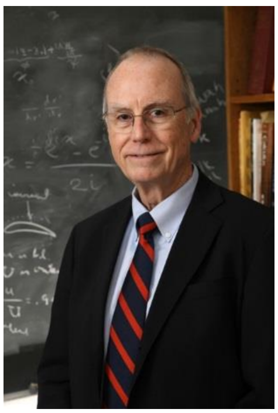
ROTATING MACHINERY & CONTROLS LABORATORY

ROMAC NEWSLETTER

Fall 2015 Issue

October 20, 2015

To ROMAC Industrial Members,



Houston Wood
Professor
Mechanical & Aerospace Eng.
Director of ROMAC

The last year was certainly an exciting one as we welcomed new students and faculty, celebrated graduations and new opportunities for those departing, and had a successful annual meeting of ROMAC members at the Wintergreen Resort. We are also happy to continue hosting many visiting scholars who have joined ROMAC labs for appointments of several months to a year. This ROMAC team is looking forward to another school year of insightful research, expanded capabilities, and new opportunities.

The summer brought about two significant changes within ROMAC and the Mechanical & Aerospace Engineering Department as a whole. Alexandrina Untaroiu, a long-serving senior scientist and associate director of ROMAC, recently accepted a position as an assistant professor at Virginia Tech. We celebrate this new opportunity for Alex and look forward to continuing our research collaborations with her as a visiting professor with ROMAC. Two graduate students who moved with her to Virginia Tech, Gen Fu and Hanxiang Jin, will also continue collaborating with ROMAC on various projects. Professor Hossein Haj-Hariri, who recently completed his tenure as chair of the Mechanical & Aerospace Engineering Department, has also rejoined ROMAC this year to support our ongoing mission of searching for new opportunities for research and expansion as an organization. Mehdi Saadat, a research scientist with a background in computational fluid dynamics who works with Hossein, also joins us to support our research program.

New ROMAC Member Companies

Our research efforts continue to expand to better serve our ROMAC member companies. In 2015, the ROMAC Consortium has added two new members in total. We welcome these newest members to the ROMAC community:

* Pioneer Motor Bearing Company, USA
* Southwest Research Institute, USA

Special points of Interest:

- *New ROMAC Member Companies*
- *New Graduate Students*
- *2015 Annual Meeting Summary*
- *Software Updates*
- *2015 ROMAC Reports*

Inside this issue:

ROMAC Graduate Students

After a significant number of ROMAC students graduated in 2014, this year only saw the graduation of two students. In May, Parinya Anantachaisilp finished his Ph.D. in Electrical & Computer Engineering and has since returned to his native Thailand to teach at the Royal Thai Air Force Academy. Jason Kaplan will graduate in December 2015 with a Ph.D. in Mechanical & Aerospace Engineering as he has begun a new position with Curtiss-Wright.

ROMAC welcomed three new graduate students for the fall 2015 semester. Xin Deng will pursue a Ph.D. in Mechanical & Aerospace Engineering with a research focus on fluid film bearings. Syed Ali Asad Rizvi is a new Ph.D. student in the Electrical & Computer Engineering department and will be performing research on magnetic bearings. Paul Gancitano also joins us as an M.S. student in Electrical & Computer Engineering with research interests in magnetic bearings related to the fluid film bearing test rig.

We also have three undergraduate students working with us this semester: Theodoric Xie and Byung Joo Shin are both in their 4^{th} year of Electrical & Computer Engineering and Kai Eubanks is a 2^{nd} year in Computer Science. Please see the ROMAC student page of the website for more details about each student.

ROMAC Visiting Scholars

ROMAC is currently host to several visiting scholars with anticipation of several more joining us during the Fall 2015 semester. Our visitors come from various locations, through various sponsorships, and with appointments ranging from a few months to a year.

*__Dr. Zhenyu Xie__, an Associate Professor at the Nanjing University of Aeronautics and Astronautics, China, has been involved in research regarding active magnetic bearing systems. His appointment continues through December 2015.

*__Dr. Jossana Ferreira__, a Professor from the Federal University of Rio Grande do Norte, Brazil, studies bearingless machines. She is collaborating with Roger Fittro and others through the end of her appointment in January 2016.

*__Dr. Yuan Yu__, a visiting scholar from the Beijing University of Chemical Technology, China, studies particle separation turbomachinery and is collaborating with Mehdi Saadat and others through February 2016.

*__Dr. Yanhua Sun__, an Associate Professor from Xi'an Jiaotong University, China, will continue collaborative research with Professor Zongli Lin on rotordynamics through May 2016.

*__Dr. Jingxin Kang__, a Lecturer at the Beijing University of Chemical Technology, China, has research interests in the simulation of heat transfer and is collaborating with Brian Weaver. Her appointment is through January 2016.

*__Yee-Hiung Kuo__, of the National Chung-Shan Institute of Science and Technology, Taiwan, is with ROMAC through November 2015. He is collaborating with Roger Fittro on rotordynamic modeling, analysis, and vibration diagnosis.

We are currently working with six additional scholars from various universities and institutes in China who will be joining ROMAC within the next few months. Please check the website for more information regarding our visiting scholars, their research interests, and appointment dates.

2015 Annual Meeting Summary

The 2015 Annual Meeting was held in early June at the mountainous Wintergreen Resort in Wintergreen, Virginia, about an hour's drive from the University of Virginia. The weather was a bit cloudy and rainy but the company was good! The meeting brought together over 40 industry members along with faculty, students, staff, visiting scholars, and invited guests.

The week began with our faculty, students, and industry participants holding a one-day Short Course. The interaction between the instructors and attendees was very engaging and we plan to offer this again in 2016. Monday evening attendees met and mingled during our welcome reception. The following morning the meeting opened with remarks by Professor James Aylor, Dean of the Engineering School, and Professor Hossein Haj-Hariri, Chair of the Mechanical and Aerospace Engineering Department, followed by an overview of the current state of ROMAC by Professor Houston Wood, ROMAC Director. Over the next few days 36 talks were given, colleagues conversed, new members met long-time members, and new research ideas were presented and discussed. Another highlight of the meeting was a tour of the Daikin-Applied facility in nearby Verona along with a sponsored lunch for attendees.

The annual meeting survey provided members with additional opportunities to provide feedback on research projects, software development, and the organization of ROMAC. Results included a general emphasis on bearings and rotordynamics, upgrades to the RotorLab+ software package and fluid film bearing analysis tools, seal code development, fluid film bearing and bearing damage test rig development, surge control, and magnetic bearing control with input delay. See the below Software Updates and Summary of Research Projects sections for recent updates on these topics.

The 2016 Annual Meeting will be held June 6 - 10 in Charlottesville, Virginia. The planning is well underway and updates on the details of the meeting will be posted to the ROMAC website. Sponsorships by member companies are welcomed. Please see the website for details.

Figure 1. 2015 ROMAC Annual Meeting Attendees.

2016 Rotordynamics Short Course

A rotordynamics and magnetic bearings short course is planned for July 11-15, 2016. 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 member companies.

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 laboratory at the University of Virginia, member locations, or other locations more convenient to attendees.

Please contact us at romac@virginia.edu for more information.

Software Updates

This year saw a number of developments in our software program, the biggest being the upcoming release of RotorLab+ 4.0. This version of our primary software suite comes with a number of new features including the API Spec Check Workspace. This workspace provides users with the ability to perform API audits in accordance with API 617 8th Ed., including automated runs of bearing and rotordynamic analyses for minimum and maximum design specifications as well as flexible graphing capabilities. See the below figure for more information on the latest version due to be released in the coming weeks. A test version, RotorLab+ 3.2, is currently available via the Early Adopters program for members to explore these new features and provide feedback to our developers.

RotorLab+ 4.0 Features

- API Spec Check Workspace
- New bearing, squeeze film damper, and seal codes MAXBRG, SQFDAMP, DamperSeal, and HybridSeal
- Linear couplings and thrust bearings for assembly analyses
- Copy projects between Assembly and API Workspaces
- Project import and export via .zip files for sharing between colleagues
- Example projects and tutorial information
- New plotting options

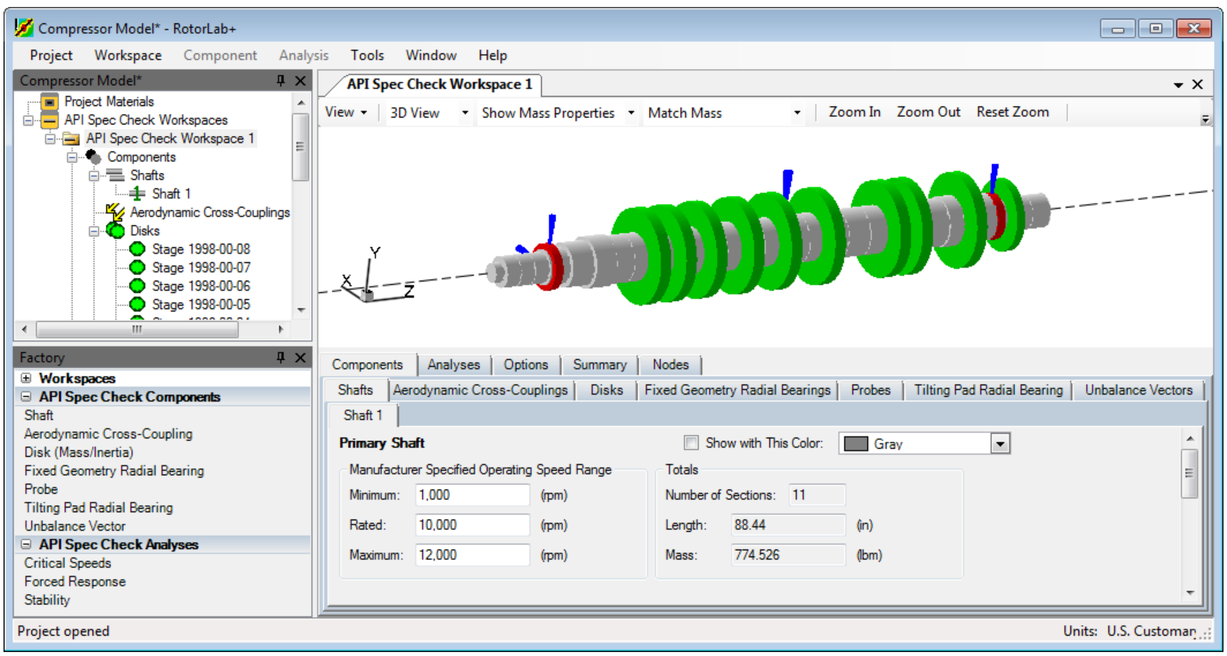


Figure 2. RotorLab+ 4.0 features and interface.

In June, the latest version of THRUST (v5.30) was released which includes new options for parallel computing control, new pad geometries, and control over inputs to the turbulence model. Our collaborative work with Ted Brockett on this code is expected to continue as additional features requested by the membership are incorporated into the program. By popular demand there are also future plans to incorporate THRUST into RotorLab+.

SLEEVEBRG, a new code for fixed geometry bearings lubricated with low-viscosity fluids, was released in September. This code is a 2D solver for an extended Reynolds equation that includes the effects of turbulence as well as convective and temporal inertias. Outputs to this code include pressure profiles, eccentricity, shaft equilibrium position, log dec, as well as stiffness, damping, and added mass coefficients. It is also planned to incorporate SLEEVEBRG into future versions of RotorLab+.

Other software releases are currently being planned for this fall and winter including the release of a new squeeze film damper code MAXSFD. Please contact our Software Engineer Brian Weaver at bkw3q@virginia.edu with any software-related questions.

Summary of Research Projects

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

A Study on State-Dependent Time-Transient Rotor Dynamics of External Spur and Helical Geared Systems

Student: Jason Kaplan
Expected Graduation Date: December 2015

Predictions of the response of rotating machinery to external forces and assessments of system-level stability for different modes are crucial from a reliability and preventive maintenance perspective. Geared systems, in particular, contain many complexities such that the use of extensive computational effort is required to achieve accurate modeling. Sources of dynamic complexity at the gear mesh include non-linear tooth contact loss due to backlash clearance and parametric excitations from state-varying mesh stiffness effects. Although various methods for determining the effects of dynamic meshing forces on the vibrations of rotor-bearing systems are presented in the literature, these models are either overly simplistic or require immense computational effort. Several time-transient and steady-state models for analyzing gear forces and deflections have been proposed, but those authors have focused primarily on the dynamics of the gearbox instead of vibration transmission through the remainder of the drive-train.

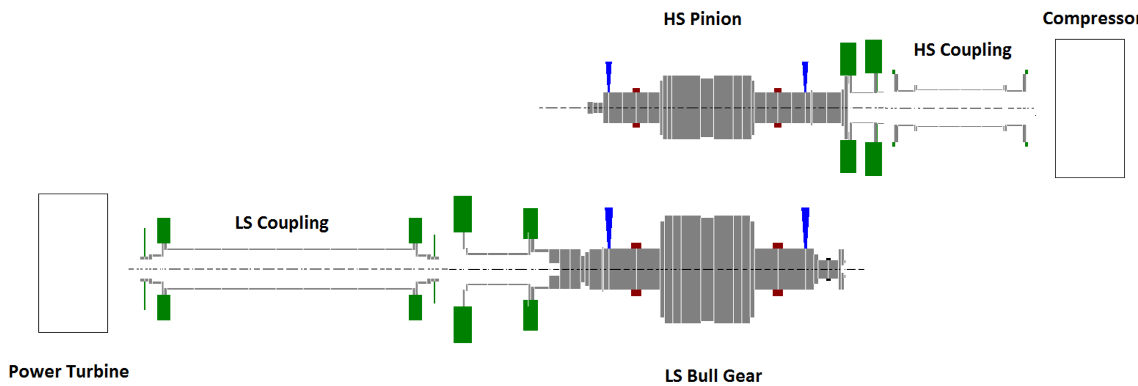


Figure 3. Finite element model of a power turbine-compressor gearbox and train.

This research uses the finite element method to couple the lateral, torsional, and axial motions of the gear and pinion to the mesh forces and moments via element stiffness matrices. A finite element formulation of complete rotor-bearing systems, which couples the axial, lateral, and torsional degrees-of-freedom of geared shafts, is developed that resolves the generalized forces and displacements along the gear mesh line of action with those of the shaft global reference frame. State-varying mesh stiffness is incorporated and contributes to parametric excitations at the gear mesh interface. Gear tooth backlash is modeled as a piece-wise linear function that is dependent on the dynamic transmission error at each time step. Rotational accelerations are accounted for in the equations of motion and are applicable to analyzing start-up or wind-down conditions. The nodal displacements, velocities, and forces are evaluated at each time step via the direct Runge-Kutta method.

The primary objective of this study is to extend the existing modeling for parametric excitations due to state-varying mesh stiffness to more realistic geared-shaft-bearing finite element models. In addition, such a study will promote discussion of the many parameters involved in the modeling of state-varying mesh stiffness and how they can influence the transient behavior.

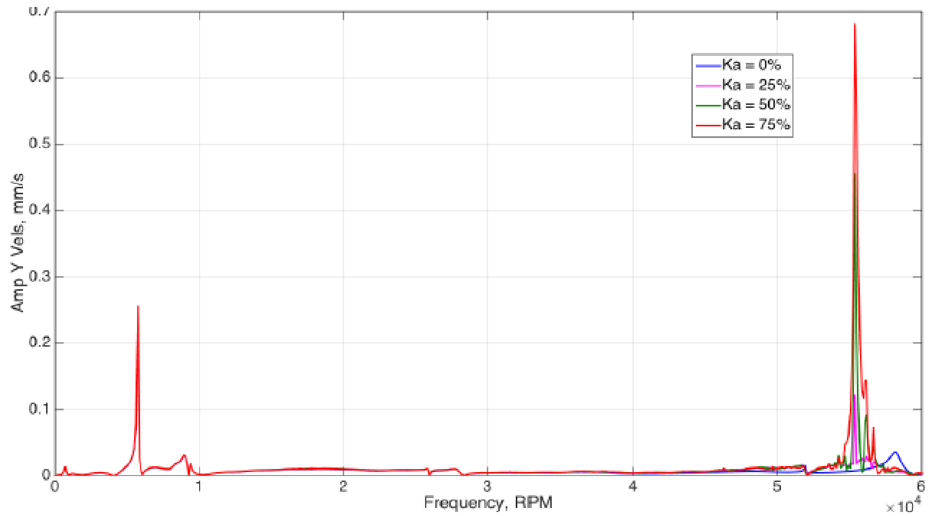


Figure 4. Y velocity FFT of a gear node illustrating 10x (57,000 RPM) sensitivity to state-varying mesh stiffness.

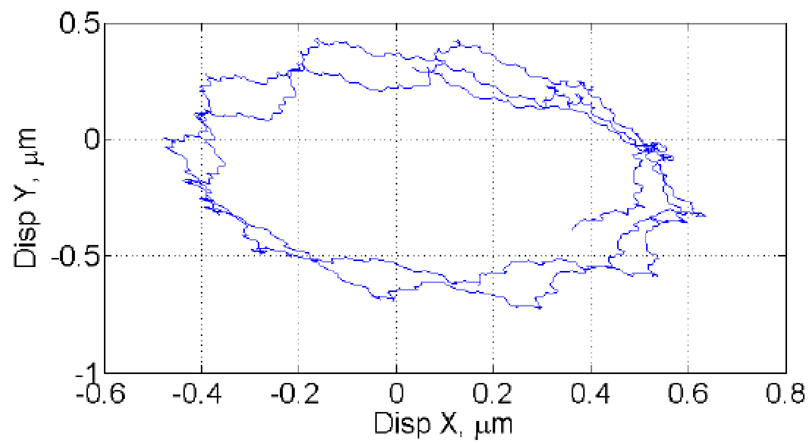


Figure 5. X-Y orbit plot of a gear node depicting 10x vibration with state-varying stiffness.

Experimental Measurements of Damping Ratios and Stability of a Flexible Rotor under Reduced Bearing Lubrication Flow Rates

Student: Brad Nichols
Expected Graduation Date: May 2016

Many high-speed rotating machines across a wide range of industrial applications depend on fluid film bearings to provide both static support of the rotor and to introduce stabilizing damping forces into the system through a developed hydrodynamic film wedge. Reduced oil supply flow rate to the bearings can cause cavitation, or a lack of a fully developed film layer, at the leading edge of the bearing pads. Reducing oil flow also has the well-documented effects of higher bearing operating temperatures and decreased power losses caused by shear forces. While machine efficiency may be improved with reduced lubricant flow, little experimental data on its effects on system stability and performance can be found in the literature.

Data collection was completed this spring for an experimental investigation designed to study the effects of incrementally reduced oil supply flow rates on both steady-state bearing performance and overall system stability. The test rig used in this study was designed to be dynamically similar to a high-speed industrial compressor. The test rig consists of a 5-foot long, flexible rotor supported by two tilting pad bearings with a nominal diameter of 2.752 inches and a span of 4 feet. The first bending mode is located at approximately 5,000 rpm. The tilting-pad bearings consist of five pads in a vintage, flooded bearing housing with a length to diameter ratio of 0.75, preload of 0.3, and a load-between-pad configuration.

Data was collected under a range of operating conditions with rotational speeds ranging from 2,000-12,000 rpm and bearing loads of 18, 35, and 53 psi. At each operating condition, the oil supply flow rate to the bearings was incrementally reduced as a percentage of the nominal rate and testing was conducted. Steady-state bearing performance indicators such as pad temperatures, journal operating position, and power loss estimates were all recorded. Sine-sweep excitations from a magnetic shaker were used to obtain experimental frequency response functions (FRFs) using a single-input, multiple-output (SIMO) frequency domain technique. Data post-processing and system identification efforts are currently underway to curve fit the data to obtain damping ratios and damped natural frequencies. All experimental results will be compared to rotordynamic models which utilize bearing coefficients obtained from MAXBRG, a bearing analysis code based on thermoelastohydrodynamic (TEHD) theory.

For nearly all operating conditions, a low-amplitude, broadband, sub-synchronous vibration pattern was observed in the frequency domain that increased in amplitude with decreasing oil supply flow rate. When the test rig was operated above its first bending mode, a distinctive peak emerged from the broadband pattern at approximately half of the running speed and at the first bending mode of the shaft. As illustrated in Figure 6, this vibration signature is often considered a classic sign of rotordynamic instability. Under all operating conditions, the amplitude of this ~0.5x sub-synchronous peak increased with decreasing oil supply flow rate. Preliminary examination of the FRFs appears to indicate an increase in the first mode's amplification factor with decreasing flow rate. Figure 7 shows the FRFs obtained under three different flow rates at 11,000 rpm and a bearing load of 18 psi. A full dissertation and report are currently in progress and will contain the identified modal parameters for all experimental test cases, as well as comparisons to the numerical models.

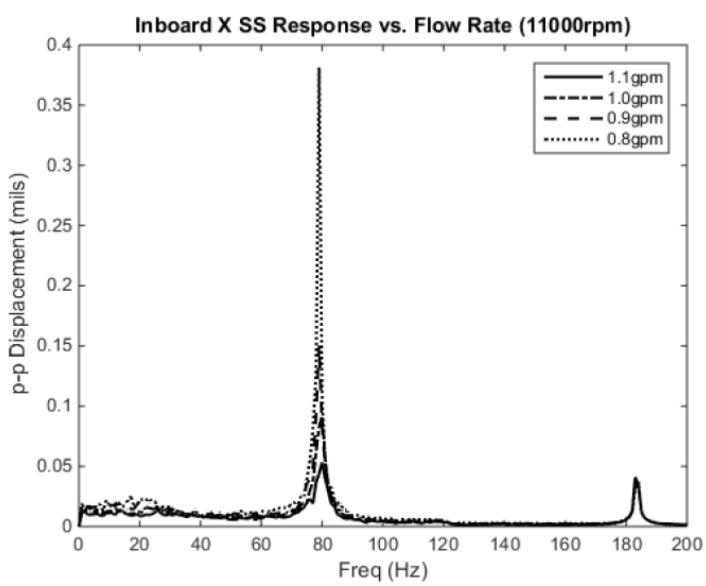
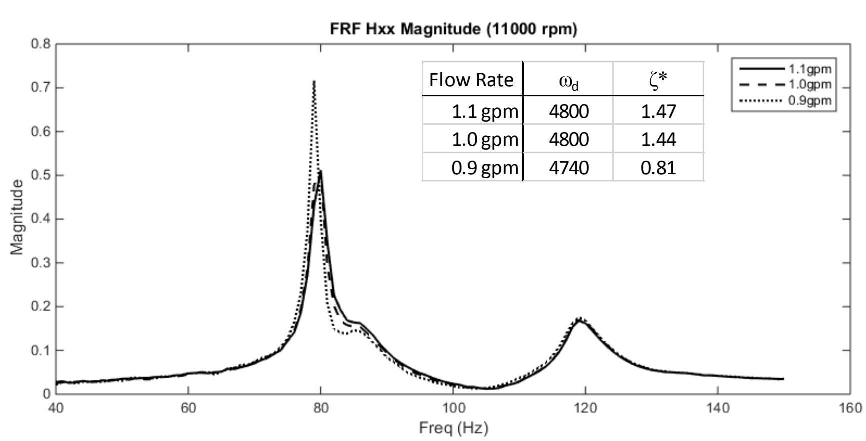


Figure 6. Sub-synchronous vibrations vs. oil supply flow rate.



**Obtained using half-power estimation method*

Figure 7. Experimental FRF, 11,000 rpm, 18 psi bearing load.

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 direct optimization methods to the design process of a labyrinth seal, and to improve design analysis tools for labyrinth seals. Current projects involve a review of analysis methods, a compilation and analysis of empirical factors used for bulk flow analysis, and research to improve the accuracy and speed of bulk flow methods for the future.

Presently, labyrinth seals are analyzed with a variety of numerical methods, the most common being computational fluid dynamics (CFD) and semi-analytical bulk flow methods. CFD is the most accurate method of determining seal leakage and stability performance. However, to determine the stability behavior of a seal with CFD a large number of full 3D simulations are required at different whirl speeds which can require very long analysis times. These simulations are often individually comprised of millions of mesh elements and may take hours or days to complete. In contrast, bulk flow methods often provide results within minutes by using comparatively large control volumes and numerically solving simplified Navier-Stokes equations and perturbations. These methods are typically less accurate because they require the use of multiple assumptions and experimentally-derived coefficients to produce reasonably accurate results. Additionally, there are multiple bulk flow methods available in the current literature that each come with different tradeoffs or are limited to use with specific applications. Unfortunately, the bulk flow analysis methods also require the use of several empirical coefficients such as friction factors. Determining these coefficients requires physical experimentation or computational simulation to measure a pressure profile along each seal wall and calculate the rotordynamic forces which can then be used to calculate the empirical coefficients. Once the empirical coefficients are found they continue to be useful, but only for the particular geometry and similar operating conditions to those tested. This presents a difficulty for the efficient analysis of seals when the rapid analysis of varied seal designs requires multiple additional experiments or simulations of considerable material or computational cost.

This study compiles empirical coefficients relating to the bulk flow analysis of annular seals from the existing literature. These coefficients are then compared and connected by statistically obtained predictive models. These models provide response surface maps of the effects of various seal design parameters and operating conditions on the empirical factors employed and allow the estimation, by interpolation, of friction factors and other empirical seal coefficients for seals not yet physically tested or computationally modeled. Additionally, methods are under investigation to improve the accuracy of bulk flow methods and the flow characterization in grooves. Potentially these methods include compressible potential flow, immersed boundary 2-D computational fluid dynamics (CFD), and hybrid bulk flow/CFD methods.

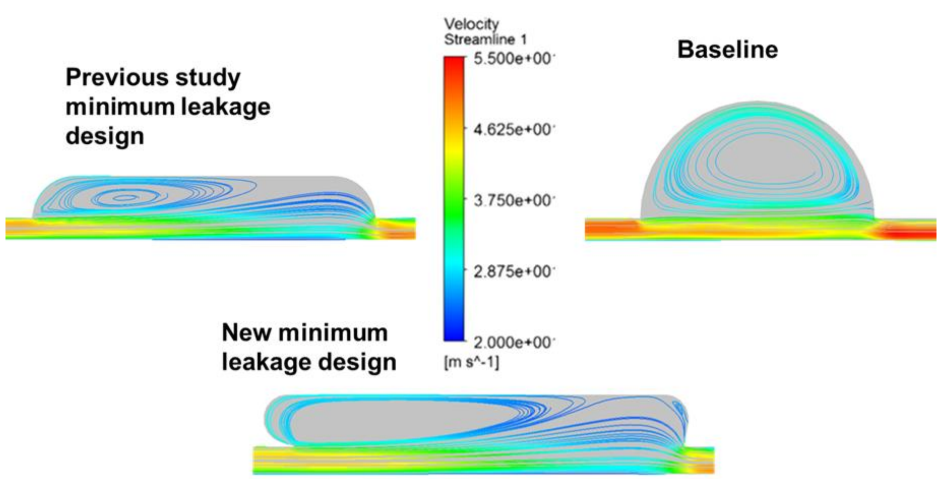


Figure 8. Groove shape comparison- baseline vs. predicted optimum.

Effect of Hole Tilt and Scale on the Performance of an Annular Hole-Pattern Seal

Students: Neal Morgan & Thomas Gresham
Expected Graduation Date: May 2016

Hole-pattern annular gas seals have been proven to be very effective in reducing leakage flow between high and low pressure sections in turbomachinery. This type of seal has two distinct flow regions: an annular jet-flow region between the rotor and stator, and cylindrical indentions in the stator that serve as cavities where flow recirculation occurs. The geometry of the cylindrical cavities has a significant effect on the overall performance of a hole-pattern annular gas seal. Previous studies have primarily focused on cylindrical cavities that are perpendicular to the axis of the seal and have indicated that the performance may be improved by varying the depths, spacing, and diameters of the cavities. However, to date the effects of the tilt of these cavities has yet to be investigated. In this study, the effects of hole pattern geometry and tilt angle on the leakage and dynamic response performance of an industry-relevant hole patter seal design are investigated using a combination of computational fluid dynamics (CFD), hybrid bulk flow/CFD analysis, and design of experiments techniques.

A CFD model of the baseline hole-pattern seal was first developed and validated against experimental data. A mesh independence study was also performed to ensure a robust analysis domain. A design of experiments study was then performed to investigate the effect that tilting the cylindrical cavities had on the leakage rate through the seal. CFD simulations were performed for multiple geometry configurations of the cylindrical cavities. The angle of axial tilt was varied between 45 and 135 degrees, measured counterclockwise from the axis of the seal. The angle of circumferential tilt was also varied from 45 to 135 degrees. From this initial set of simulations, the optimum angle of tilt was chosen as a reference angle from which to conduct further simulations. The next set of simulations involved varying the angle of tilt by a small amount, while also varying the hole depth, diameter, and spacing between adjacent rows of holes.

This detailed analysis allowed for a greater understanding of the interaction effects from varying all of these design parameters together as opposed to studying them one variable at a time. Response maps generated from the calculated results demonstrate the effects of each design parameter on seal leakage as well as the relationships between the design parameters. The data from this analysis was also used to generate linear regression models that demonstrate how these parameters affect the leakage of the seal. When completed, the results of this study can be used to improve future designs of hole-pattern annular gas seals.

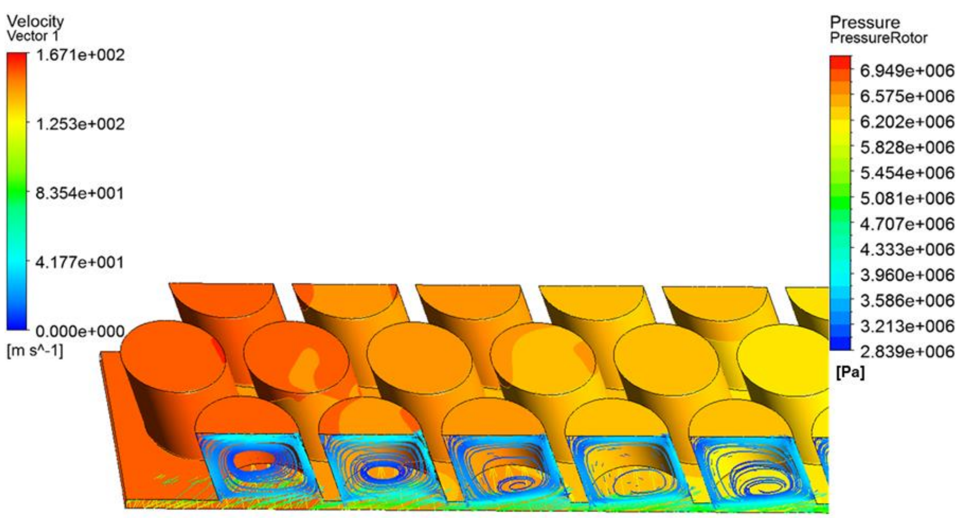


Figure 9. CFD analysis of a tilted hole-pattern seal design.

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. 10 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.

The task of modeling a brush seal and accurately predicting its performance has proven to be a complicated multi-disciplinary engineering problem. The use of CFD and empirical data allows for further development of the governing equations and empirical correlations. Some of the relevant modeling challenges include: bristle flutter, turbulent flow, blow-down effect, bristle-heating, prediction of leakage, and prediction of rotordynamic coefficients.

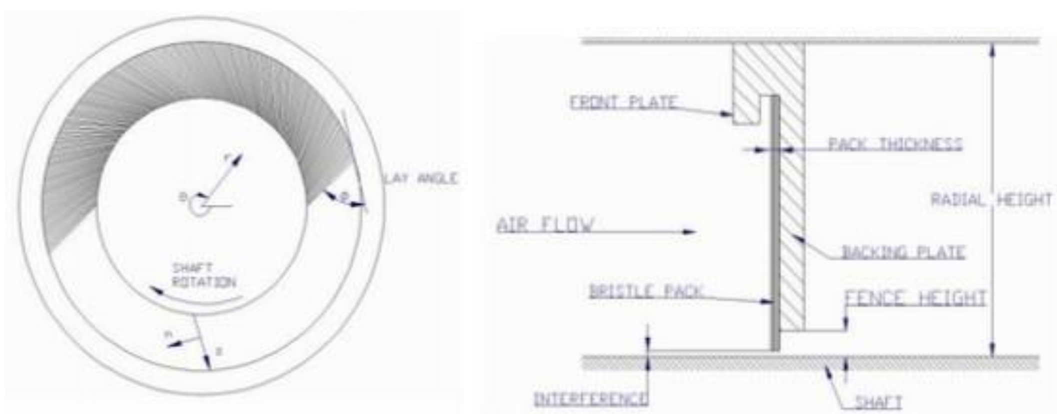


Figure 10. Schematic of a brush seal.

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.
*Characterize the changes in permeability of the seal as operating conditions are varied.
*Explore ways to improve the design of a brush seal by using analytical methods and numerical simulations.
*Develop a bulk flow method for analyzing brush seals to quickly obtain reliable information on how a particular design would perform.

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.

In the first half of 2015 a comprehensive analysis of predicted uncertainty in measured dynamic coefficients was completed and the results indicated that the design of the test rig needed to be modified. To minimize the final measurement uncertainty new technologies such as the "Active Load Cell" concept are being evaluated. All of the possible design changes are being simulated in a high-fidelity Simulink model in an attempt to fully understand the dynamics of the system and make sure significant factors are not overlooked.

The goal of fall 2015 and spring 2016 is to complete the high-fidelity model and determine the final design of the FFBTR. This will allow for the procurement of parts and creation of detailed drawings for manufacturing.

During this entire process we desire to continue working 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 upcoming progress review meetings where current progress and future plans will be presented and discussed.

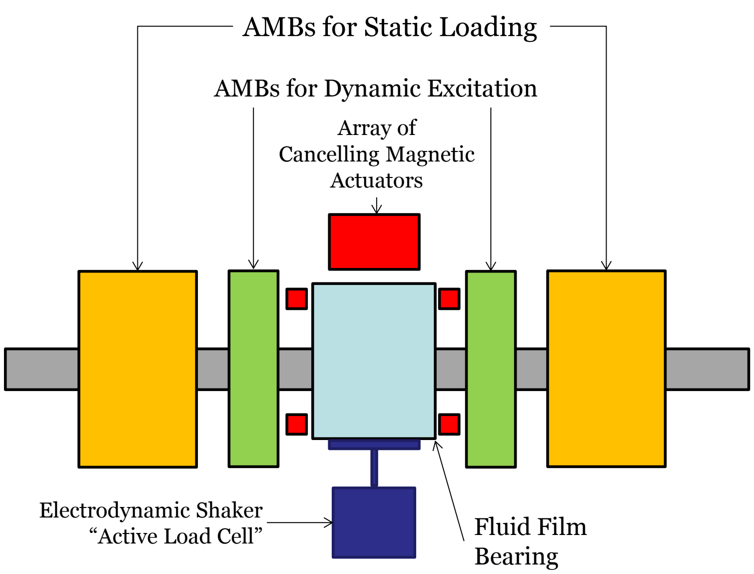


Figure 11. Proposed redesign of the FFBTR.

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. By developing a specialized test rig, the reduction in load capacity of a scratched journal bearing will be quantified by temperature, pressure, and film thickness measurements. A combination of artificial scratches (of varying depth and width) will be tested at various loads and speeds. The damaged and undamaged bearing temperatures, film pressures, and 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 and will be used by ROMAC to enhance the capabilities of existing bearing codes.

The test rig design consists of a 3" (76.2mm) diameter shaft located in a fluid film journal bearing (L/D=1 to L/D=.5). A load can be applied by means of a pneumatic cylinder and the shaft is driven by a 5 HP motor. The test rig has been designed for unit loads up to 350 PSI and speeds up to 5400 RPM.

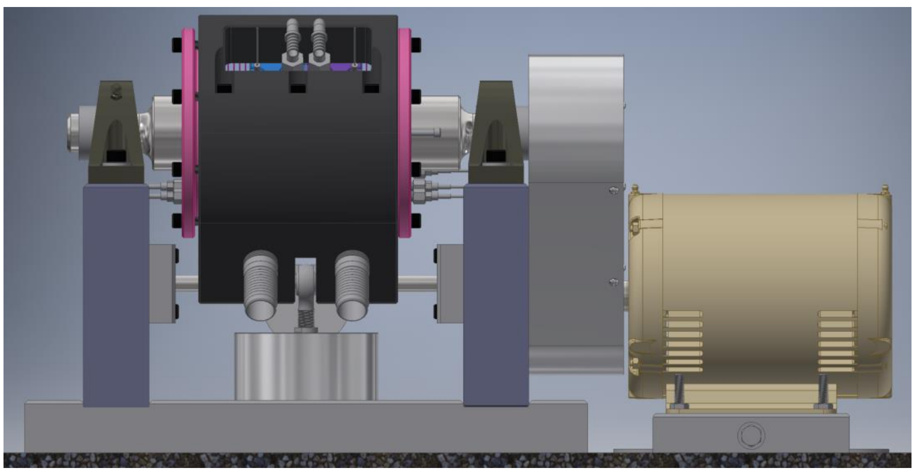


Figure 12. Side view of the scratched bearing test rig design.

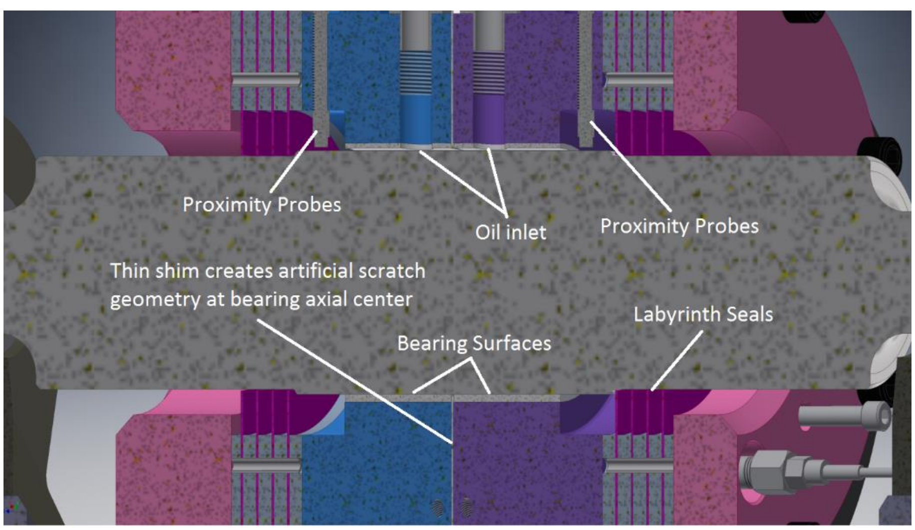


Figure 13. 45 degree cross-section of the bearing test section. Note the shim between the two bearing halves which creates an artificial scratch geometry.

Study of API Standard Paragraph 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. This specification allows manufacturers to neglect pedestal dynamics, thereby saving analytical expenses, if the pedestal exceeds this threshold. Due to the suspected influence of pedestal dynamics on potentially problematic machines in industry, the effectiveness of the 3.5 threshold ratio is being investigated. The current state of this project shows that the pedestal stiffness alone does not validate the neglect of support dynamics.

Three system models of increasing complexity are analyzed in the investigation; they are shown in the schematic below.

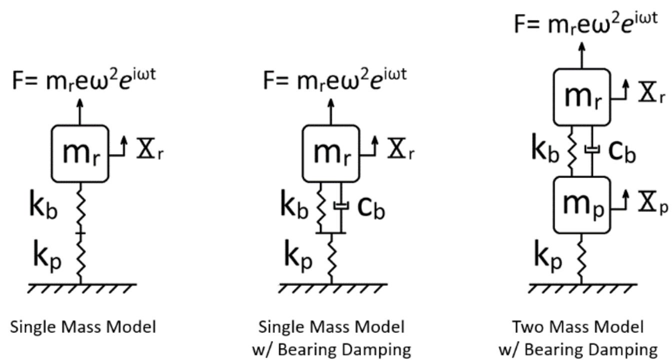


Figure 14. Models analyzed for the pedestal support investigation.

The initial single-degree-of-freedom model shows that a support stiffness ratio of 3.5 relative to the bearing stiffness results in an equivalent stiffness of 78% of the bearing stiffness and a natural frequency of 88% of the rigid support natural frequency. This natural frequency can be interpreted as the first critical speed of the rotor. When the bearing damping is included in the model, a system with a stiffness ratio of 3.5 results in an amplification factor of 3.92 as compared to a system with a rigid support having an amplification factor of 2.5. The third system includes a support mass, which splits one critical speed into two, significantly changing the natural frequency of both modes. Further analysis of the two-degree-of-freedom model shows that although a support may have a static stiffness well above the threshold ratio of 3.5, the natural frequency of the compliant support system may lie well within the operating speed range of the machine. The inclusion of the support mass (or natural frequency) reveals that the effect of the support structure is not limited to static stiffness alone; a dynamic influence must be considered as well.

Unbalance Compensation for AMB Systems with Input Delay: an Output Regulation Approach

Student: (Dee) Long Di
Expected Graduation Date: August 2016

Unbalance compensation is an important technique for reducing rotor vibration in high speed rotating machines caused by residual rotor unbalance. As rotating machines in remote applications aim for higher speeds to gain efficiency and reduce footprint, there is a need to extend the unbalance compensation techniques to active magnetic bearing (AMB) systems with delays in the control loop.

A technical challenge that needs to be addressed in the control of AMB systems in remotely operated compressors has to do with the communication delay introduced by the cabling system. Because the electronics driving the AMB actuators are sensitive to their environment, manufacturers many times choose to install the AMB control electronics at the control site, separated from the AMB actuators that are integrated to the remote machine. Long cables are then needed to connect the electronics to the actuators which may add significant transmission delays in the control loop. Such delays may rapidly degrade the performance and stability of AMB systems, leading to undesired machine downtime or even catastrophic machine failures. Therefore, the presence of input delays in the control of AMB systems needs to be explicitly addressed in the design of the rotor levitation controller.

High speed rotating machines are also susceptible to large disturbance forces caused by rotor unbalances. A residual unbalance on a rotor can generate disturbance forces synchronous to the rotating speed, causing the rotor to go into a whirling motion. To reduce the effect that the rotor unbalance has on high-speed AMB systems, unbalance compensation, or autobalancing methods, have been studied and developed over the years. When designed and implemented correctly these methods can significantly reduce the disturbance forces acting on the rotor by allowing it to spin about its center of mass. The interest on rotor unbalance methods has increased rapidly in recent years as high speed AMB applications become more common, and the accessibility of digital controllers makes complex control algorithms easily implementable.

This work investigates an unbalance compensation problem for AMB systems with input delays. In particular, we derive and experimentally validate an unbalance compensation method based on the solution to an equivalent output regulation problem. Precise location and eccentricity of a rotor unbalance are difficult to measure in rotating machines. Instead, the locations of the unbalance forces in our mathematical model are strategically selected to reproduce the relevant rotor vibration patterns. The resulting model-based unbalance compensation controller is demonstrated experimentally to significantly reduce the synchronous rotor vibrations and the magnitude of the AMB control input.

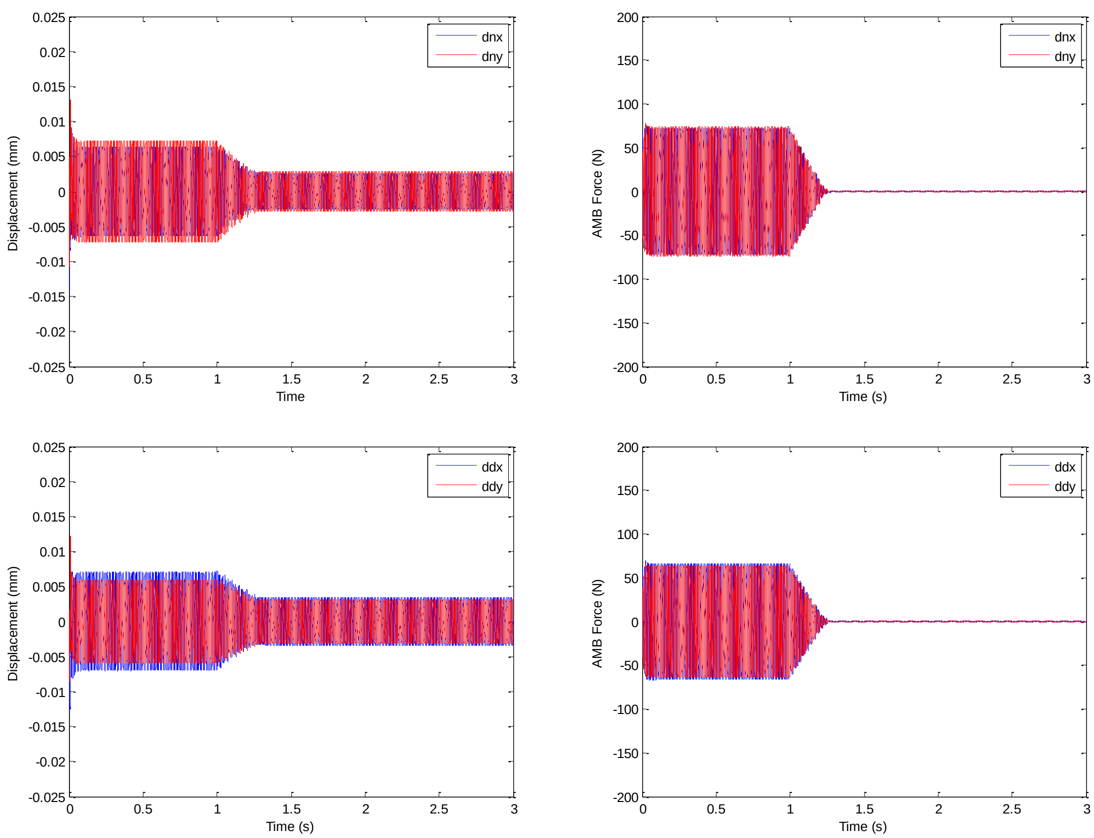


Figure 15. AMB force regulation (6,000 rpm and delay τ = 0.5 ms).

Table 1. Experimental result comparisons (6,000 rpm and delay τ = 0.5 ms).

	DEX Vib/mm (pk-pk)	DEY Vib/mm (pk-pk)	DEX Control/v (pk-pk)	DEY Control/v (pk-pk)	NDEX Vib/mm (pk-pk)	NDEY Vib/mm (pk-pk)	NDEX Control/v (pk-pk)	NDEY Control/v (pk-pk)
Without regulation	0.0413	0.0316	0.5779	0.5826	0.0552	0.0629	1.0874	1.5233
Displacement regulator	0.0257	0.0266	0.6644	0.8082	0.0214	0.0264	1.0462	1.3011
Force regulator	0.0206	0.0296	0.3411	0.4492	0.0280	0.0270	0.4016	0.5126

Improved Fluid Film Bearing Prediction Tools

Student: Michael Branagan
Expected Graduation Date: May 2017

Predicting the response of bearings is a vital part of rotor system design, particularly as machines are being run at ever-increasing speeds and energy densities. The ROMAC code MAXBRG is a powerful predictive tool for several types of fluid film bearings. However, maintenance and upgrades are imperative for keeping the code at the forefront of fluid-film bearing analysis. In particular, validation cases have shown that the dynamic coefficients calculated by MAXBRG may be approximately correct but still have room for improvement. Power loss, operating eccentricity, pressure, and temperature tend to be accurately predicted, at least for the suite of validation cases available to ROMAC. Unfortunately, validation cases relating to pressure dam bearings, leading edge groove bearings, and bearings operating in a starved condition are largely absent in the open literature.

Specific upgrades for MAXBRG that have been identified include an improved mixing model for hot-oil carryover, improved turbulence models that could apply to low viscosity operating fluids, and the ability to include bearing surface irregularities such as jacking grooves and scratches. Additionally, specific solution cases have been known to cause poor convergence in MAXBRG as well as extremely long run times. This has been addressed in part by recompiling the MAXBRG source code with a more up-to-date FORTRAN compiler than was used previously. Typical run time reductions of 50% or more have been demonstrated using a number of MAXBRG test cases. Further reductions in the run time would make MAXBRG a more useful design tool for doing parametric and trade studies.

Table 2. MAXBRG test cases show a significant reduction in run time.

Bearing	Flow Type	Thermal	Deformation	Old (sec)	New (sec)	% Diff
LEG Tilt Pad	Reg Flooded	Full Thermal	No Deformation	1338.2	624.3	53.3
Tilt Pad	Reg Flooded	Full Thermal	Shaft, Shell, Pad, and Pivot Def	1681.5	776.0	53.8
Tilt Pad	Reg Flooded	No Thermal	No Deformation	71.8	33.1	54.0
Tilt Pad	Reg Flooded	No Thermal	No Deformation	62.3	26.6	57.3
Tilt Pad	Starvation Model 1	Full Thermal	Shaft, Shell, Pad, and Pivot Def	2274.5	1083.6	52.4
Tilt Pad	Reg Flooded	Full Thermal	No Deformation	1309.3	596.4	54.4
Spray Bar	Reg Flooded	Full Thermal	No Deformation	570.4	273.4	52.1
Tilt Pad	Reg Flooded	Full Thermal	Shaft, Shell, Pad, and Pivot Def	9661.0	4008.4	58.5
Tilt Pad	Starvation Model 1	Full Thermal	Shaft, Shell, Pad, and Pivot Def	65729.9	27063.2	58.8
Tilt Pad	Reg Flooded	Full Thermal	Shaft, Shell, Pad, and Pivot Def	10523.5	4392.5	58.3
Tilt Pad	Reg Flooded	Full Thermal	Shaft, Shell, Pad, and Pivot Def	9573.7	4001.9	58.2
					Average	55.6

RotorSol - Continual Development Plans

Student: Michael Branagan
Expected Graduation Date: May 2017

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 preventative maintenance perspective. ROMAC has multiple tools to assist with this prediction ranging from critical speed maps 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 currently being linked with RotorLab+, ROMAC's latest software platform. 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: i) adding new components such as gears; ii) new forces such as shaft bow and nonsynchronous forces; iii) new element capabilities such as internal damping, tapered elements, and distributed mass; iv) new analytical tools such as critical speed maps and Campbell diagrams; and v) new options such as inclusion of user specified matrices.

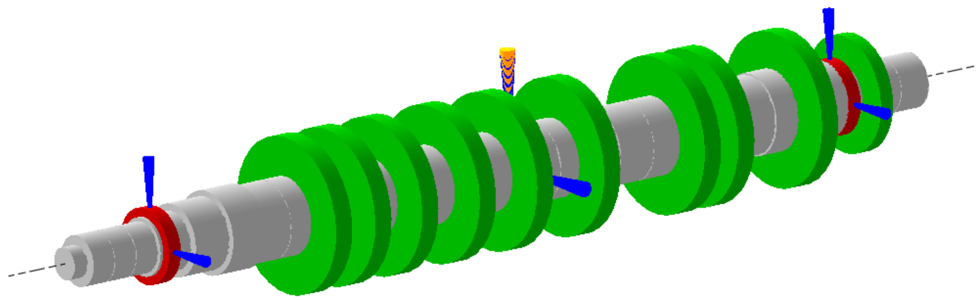


Figure 16. Rotor finite element model.

Bulk Flow Methods for Helical Groove Seals

Student: Cori Watson
Expected Graduation Date: May 2017

Helical groove seals are non-contacting annular seals used in rotating machinery to reduce the leakage of fluid. In the helical groove seal, a groove is continuously cut, like the threads of a screw, across the surface of the rotor, the stator, or both. Helical groove seals are often viewed as a subset of labyrinth seals because they have the same axial profile, and because both seals work by dissipating kinetic energy as the fluid expands in each groove and is then forced through the jet stream region. However, unlike the labyrinth seal, the helical groove seal also benefits from acting as a pump. The geometry is equivalent to a screw pump and displaces the fluid forward as the rotor spins. In other words, helical groove seals reduces leakage by pushing back the fluid as fast as it tries to escape. Because of the combination of these two sealing mechanisms, helical groove seals can sustain higher pressure drops than labyrinth seals. Helical groove seals have also been shown to be more stable than labyrinth seals because the pumping action reduces circumferential velocity. Unfortunately, helical groove seals are not axially or circumferentially symmetric and therefore are difficult to analyze using computational fluid dynamics methods such as ANSYS CFX. The objective of this research is to develop a computationally efficient code for analyzing these seals. Hirs bulk flow method with three control volumes has been utilized for this code which is written in MATLAB.

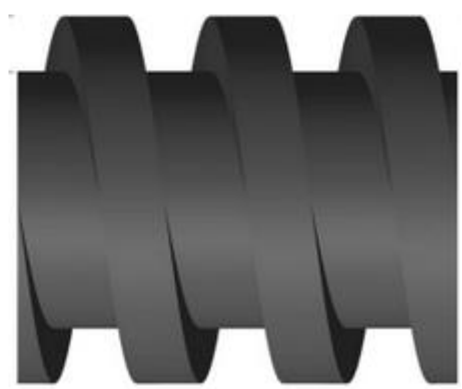


Figure 17. Stator surface with a helical groove.

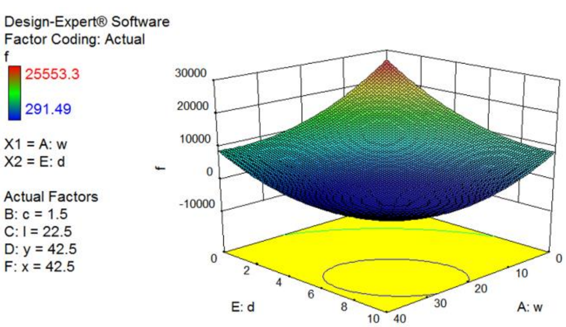
There are three configurations possible: a helical groove on the stator, a helical groove on the rotor, and helical grooves on both surfaces. So far, only the first case has been studied. This was done for both incompressible and compressible flow and the results have been validated against both experimental and computational data. Future work in this project will yield solutions for the other two cases. Studies are also currently being conducted to compare the bulk flow results with full 3D ANSYS CFX and to map response surfaces for both leakage rate and rotordynamic coefficients against various design parameters.

Effect of Recess Groove Shape on the Performance of a High-Speed Hybrid Journal Bearing Using CFD and DOE Analysis

Student Collaborator: Gen Fu (Virginia Tech)
Graduation Date: May 2018

Hybrid bearings are capable of providing both hydrodynamic support for high speed rotors as well as hydrostatic lift in low speed conditions such as during startup. Hybrid bearings are typically designed with recess grooves to modify the pressure profile and as a result to enable the lift capacity of the bearing under various operating conditions. The goal of this research is to build a robust and precise 3-D analytical model for a hybrid recessed bearing and provide a comprehensive analysis of recess geometry shape on the overall performance of the bearing.

In the current study, a baseline model selected from the literature is constructed and validated using the ANSYS CFX computational fluid dynamics software package. A sensitivity analysis of the design variables on the performance of the bearing has been performed using Design Expert software. The length, width, and depth of the rectangular recess, as well as the diameter and location of the five inlet ports have been selected as design variables. Figure 18 shows the response plot of lift force, varying with the geometry parameters. A multi-variable and multi-objective optimization algorithm has also been solved using Isight software with the goal of optimizing the geometry of the recess to maximize load capacity while minimizing bearing power loss from friction torque.



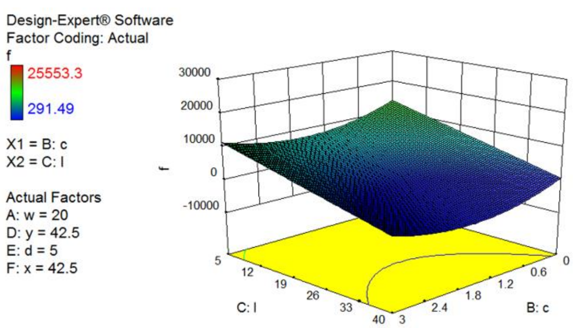


Figure 18. Response surface plot of lift force.

The results for the baseline model show reasonable agreement with the experimental data published in the literature. Figure 19 shows the comparison of the baseline model and the predicted optimal design. A follow-up study will extend the recess geometry shape to circular, triangular, annular, and elliptical shapes. A new statistical method to determine the equilibrium position of the recessed bearing will also be employed. The comparison of different recess shapes under the same operating condition will be analyzed. This study will improve the understanding of flow conditions inside the recess and provide a clear relation between bearing performance and recess shape parameters.

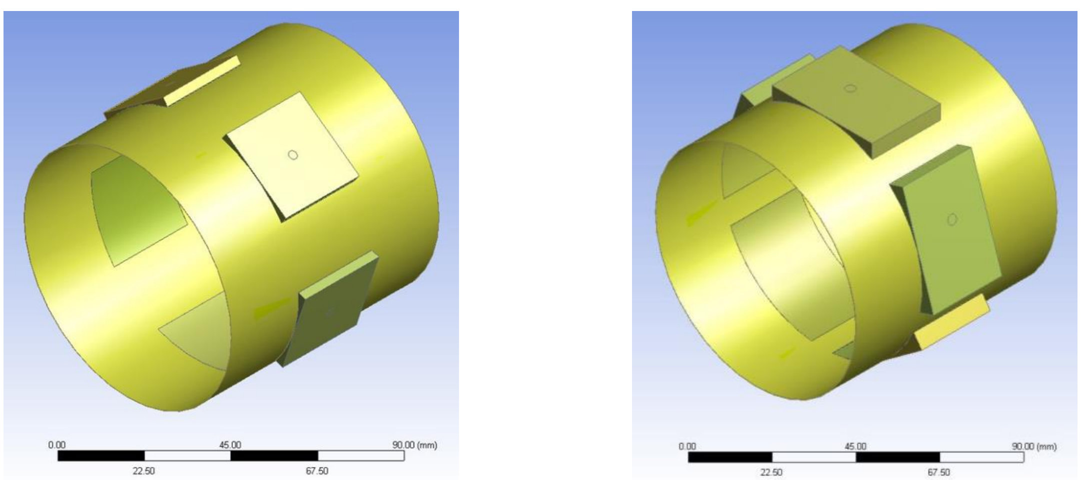


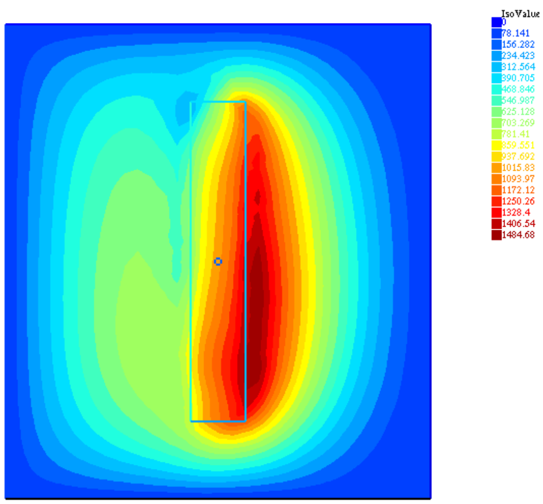
Figure 19. Comparison between the baseline and optimal bearing design.

The Influence of Jacking Groove on Tilting-Pad Bearings

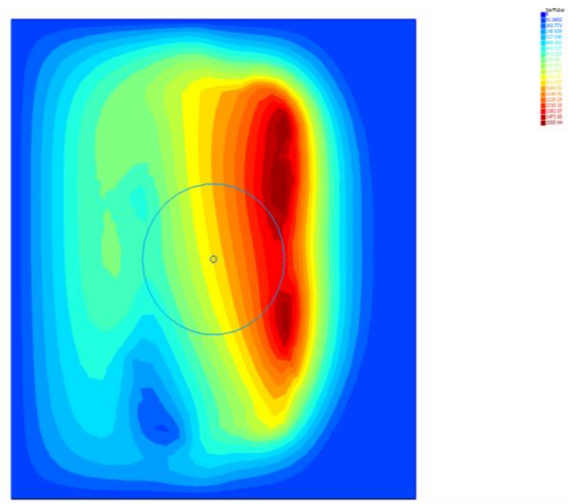
Student Collaborator: Gen Fu (Virginia Tech)
Graduation Date: May 2018

In large machines the startup of the machine can be challenging due to the heavy load on the bearing. If the machine has been idle for several days, the coefficient of static friction can be very high. Jacking grooves are designed to assist the oil film build-up in tilting pad bearings during the transient stage before hydrodynamics can take over at higher operating speeds. The objective of this study is to theoretically predict bearing performance with different jacking groove shapes.

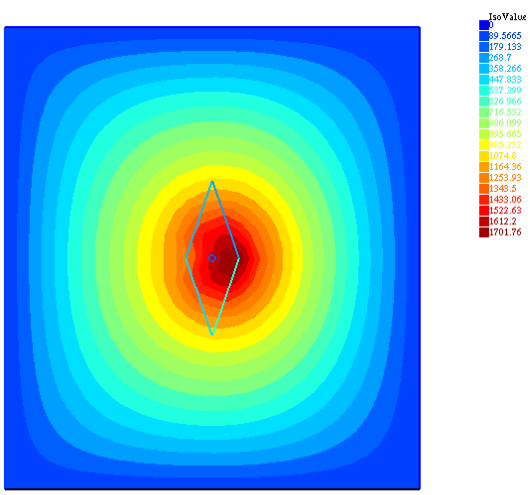
A 2D code to calculate tilting pad bearing performance has been built with FreeFem++ software. The FreeFem++ code will provide a base assumption for axial pressure on the pad surface, which could then be applied to other bearing codes. The current FreeFem++ code can calculate the performance of a single pad bearing. Pressure distributions of different groove shapes under the same operating condition are compared in Figure 20. This study will facilitate a deeper understanding of the fluid behavior of tilting pad bearings with jacking grooves.



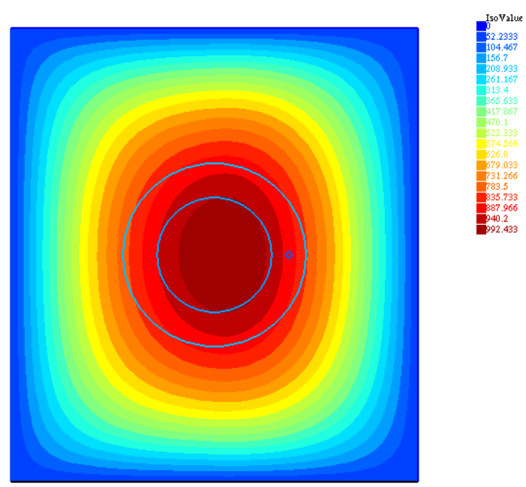
(a) Rectangular groove



(b) Circular groove



(c) Diamond groove



(d) Annular groove

Figure 20. Pressure distributions corresponding to different recess groove shapes.

Evaluation of Swirl Brake Effects on Performance of Labyrinth Seals Using Computational Fluid Dynamics and Design of Experiments Techniques

Student Collaborator: Hanxiang Jin (Virginia Tech)
Graduation Date: May 2018

In non-contacting annular labyrinth seals used in turbomachinery, fluid preswirl in the direction of shaft rotation effectively increases fluid velocity in the circumferential direction and generates fluid forces with potential destabilizing effects that are exerted on the rotor. Swirl brakes are typically employed to reduce the fluid preswirl at the inlet of the seal. The inlet flow separates as it follows the swirl brake, and the ratio between the tangential component of the velocity at the seal and the velocity of the rotor surface consequently varies. Effective swirl brakes can significantly suppress the destabilizing fluid forces as it is effectively reducing the tangential velocity. Literature shows that leakage rate also can be reduced by using swirl brakes with "negative-swirl."

In this study, a labyrinth seal with an inlet swirl brake is selected from the literature and considered the baseline design. The seal performance is evaluated using ANSYS-CFX. A design of experiments (DOE) approach is used to investigate the effects of various design variables of the vanes on the seal performance. The design space consists of the swirl brake length, width, curvature at ends, the tilt angle, as well as the number of vanes in the circumferential direction. A simple random sampling method with Euclidean distances for the design matrix is used to generate the design points. The steady-state computational fluid dynamics simulations are then performed for each design point to analyze the performance of the swirl brake. Quadratic polynomial fitting is used to evaluate the sensitivity of the average circumferential velocity with respect to the design variables, which gives a qualitative estimation for the performance of the swirl brakes. The results will assist in better understanding which design variables are critical and more effective in reduction of the destabilizing forces acting on the rotor, and thus will support swirl brake design for annular pressure seals. It is envisioned that this work could also lead to the development of a bulk-flow code to evaluate swirl brake designs and predict its effect on labyrinth seal dynamic performance. Once developed, the module could then be applied to various existing seal analysis tools.

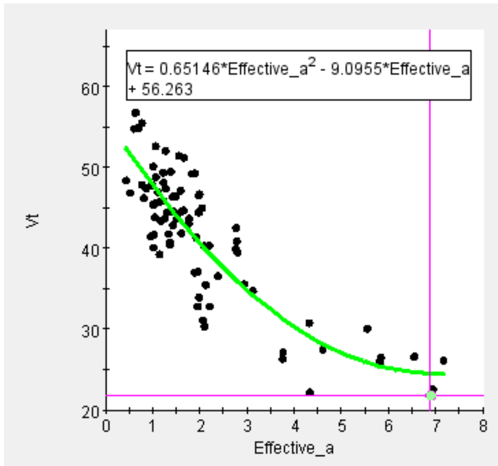
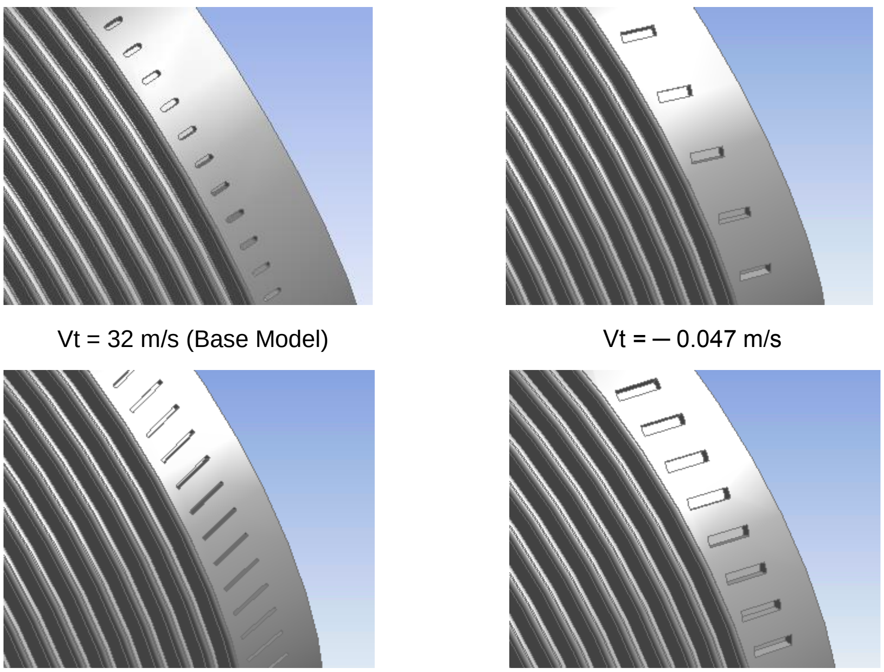


Figure 21. Circumferential velocity chart of effective swirl brake length.



Vt = 32 m/s (Base Model) Vt = — 0.047 m/s

Vt = — 0.070 m/s Vt = — 0.044 m/s

Figure 22. High performance model compare to the baseline model. *Vt* is the average circumferential velocity.

Energy Decomposition and Flow Field Reconstruction for Hole-Pattern Seals Using Reduced Order Modeling Technique

Student Collaborator: Hanxiang Jin (Virginia Tech)
Graduation Date: May 2018

In non-contacting annular seals used in turbomachinery, the leakage of the working fluid is reduced through the acceleration and deceleration effect of the fluid through a convoluted path. Therefore, the geometric characteristics of the leakage path play an important role on the sealing performance of annular seals. In order to better understand the mechanism that leads to the leakage of the working fluid due to the pressure gradient and stator-rotor interaction in turbomachinery, this study proposes the utilization of the Reduced Order Model (ROM) method and snapshot techniques. The goal of this work is to study the energy distribution of the flow field in sealing components by replacing a large number of governing PDEs describing a complex system with only a few ODEs.

A hole-pattern seal is selected for this study and the CFD model is built in ANSYS-CFX. Transient simulations are then performed to calculate the leakage rate and flow field velocity distribution. By using the POD method, the flow field is deconstructed into elementary modes which contain the corresponding energies of each mode. In the flow fields of gas sealing components some highly organized flow patterns were identified, which suggests that some coherent flow structures may exist and can be described quantitatively by some lower order modes. These flow structures provide insight into the physics of the internal flow, while traditional time and frequency domain approaches only predict the flow field for a specific operating condition. Preliminary work shows that the first few modes contain the majority of the energy, and thus the flow field can be accurately reconstructed using only a few modes whose flow patterns include most of the information from the original flow field. As full 3D-CFD simulation is extremely time consuming for optimization problems, the method proposed for this study is more practical. It will allow for the generation of the details of the flow field with enough accuracy using only a few modes from the energy composition standpoint and has the potential of greatly accelerating the optimization process.

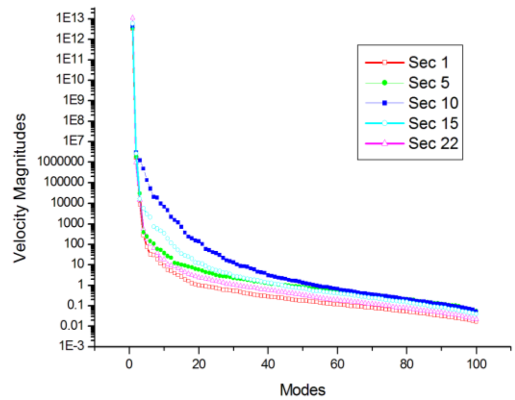


Figure 23. Velocity magnitude (energy) plot for all modes in whole section.

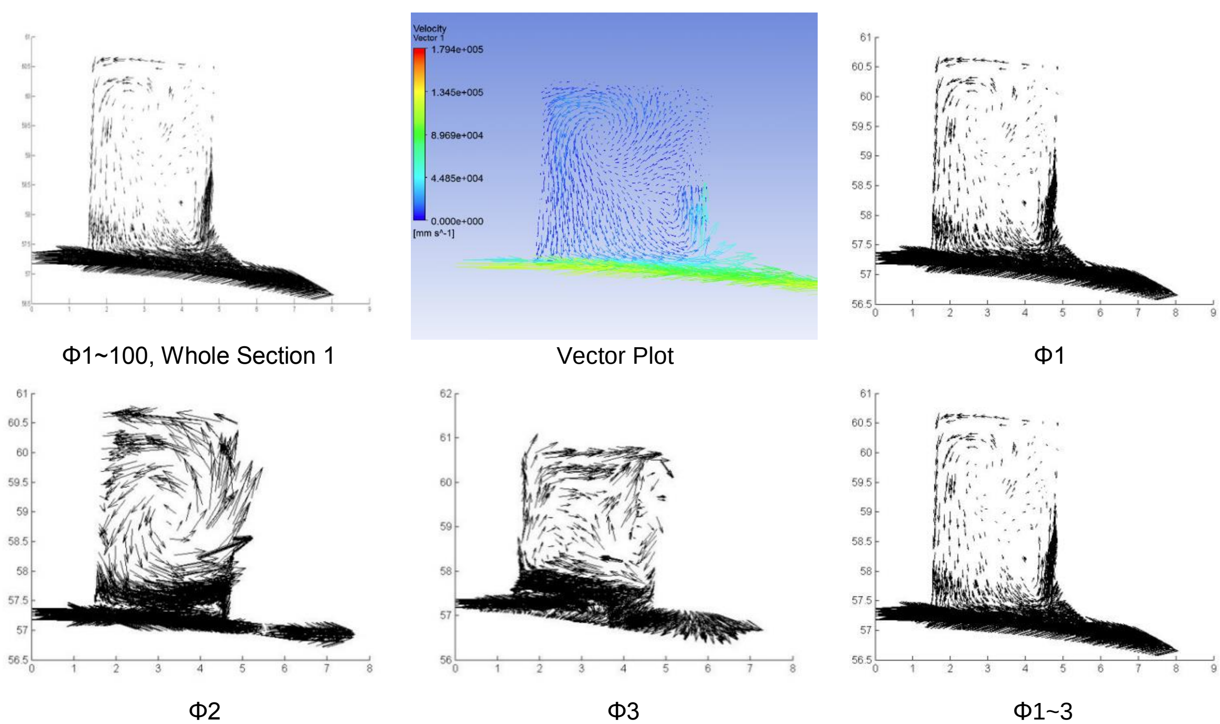


Figure 24. Flow pattern for the first three modes in whole section 1.

2015 ROMAC Reports

In 2015 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 2015 is included below. These papers and past reports will be made available on the ROMAC Reports website. Look for a major update to this website in the next few weeks.

Branagan, M., Griffin, D., Goyne, C., Untaroiu, A., "Compliant Gas Foil Bearings and Analysis Tools", Proceedings of ASME Turbo Expo 2015, GT2015, Paper no. GT2015-43650, June 15-19, 2015, Montreal, Canada.

Branagan, M., Morgan, N., Weaver, B., and Untaroiu, A., "Numerical optimization and response surface mapping by experimental design of tilting pad bearings", Proceedings of EDF Pprime 2015, October 8-9, 2015, Poitiers, France.

Dousti, S., and Fittro, R., “An Extended Reynolds Equation Including the Lubricant Inertia Effects: Application to Finite Length Water Lubricated Bearings,” Proceedings of ASME Turbo Expo: Turbine Technical Conference and Exhibition, GT2015-43826, June 15-19, 2015, Montréal, Canada.

Kaplan, J., Fittro, R., Untaroiu, A., and Wood, H., “Non-Linear Time-Time Transient Rotor Dynamic Analyses of Geared Systems,” Proceedings of ASME Turbo Expo: Turbine Technical Conference and Exhibition, GT2015-43481, June 15, 2015, Montréal, Canada.

Lyu, X., Di, L., Yoon, S.Y., Lin, Z., and Hu, Y., "A platform for analysis and control design: emulation of energy storage flywheels on a rotor-AMB test rig", IFAC Mechatronics, to appear.

Morgan, N.R., Untaroiu, A., and Wood, H.G., “Numerical Optimization of Leakage by Multifactor Regression of Trapezoidal Groove Geometries for a Balance Drum Labyrinth Seal”. Proceedings of ASME Turbo Expo: Turbine Technical Conference and Exposition, GT2015-43794, June 15-19, 2015, Montréal, Canada.

Weaver, B., Kaplan, J., Clarens, A., and Untaroiu, A., “Transient Analysis of Gas-Expanded Lubrication and Rotordynamic Performance in a Centrifugal Compressor,” Proceedings of ASME Turbo Expo: Turbine Technical Conference and Exhibition, GT2015-43547, June 15-19, Montréal, Canada.

Weaver, B., Fu, G., Clarens, A., and Untaroiu, A., “Performance Analysis of Gas-Expanded Lubricants in a Hybrid Bearing Using Computational Fluid Dynamics,” Proceedings of the ASME 2015 International Mechanical Engineering Congress and Exposition, IMECE2015-53735, November 13-19, Houston, Texas.

Yoon, S.Y., Di, L., Anantachaisilp, P., and Lin, Z., "Truncated Predictor Feedback Control for Active Magnetic Bearing Systems with Input Delay", IEEE Transactions on Control Systems Technology, to appear.

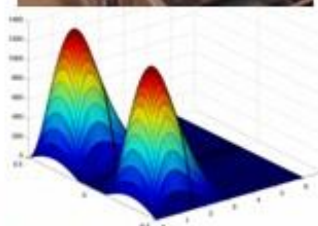
Yoon, S.Y., Di, L., and Lin, Z., "Unbalance Compensation for AMB Systems with Input Delay: an Output Regulation Approach", IFAC Control Engineering Practice, under revision.

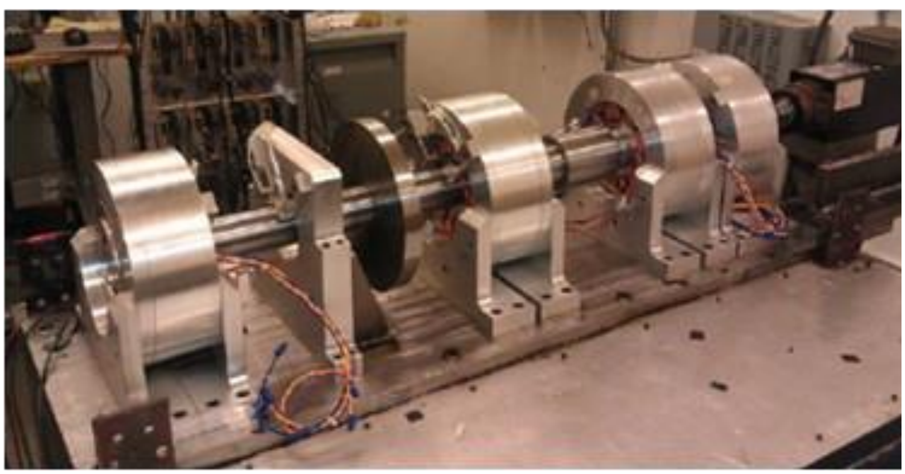
Yoon, S.Y., and Lin, Z., “Robust output regulation of linear time-delay systems: A state predictor approach,” International Journal of Robust and Nonlinear Control, July 2015.

Yoon, S.Y., and Lin, Z., “Predictor based control of linear systems with state, input and output delays,” Automatica, Vol. 53, pp. 385-391, 2015.

ROTATING MACHINERY & CONTROLS LABORATORY

- Software Development and Test Rig Validation
- Finite Element Analysis (FEA)
- Computational Fluid Dynamics (CFD)
- Fluid Film and Rolling Elements Bearings
- Seals
- Squeeze Film Dampers
- Foil Bearings
- Rotordynamics
- Magnetic Bearings and Controls
- Optimization of Rotor-Bearing Systems
- Experimental, Computational, and Theoretical Studies





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