composition and viscosity via pressure control while modeling work has shown significant power loss reductions as a result of GEL usage when compared to conventional lubricants. Lower operating temperatures and significant effects on rotordynamic stability were also predicted by the modeling effort (Figure 4).

Recent work has focused on the development of a seal test rig that will be used to study seal performance in a wide range of fluid conditions including high-pressure gases, liquids, multi-phase mixtures, and GELs. Understanding how GELs will affect seal performance and design will be critical to ensuring proper machine performance under GEL-lubricated conditions. Other recent projects performed and planned in this area include the effects of tunable lubricants and other adjustable bearing parameters on rub-impacted machines, real-time control of machine rotordynamics via lubricant adjustment, the inclusion of lubricant properties in bearing design optimization, and the application of GELs utilizing a combination of hydrostatic and hydrodynamic principles in bearings designed for lower pressures.

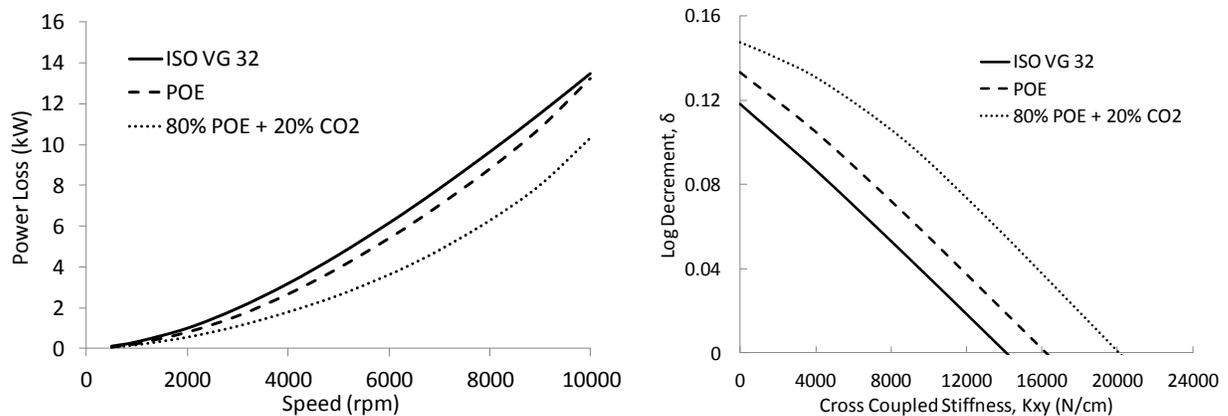


Figure 4. GELs were found to significantly increase bearing efficiency and rotordynamic stability in a high-speed centrifugal compressor when compared to conventional fluids.

## Modeling and Control of Non-laminated Active Magnetic Thrust Bearings

**Student: Zack Whitlow**

**Expected Graduation Date: December 2014**

Non-laminated magnetic thrust bearings exhibit reduced dynamic performance when compared to laminated radial bearings due to eddy current effects. Segmented thrust bearing stators have been introduced to increase actuator performance by disrupting eddy current paths in the same manner as laminations in radial magnetic bearings. However, due to manufacturing limitations thrust bearing stators cannot be easily segmented to the extent that they would be considered fully laminated. Therefore, eddy currents continue to affect their dynamic performance significantly. This work aims to improve the performance of non-laminated thrust active magnetic bearings through improved modeling and control design.

Currently, accurate modeling of segmented stator performance relies on finite element analysis, which is a time consuming process. In this work, an analytic model of cylindrical segmented electromagnetic actuators, including eddy currents effects, is developed. The model is an extension of the analytic model for C-type electromagnetic actuators developed by Zhu et al.. Zhu's work on cylindrical magnetic actuators is also continued in order to develop an analytic model for cylindrical electromagnetic actuators with a center hole, i.e. non-laminated active magnetic thrust bearings. All analytic models developed in this work are verified via finite element analysis.

Based on analytic and finite element modeling, it is found that thrust bearing stator segmentation results in dramatic improvements in dynamic performance. With six stator cuts, and depending on the specific geometry, bandwidth from current input to force output is typically improved by more than two-fold.

The potential for dynamic performance improvements for non-laminated magnetic thrust bearings by non-linear and dynamic compensation is also investigated. Simulations using a detailed non-linear model suggest that compensation, combined with proportional-integral-derivative control, will improve performance consistency and disturbance rejection for non-laminated thrust bearings.

## Modeling and Control of Magnetic Bearings with Nonlinear Material Saturation

**Student: Ali Gerami**

**Expected Graduation Date: December 2014**

In most current Active Magnetic Bearing (AMB) systems, operation is limited to the linear region of the magnetic material. It is assumed that the relative permeability of the core material is a constant up until the magnetic flux reaches a knee value at which point the material is assumed to be saturated. In addition, it is standard practice to design an AMB system such that the worst-case operating condition for a given application remains within this linear region. However, this results in designs that can be significantly oversized for standard operating conditions. In order to better optimize new AMB system designs or get higher load capacities out of existing AMB systems, operation in the nonlinear region is desirable. In order to achieve this, a more precise model and an improved control design is necessary.

In this research, a new nonlinear modeling and control design approach is investigated to operate magnetic bearings above the linear range and near the material saturation point. Since it is a common industrial practice to include amplifiers with more capacity than needed for AMB systems as a safety factor, the proposed method can potentially increase the load capacity by just a change in the software. Analysis reveals that operating in this fashion results in approximately twice the force capability. Therefore the proposed method can offer a low cost solution for occasional harsh situations with high transient loads that need to be handled by an AMB.

Even though magnetization nonlinearity has been modeled in some previous work, these models were not used for controller development. In this work, the magnetization nonlinearity is modeled precisely using the Lur'e method, which makes it more suitable for control design.

A SDOF balance beam test rig is used for the dynamic modeling, simulation and experimental validation of this new approach. The resulting control system design has been demonstrated to achieve the desired increased load capacity. In addition, better transient response and disturbance rejection capabilities compared to traditional approaches have also been achieved.

## Experimental measurements of damping ratios and stability of a flexible rotor under reduced bearing lubrication flow rates

**Student: Brad Nichols**

**Expected Graduation Date: May 2015**

Reducing the oil supply flow rate provided to a fluid film bearing leads to an increase in operating temperature, a decrease in lubricant viscosity, and a reduction in power losses due to churning and shear effects. In some cases reduced flow rates can lead to starvation or a lack of a developed film layer at the leading edge of one or more of the pads. A saving in power loss may lead some end-users to operate their bearings at reduced flow rates. However, little is known about the effects of these reduced flows on system stability.

An experimental investigation is underway to investigate the effects of incrementally reduced oil supply flow rates to tilting-pad bearings on both steady-state performance indicators such as pad temperature, journal operating position, and power loss, as well as overall system dynamics. The test plan includes collecting data at various operating speeds ranging from 2,000-12,000 rpm under both lightly and moderately loaded conditions. At each speed and load case, data will be collected at oil supply flow rates of 120, 100, 80, 60, 40, and 20 percent of the nominal rate. Sine-sweep excitations by a magnetic shaker will be used to obtain frequency response functions (FRFs) using a single-input, multiple-output (SIMO) technique. System identification techniques will then be performed on these FRFs to obtain damping ratios and natural frequencies. All experimental results will be compared to rotordynamic models which utilize bearing coefficients predicted from numerical methods based on thermoelastohydrodynamic (TEHD) lubrication theory.

The test rig, designed to have dynamic characteristics similar to those found in industrial rotating machines, consists of a 1.549 m long shaft with an 88.9 mm mid-span diameter. The rotor is supported by two, five-pad tilting pad bearings with a nominal diameter of 70 mm and span of 1.219 m. Specifications of the test bearing also include an L/D ratio of 0.75, diametral clearance of 173 microns, and a 0.3 preload. Two different bearing designs will be tested in this study.

First, the bearings will be tested in traditional, flooded bearing housings under the various operating conditions previously described. Once testing is completed on these bearings, they will be modified to include directly lubricating spray-bar blockers and tested under the same speed, load, and flow conditions. Additionally, the end seals will be removed creating an evacuated housing.

Experimental testing is currently underway. To date, steady-state performance measurements of the traditionally flooded bearing in lightly loaded conditions under various flow rates and speeds has been completed. Simultaneous work has been completed by modeling these bearings in MAXRG and comparing the predicted results to the experimental data. Dynamic testing will begin soon, in which damping ratios are obtained from the excitation method described above using the same bearings under all of the operating conditions tested during steady-state testing. All tests will then be repeated under moderately loaded bearing conditions. Testing will conclude with a repetition of all the tests using the modified bearing. All experimental testing is expected to be complete near the end of the calendar year 2014.

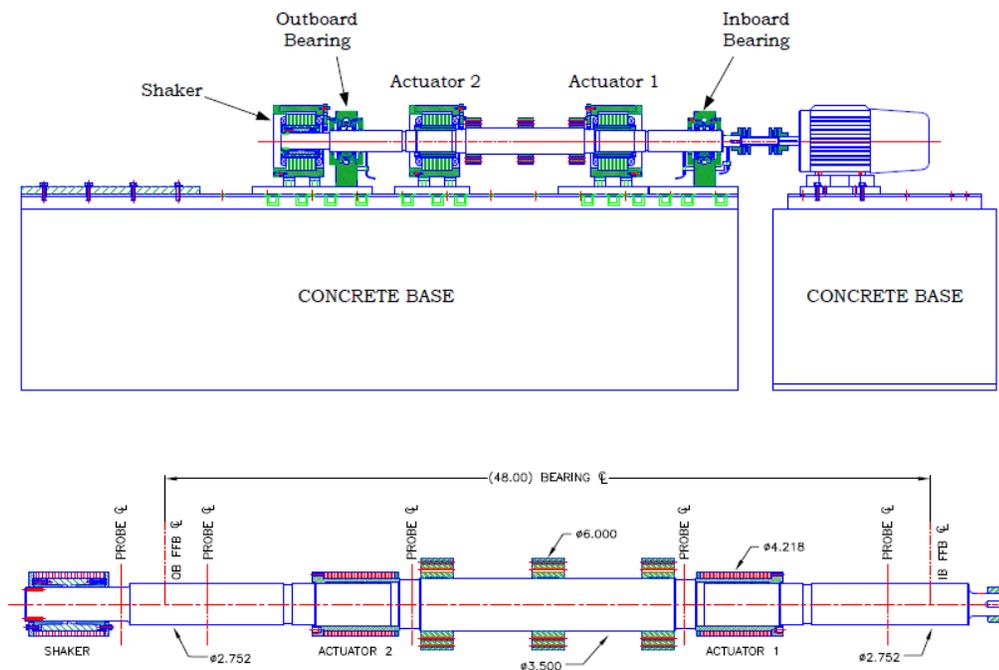


Figure 5. Schematic of the stability test rig (ROMAC Report # 515)

## Non-linear rotor dynamics of parallel-stage geared systems with time-varying mesh stiffness and backlash

Student: Jason Kaplan

Expected Graduation Date: May 2015

### Project Goals:

- \* Enhanced understanding of the vibration transmission from the gear mesh through the rotor-bearing structure during start-up and steady operating conditions.
- \* Exploration of the effects of mesh phasing, backlash, and time-varying mesh stiffness magnitude on more realistic models of geared systems. No lumped-parameter modeling.
- \* Enhanced understanding of the damping of torsional modes via the lateral-torsional coupling of geared systems.

The ability to accurately predict the response of rotating machinery to external forces and to assess system-level stability for different modes is crucial from a reliability and preventive maintenance perspective. Geared systems, in particular, contain many complexities such as non-linear tooth contact loss due to backlash and parametric excitations from the time-varying mesh stiffness which may lead to instability and even chaotic vibration behavior. No methods

for determining the effects of the dynamic meshing forces on the vibrations of complete shaft/bearing systems have been proposed in the literature. Several time-transient and steady-state models for analyzing gear forces and deflections have been proposed, but they typically either focus on the dynamics of the gearbox itself or neglect vibration transmission through the remainder of the drive-train. Models that do incorporate other components of the drive-train propose simplified lumped-parameter models for the shafts and bearings. Recent models have used the finite element method to couple the lateral, torsional, and axial degrees-of-freedom of geared shaft systems to the forces and moments exchanged between the gears via stiffness matrices. Other models in the literature capture the backlash non-linearity and time-varying mesh stiffness and observe the time-transient response of the gearbox and simplified shaft/bearing structure. A finite element formulation of complete geared systems, which couples the axial, lateral, and torsional degrees-of-freedom of the connected shafts, is developed. The shaft structure is modeled with Timoshenko beam elements and captures the forces and moments due to gyroscopic effects, as well as rotational accelerations from start-up or wind-down. It includes the capability of modeling non-linear contact loss due to backlash and parametric excitations resulting from time-varying mesh stiffness and solves the time-transient state equations for the displacements and velocities of the shafts using the direct Runge-Kutta method.

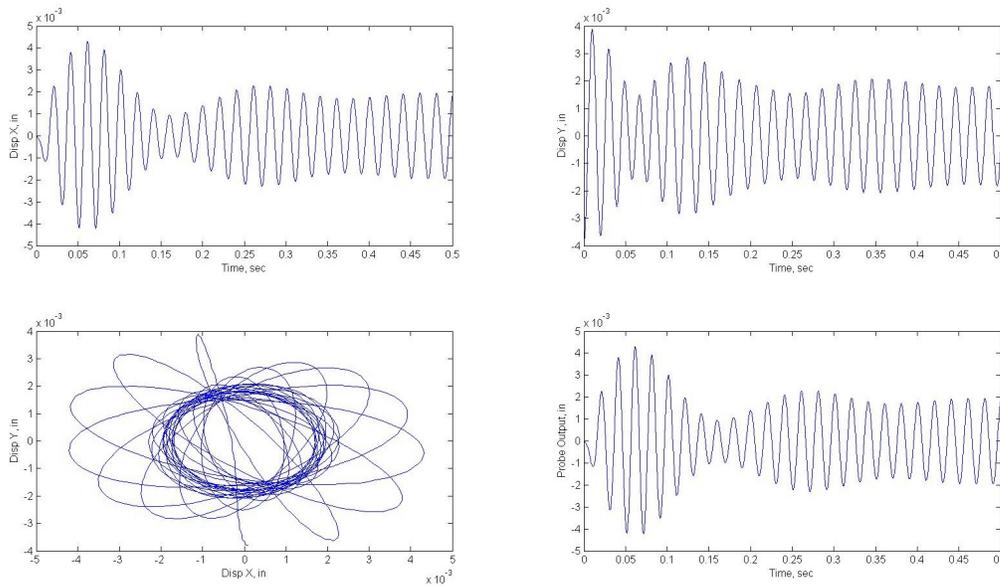


Figure 6. X and Y displacements of a shaft node as a function of time.

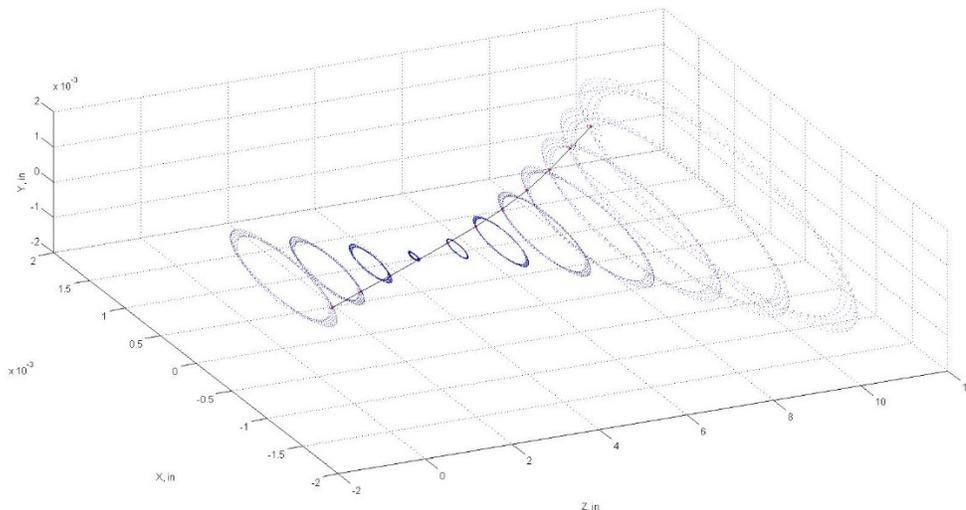


Figure 7. Conical whirl mode of a shaft excited by unbalance forces.

## Fractional Order Control of Active Magnetic Bearing Systems

Student: Parinya Anantachaisilp

Expected Graduation Date: May 2015

Controller design for an active magnetic bearing (AMB) system is a challenging task since the AMB system is an open loop unstable system and it also has very complex dynamics. In most cases, PID is the chosen controller due to its simplicity and users can tune controller parameters intuitively. However, sometimes the conventional PID controller cannot fulfill the required performance specifications of AMB systems. Therefore, the more complex controllers such *LQG*,  $H_\infty$  and  $\mu$ -synthesis controller, were developed and designed to meet the specifications. The tradeoff between the simplicity of controller structure and good performances achievement is always one of the goals that control engineers want to optimize. Recently, fractional order calculus theory, which is the generalized version of integer order calculus, has been adopted in many applications due to its accuracy to model the dynamics of the systems and its simplicity in model structure to represent high order processes. The fractional order control is one of the fields that many researchers and engineers are interested in, especially the so called fractional order PID (FOPID) controller. FOPID has two extra parameters, the non-integer order of integral and derivative terms (Fig. 8), in addition to the integer order PID controller. It has been revealed that an FOPID controller can improve performance and robustness when compared to a conventional PID controller in many applications while keeping the controller structure simple. This suggests that FOPID controllers have a good potential to reduce the gap between the simplicity of the structure and high performance aspects as mentioned above.

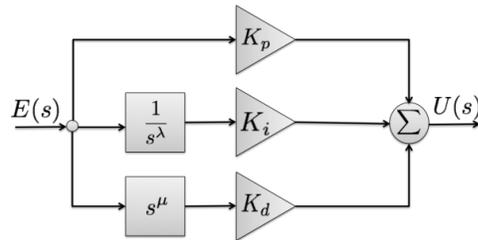


Figure 8. FOPID controller structure

As of now, the feasibility of FOPID to AMB systems is investigated in two aspects. The first aspect is the control of rotor suspension by magnetic bearings both in radial and axial directions. Second is the surge control in a centrifugal compressor which uses a thrust AMB to modulate the impeller tip clearance for stabilization. Also, a tuning method will be developed for searching the optimal values of controller parameters. Then, the resulting FOPID controller will be tested and compared to an integer order PID as well as an advanced controller such as *LQG* and based on several stability performance and robustness specifications and the controller size as implemented. Lastly, to validate  $\mu$ , the proposed method, the experimental testing will be carried out on a centrifugal compressor equipped with magnetic bearing test rig (Fig 9).

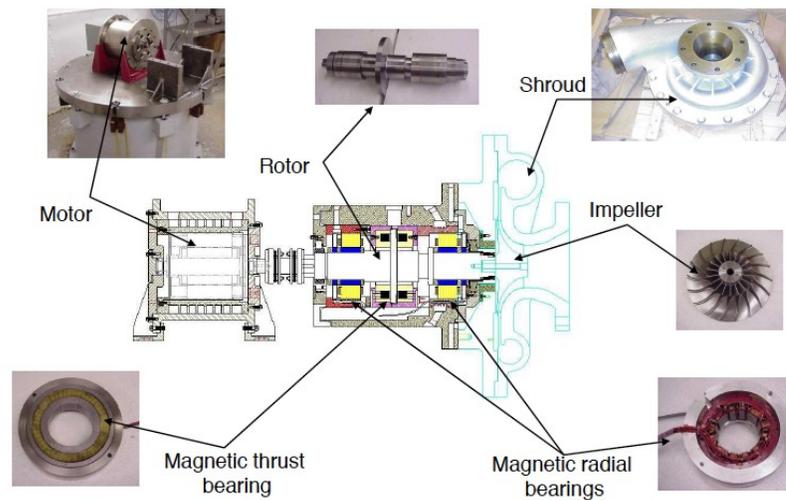


Figure 9. Centrifugal compressor equipped with AMB test rig

# Optimization of the Static and Dynamic Performance of Labyrinth Annular Seals

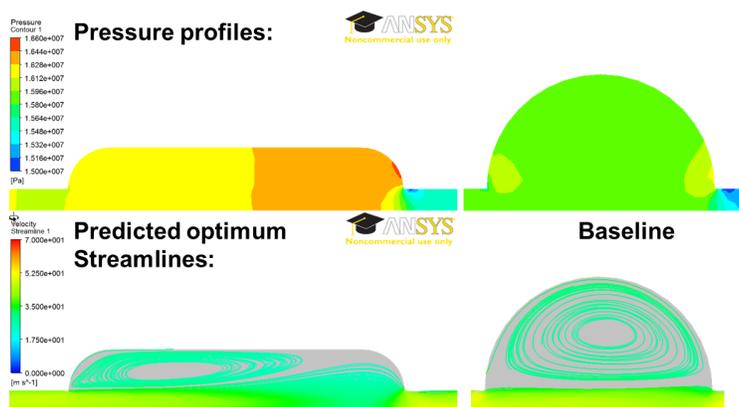
Student: Neal Morgan

Expected Graduation Date: May 2016

The objective of this research project is to apply statistical experimental design and optimization methods to the design process of a labyrinth seal. Current progress includes a study in which a semi-circular grooved balance drum labyrinth seal, with a working fluid of water, was selected as the baseline geometry. The original seal cross-sectional geometry is defined by a 0.305 mm clearance height and 1.59 mm radii grooves. A design of experiments study was performed by varying five design variables defining alternative groove shapes between the extrema of semi-circular, rectangular, and triangular groove shapes. Each of the 20 grooves along the seal were identical to each other and evenly spaced, allowing only the shape and scale of the grooves to change. The 267 mm seal flow path was modeled without rotor eccentricity as a 5 degree sector and also included an upstream cavity simulating the connection with the back of the pump impeller. CFD analysis was performed in ANSYS CFX on the flow through the various groove geometries. The viable experiments from a full five level factorial designed experiment, consisting of 98 simulation experiments, was selected based on the geometric constraints to investigate the effects of groove shape and scale on the leakage. A regression model was generated from the results to predict a groove shape that would cause minimal leakage. Flow visualization through streamlines allowed for discussion of the underlying flow behavior. This study exemplifies the application of design of experiments and design optimization to the minimization of leakage through annular labyrinth seals, predicting a new seal groove shape, shown in Figure 10, which reduced leakage rate by 7.28% when compared to the baseline geometry. A simplified hybrid bulk flow/CFD method was employed to estimate the rotordynamic coefficients of each seal and regression models were also fit to these results for an eventual goal of tuning a seal to meet specific stability requirements. The one dimensional relationships between the design variables and the seal performance characteristics are shown below in Figure 11. These relationships are slices of a five dimensional cubic regression model taken at the factor values representing the simulation optimized for minimum leakage rate.

A subsequent study is in progress that relaxes the geometric constraints, allowing the entrance and exit angles of the grooves to vary between  $10^\circ$  and  $170^\circ$ . This study consists of 330 selected geometries. The simulation results will be processed and fit with a regression model to optimize the leakage of the seal.

The results from these studies will be applied to the investigation of vortex tracking and strength in annular labyrinth seals. Initially, regression models will be constructed to predict the vortex behavior and its effects on the seal performance characteristics. These models will be used to inform improvements to the understanding of flow behavior in the seal grooves and potentially modify future analytical models.



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Figure 10. Groove shape comparison- baseline vs. predicted optimum

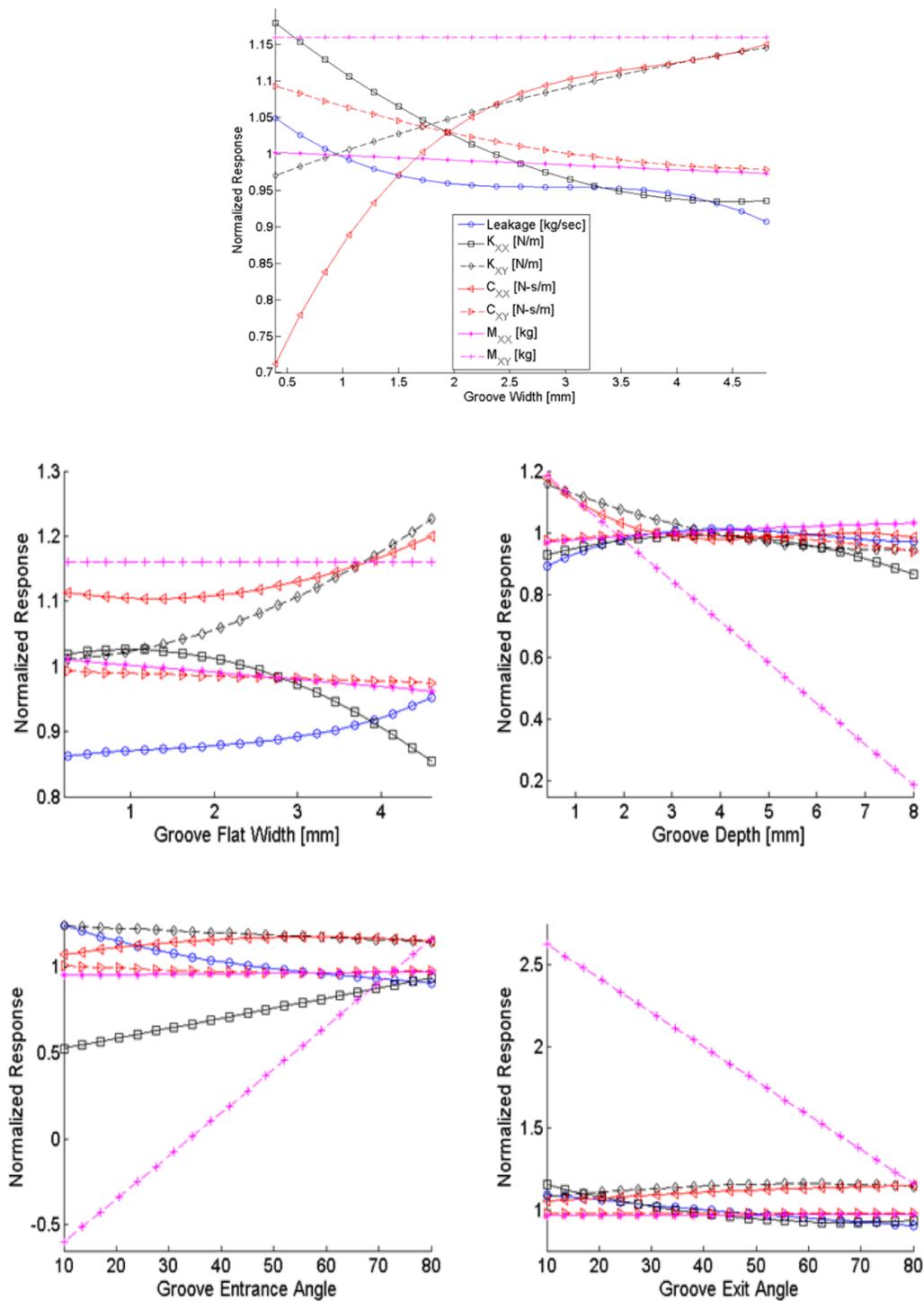


Figure 11. One dimensional relationships between design variables and seal performance characteristics

## Brush Seal Performance Modeling

Student: Thomas Gresham

Expected Graduation Date: May 2016

Brush seals have been shown to be extremely effective at reducing leakage in turbomachinery applications. Brush seals are designed to impede the flow between rotating and stationary parts in order to improve the efficiency of a machine such as a turbine or a pump. Previous research has demonstrated that for certain applications a brush seal may be far more effective than other types of seals that are commonly used in industry.

As Fig.12 shows, a brush seal has stiff bristles attached to the stator. These bristles extend toward the rotor and can be designed to have a small clearance, or as in some cases, no clearance. The fact that a brush seal can be feasibly designed to have contact with the rotor makes it very unique in comparison to other commonly used annular seals.

The bristles are packed together at a certain density and there is an even spacing between each bristle pack. There is a backing plate on the downstream side of each bristle stage and there must be a radial clearance between the backing plate and the shaft. The fluid flow through the bristles is very complex and is difficult to model analytically. The use of CFD software allows for detailed analysis of the flow field and can provide insight into ways that brush seals can be improved.

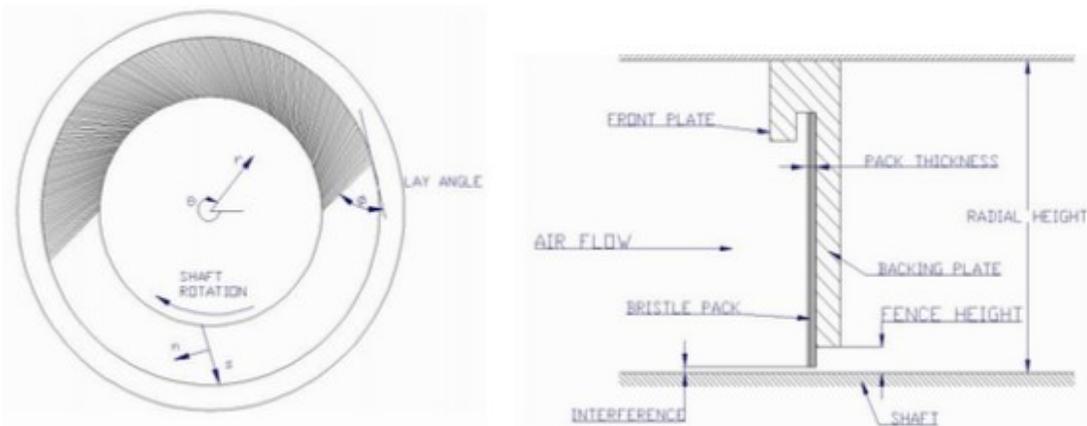


Figure 12. Schematic of a brush seal

Project Goals:

- \* Collect and synthesize current knowledge of brush seals from industrial and academic sources.
- \* Identify design parameters which have a significant impact on the performance of the seal and can feasibly be altered to improve the seal.
- \* Explore ways to improve the design of a brush seal by using analytical methods and numerical simulations.

## Fluid Film Bearing Test Rig

Student: Benstone Schwartz

Expected Graduation Date: May 2016

As fluid-film bearing applications continue to push the envelope on operating speed, load, and performance, bearing technologies need to keep pace as well. Modern applications commonly involve bearing operation in the transition and turbulent flow regions. Presently, there is little data available for dynamic properties of bearings in this range and the Fluid-Film Bearing Test Rig (FFBTR) is being designed to make these measurements possible.

Another objective of the FFBTR is to provide additional validation of ROMAC codes including THPAD and MAXBRG. This effort will lead to upgrades and further validation of ROMAC bearing analysis tools for years to come.

During the summer months a thorough design review of the FFBTR was undertaken. Over the past few months an analysis and redesign effort has since begun. Beginning with the performance specifications, a nonlinear bearing analysis, bearing coefficient uncertainty estimate, and sensor requirement specification have all been performed. A preliminary redesign and system analysis is presently being finalized, with a design review involving ROMAC member companies interested in the FFBTR targeted for the month of November. Once the preliminary design review is complete, work will progress into the detailed design stage with another member company design review meeting targeted

for the spring of 2015. The goal of this year's effort is to:

- \* Complete the detailed design and design review process.
- \* Complete detailed design drawings and specifications ready for component manufacturing and acquisition.
- \* Create a full nonlinear simulation model capable of accurately simulating the actual test rig operation and bearing coefficient identification procedure.
- \* Complete a detailed dynamic bearing coefficient uncertainty analysis.

During this entire process we desire to work closely with industry members to ensure that the capabilities of the FFBTR matches the needs of the ROMAC community. We value and encourage member company representative involvement and encourage involvement in both the Fall 2014 and Spring 2015 progress review meetings where current progress and future plans will be presented and discussed.

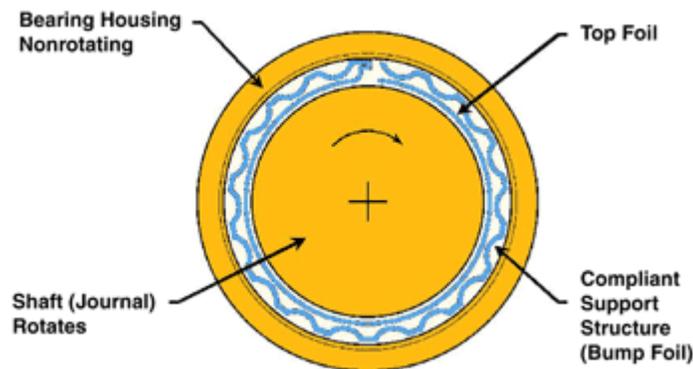
## Improved Fluid Film Bearing Prediction Tools

**Student: Michael Branagan**

**Expected Graduation Date: May 2016**

Predicting the response of bearings is a vital part of rotor system design as bearings are used to support and stabilize the system. Fluid film bearings are commonly used bearings that can be found in many applications today. Air foil bearings are a relatively new bearing design that is seeing increasing use in industry (Figure 13). However, there currently exist gaps in the capabilities of many of the predictive tools out there used to analyze these bearings. ROMAC is currently beginning an investigation into this field of study with the intention of developing a predictive air foil bearing code that will help fill in these gaps and improve the abilities to predict the impact that these bearings will have in rotor systems.

MAXBRG is also a powerful predictive tool for several types of fluid film bearings. However, it can suffer from convergence issues as well as extremely long run times. Working to improve these issues as well as add new features to MAXBRG will help improve the ability of engineers to predict the behavior of fluid film bearings.



<http://www.nasa.gov/centers/glenn/about/fs14grc.html>

Figure 13. Bump foil bearing

## RotorSol - continual development plans

**Student: Michael Branagan**

**Expected Graduation Date: May 2016**

The ability to accurately predict rotating machine resonant frequencies and to assess their stability and response to external forces is crucial from a reliability and preventive maintenance perspective. ROMAC has multiple tools to assist with this prediction ranging from critical speed map to forced response analyses in lateral, torsional and axial degrees-of-freedom. RotorSol was developed to combine these tools into one comprehensive package. RotorSol uses a finite element model composed of 12 degree-of-freedom beam elements coupling lateral, torsional, and axial degrees-of-freedom together. RotorSol is being linked with RotorLab+, ROMAC's new GUI. Tilting pad bearings with full coefficients, aerodynamic cross coupling, thrust bearings, flexible couplings, flexible supports and disk stiffness properties

are all new components which have been added to RotorSol's capabilities. Considerable work has also been put into improving the efficiency and reducing the run time of RotorSol. Future work for this project includes adding new components such as AMBs, gears, new forces such as shaft bow and nonsynchronous forces, new element capabilities such as internal damping, tapered elements, distributed mass, new analytical tools such as critical speed maps, Campbell diagrams, and new options such as inclusion of user specified matrices.

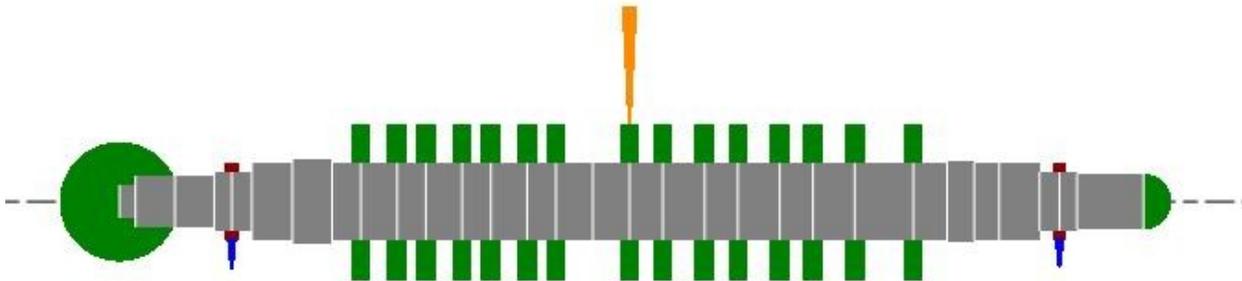


Figure 14. Rotor model

## Empirical study on the effect of circumferential scratches in fluid film journal bearings

Student: Day Griffin

Expected Graduation Date: May 2016

In operation, fluid film bearings inevitably develop damage due to foreign particles in the oil supply. Depending on the severity of the damage, the load capacity of the bearing can be significantly reduced. Theoretical approaches have estimated the effect of circumferential scratches on load capacity but there is little to no empirical data for validation. Using an existing fluid film bearing test rig, the reduction in load capacity of a scratched journal bearing will be quantified by temperature and minimum film thickness measurements. A combination of artificial scratches (varying depth, scratch density, axial location, etc.) will be machined into a plain cylindrical bearing and then tested at varied loads and speeds. The damaged and undamaged bearing temperatures and minimum film thicknesses will be compared and a reduction in load capacity will be calculated based on an accepted criterion of bearing operation. This data will provide end users and original equipment manufacturers with a better understanding of the load capacity of scratched bearings.

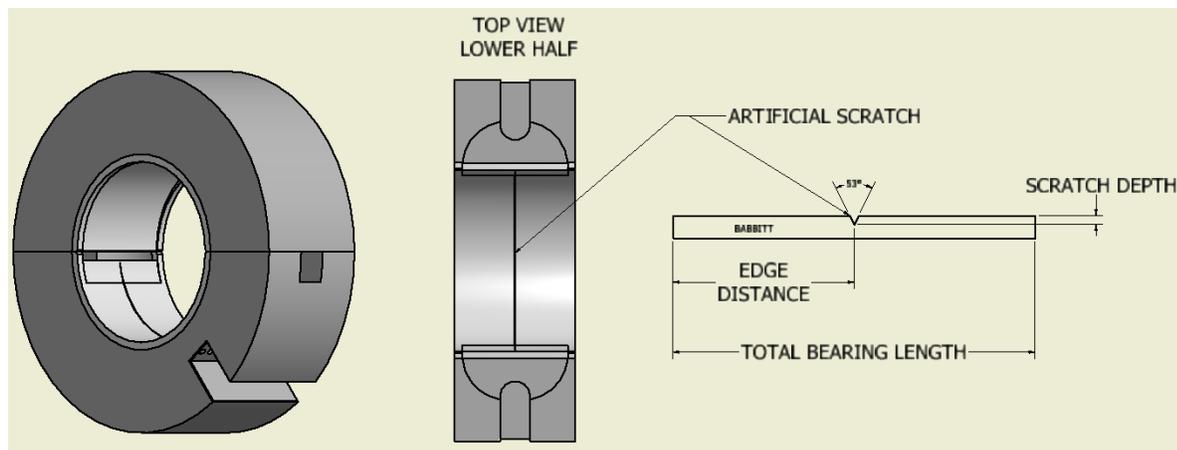


Figure 15. Example of a cylindrical fluid film bearing with one axially centered artificial scratch.

## Study of API specification on necessity of bearing support analysis

**Student: Day Griffin**

**Expected Graduation Date: May 2016**

The current API specification requires that a machine's support stiffness be included in the rotordynamic analysis if the support stiffness is less than or equal to 3.5 times the bearing oil film stiffness. The specification allows manufacturers to neglect pedestal dynamics, saving analytical expenses, if the pedestal exceeds this threshold. Due to the suspected influence of pedestal dynamics on problem machines in industry, a concern with the 3.5 threshold ratio is being investigated. The current state of this project shows that the pedestal stiffness alone may not validate the neglect of support dynamics.

## Unbalance Response Based Approach to the Identification of the AMB Stiffness and Damping Coefficients

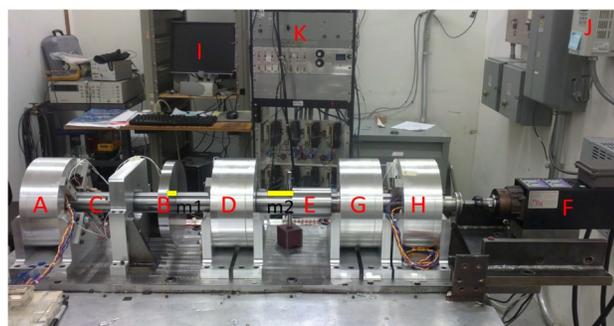
**Student: (Dee) Long Di**

**Expected Graduation Date: May 2016**

The stiffness and damping coefficients of active magnetic bearings (AMBs) have direct influence on the dynamic response of a rotor bearing system, including the bending critical speeds, modes of vibrations and stability. Rotor unbalance response is informative in the identification of these bearing support parameters. In this research, we propose a method for identifying closed loop AMB stiffness and damping coefficients based on the rotor unbalance response. We will use a flexible rotor-AMB test rig to help describe the proposed method as well as to validate the identification results (Figure 16).

First, based on a rigid body model of the rotor, a formula is derived that computes the nominal values of the bearing stiffness and damping coefficients at a given rotating speed from the experimentally measured rotor unbalance response at the given speed. Then, based on a finite element model of the rotor, an error response surface is constructed for each parameter to estimate the identification errors induced by the rotor flexibility. The final identified values of the stiffness and damping coefficients equal the sums of the nominal values initially computed from the unbalance response and the identification errors determined by the error response surfaces.

The proposed identification method is carried out on the rotor-AMB test rig. In order to validate the identification results, the identified values of the closed-loop AMB stiffness and damping coefficients are combined with the finite element model of the rotor to form a full model of the rotor-AMB test rig, from which the model unbalance responses at various rotating speeds are determined through simulation and compared with the experimental measurements. The close agreement between the simulation results and the measurements validate the proposed identification method (Figure 17).



A: Non-driven End Support AMB      B: Gyroscopic Disk 1      C: Rotor Shaft  
 D: Mid-span Disturbance AMB      E: Gyroscopic Disk 2      F: Electric Motor  
 G: Quarter-span Disturbance AMB      H: Driven End Support AMB      I: Control Station  
 J: Variable Frequency Drive      K: Amplifiers & Sensor Conditioning Station

Figure 16. The flexible rotor-AMB experimental test rig.

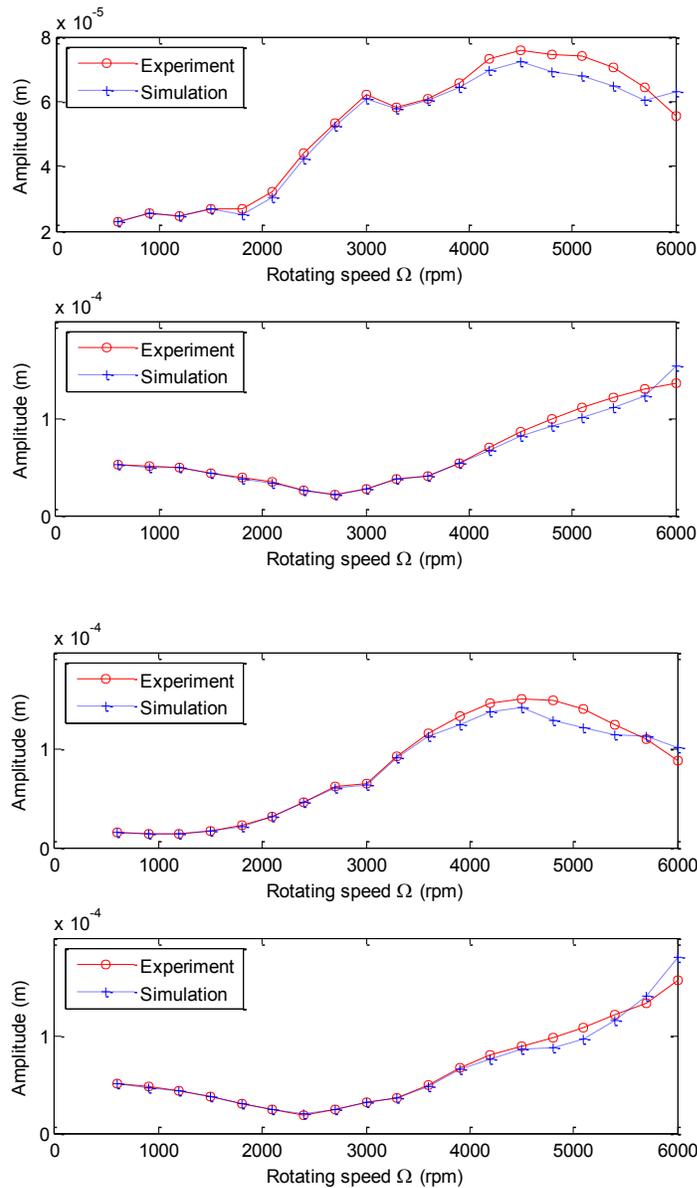


Figure 17. Displacement comparisons for  $x_1$  and  $x_2$  (upper two plots),  $y_1$  and  $y_2$  (lower two plots).

## Emulation of Energy Storage Flywheels on a Rotor-AMB Test Rig

Xujun Lyu, visiting student from Wuhan University of Technology

Student: (Dee) Long Di

Expected Graduation Date: May 2016

Advanced flywheels operate at high rotating speeds to store a large amount of energy, which results in a high demand on the bearing system for stability and performance. Conventional rolling element bearings, sliding bearings and hydraulic bearings are not adequate to meet such a demand. Active magnetic bearings use magnetic forces to suspend the rotor and the forces they produce can be actively controlled. Moreover, they possess appealing features such as no mechanical contact, no friction losses, no wear, high speed capability and clean operation. As a result, active magnetic bearings are ideal for supporting high-speed flywheel rotors.

Compared with rotors in many other applications, rotors in flywheel systems are highly complex. First, in an effort to minimize the overall size of the system, the flywheel disk and the generator are usually mounted on the same shaft, causing a coupling effect between the generator and the rotor dynamics. Second, unlike applications where the ratio of polar-to-transverse moments of inertia is small and the gyroscopic effects can be neglected, the large flywheel disks generate strong gyroscopic effects that have to be taken into account in the design of the AMB controller.

The complexities of the flywheel systems entail sophisticated AMB controllers and the control of flywheel AMB systems has been studied extensively in the literature. Despite this abundance of resources in the literature, the experimental validation of the theoretical results presented in many of these papers has always been a difficult task. The reason is that it is very expensive and technically challenging to build a flywheel AMB test rig. Among many difficulties, specialized material and complex manufacturing techniques are required to withstand the stress of high speed rotation. We propose to emulate the rotordynamic characteristics of energy storage flywheels on the ROMAC flexible rotor AMB test rig (Figure 18). The test rig contains four AMBs with two located at the two ends of the rotor, one at the mid span and the other at the quarter span. The two AMBs at the mid and quarter spans of the shaft are used to emulate the negative stiffness of the generator and the gyroscopic effect of the flywheel disk. The simulation results have shown the negative stiffness provided by the generator causes a negligible effect on the rotor dynamics. The emulated gyroscopic forces generated by the exciter AMBs are similar to the actual gyroscopic forces produced by the gyroscopic matrix obtained from a previous finite element analysis, which demonstrates that the emulation approach presented is feasible.

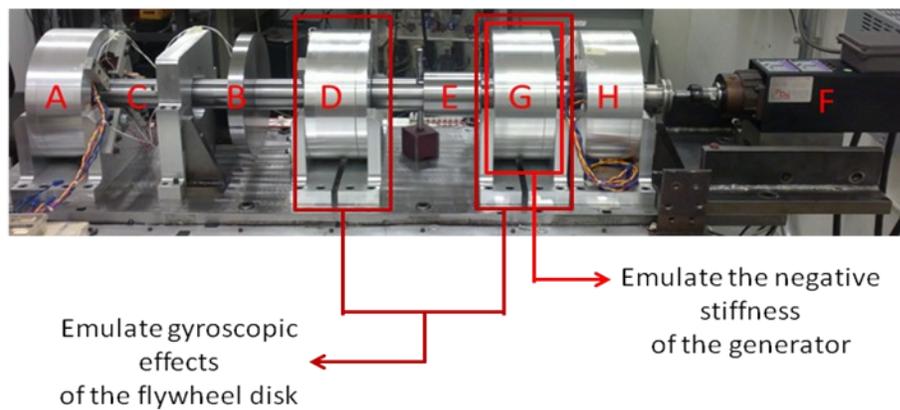


Figure 18. Exciter AMB functions.

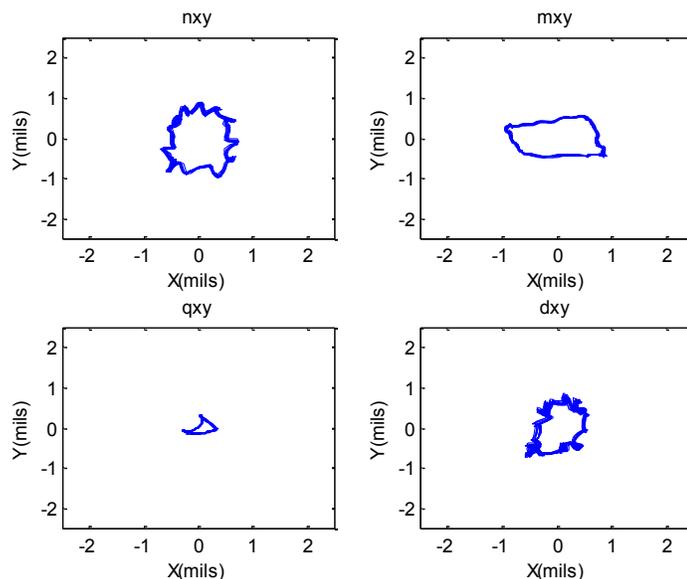


Figure 19. Rotor orbits without excitation forces.

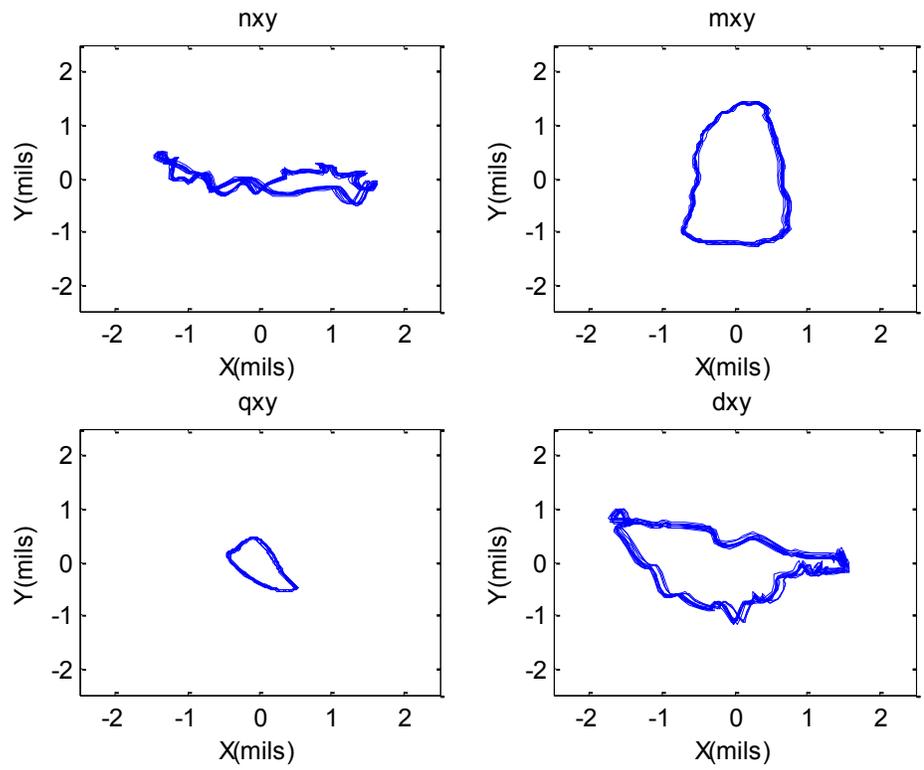
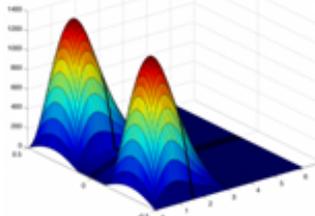


Figure 20. Rotor orbits with excitation forces.

## ROTATING MACHINERY & CONTROLS LABORATORY



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- Seals
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- Rotordynamics
- Magnetic Bearings and Controls
- Optimization of Rotor-Bearing Systems
- Experimental, Computational, and Theoretical Studies

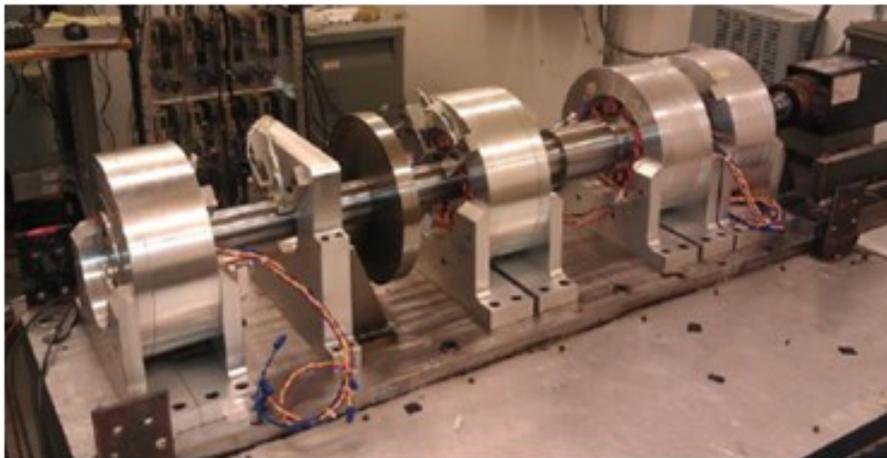


### Contact Us:

**Dr. Houston Wood**  
Professor and ROMAC Director  
Contact: [hwood@virginia.edu](mailto:hwood@virginia.edu)  
Office Phone: (434)924-6297

**Dr. Alexandrina Untaroiu**  
ROMAC Associate Director  
Contact: [au6d@virginia.edu](mailto:au6d@virginia.edu)  
Office Phone: (434)924-4547

**Dr. Roger Fittro**  
ROMAC Associate Director  
Contact: [rlf9w@virginia.edu](mailto:rlf9w@virginia.edu)  
Office Phone: (434)924-7703



**Dr. Christopher Goyne**  
Associate Professor  
Contact: [goyne@virginia.edu](mailto:goyne@virginia.edu)  
Office Phone: (434)924-5355

**Dr. Andres Clarens**  
Civil and Environmental Engineering  
Associate Professor  
Contact: [afc7r@virginia.edu](mailto:afc7r@virginia.edu)  
Office Phone: (434)924-7966

**Dr. Zongli Lin**  
Electrical and Computer Engineering  
Professor  
Contact: [zl5y@virginia.edu](mailto:zl5y@virginia.edu)  
Office Phone: (434)924-6342

### University of Virginia ROMAC Laboratory

Department of Mechanical and Aerospace Engineering  
P.O. Box 400746  
Charlottesville, VA 22904

(434) 924-3292  
[www.virginia.edu/romac](http://www.virginia.edu/romac)



**Dr. Robert Rockwell**  
Senior Scientist  
Contact: [rdr4u@virginia.edu](mailto:rdr4u@virginia.edu)  
Office Phone: (434)982-6129

For General Inquiries:

**Lori Mohr Pedersen**  
Administrative Office Assistant  
Contact: [Lori Mohr Pedersen](mailto:Lori Mohr Pedersen)  
Office Phone: (434)924-3292