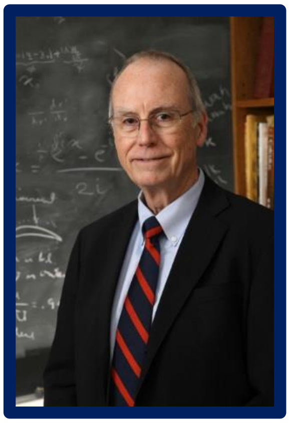
ROMAC
ROTATING MACHINERY and CONTROLS LABORATORY
UNIVERSITY of VIRGINIA
SCHOOL of ENGINEERING & APPLIED SCIENCE

ROMAC Newsletter Fall 2016 Issue

November 2016

A Message from our Director



Houston Wood, Professor
Director of ROMAC

We are all asked by colleagues and friends, "when is your slow time?" It seems that a slower pace passed us by this year. In early June we held our ROMAC Annual Meeting in Charlottesville, followed by the 5-Day Short Course in mid-July, and the new academic year began in late August. This is the 37th year of ROMAC, that is according to the first report in our ROMAC Technical Report directory which is now up to date on the ROMAC website.

We welcome, Harrison Gates, a Ph. D student, whom some of you had the opportunity to meet if you attended the annual meeting or the short course. In addition, I am pleased to say that we have extended an offer to a student to begin her studies in the summer of 2017 and she has accepted. We will continue to review graduate student applications and recruit and accept the best of the best. Many students are preparing for conference talks, qualifying exams, and dissertation defenses as well. We expect several of our students to be finishing their studies in time for May 2017 graduation.

As we discussed in June, we have put together our ROMAC Advisory Board with six volunteer members and our first tele-conference took place in October. For a list of members and more information see page two of this newsletter.

It is important to note that the week for the 2017 ROMAC Annual Meeting has changed. It came to our attention that due to the ASME Turbo Conference taking place in Charlotte, NC, June 26-30, it would be more convenient for our international members to attend our meeting if it was the week before the ASME Turbo conference. We asked for input from the membership and of those responding it was evident that we should change the date. See more about the new location of the meeting on the following page.

New ROMAC Member Companies

Our research efforts continue to expand to better serve our ROMAC member companies. In 2016, the ROMAC Consortium added two new members. We welcome the newest members to the ROMAC community.

Honeywell Federal – Brent Hower and Scott Yerganian attended the one-day short course and joined us as guests for the annual meeting in June.

Beijing Institute of Technology – ROMAC and BIT have had a long standing research collaboration. We welcome many BIT students and faculty as visiting scholars.

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2017 Annual Meeting Date and Location Changes

The ROMAC Annual meeting will take place June 19 – 23, 2017 at the Stonewall Jackson Hotel in Staunton, Virginia. Staunton is located in the Shenandoah Valley, just 35 miles west of Charlottesville.

Staunton has something for everyone and is a very walkable little city. History, Arts, Shopping, Entertainment, Some recent press includes: "Best Main Streets in the USA" – USA Today, "9 of the Best Small Towns for Food in the U.S." – Tasting Table

See the 2017 Annual Meeting page on the ROMAC website for more information.

Nestled in Historic Downtown Staunton in the heart of the picturesque Shenandoah Valley, this 124-room hotel captures the spirit, history, and charm of the old South. Originally built in 1924 and a member of Historic Hotels of America, this modern yet refined Virginia gem underwent a complete top to bottom renovation in 2005 and has been lovingly restored to it's original grandeur. Staunton was recently named as one of the top 20 Small Towns in America by Smithsonian Magazine.

From the Stonewall Jackson Hotel website

ROMAC Advisory Board

At the annual meeting we discussed putting together a board of advisors from our membership to provide an additional means of input and communication between the faculty and member companies. We received an enthusiastic response. We currently have an active ROMAC Advisory Board composed of six industry members who have volunteered their time and expertise to serve in an advisory role to the ROMAC faculty: **Kris Altiero**, Bechtel Plant Machinery, Inc., **Lyle Branagan**, Pioneer Motor Bearing Inc., **Christoph Hentsche**, RENK, **Ed Memmott**, Dresser Rand, **Lorenzo Naldi**, GE Oil & Gas, and **Balaji Venkataraman**, Solar Turbines.

The overall purpose of this board is to help ROMAC grow and improve now and into the future as well as enable increased input and ownership for the member companies. We held our first conference call on October 18, with plans to meet quarterly and a face to face meeting held each year at the ROMAC Annual Meeting. We will have our next meeting in the first quarter of 2017 and plan to have a report to the overall membership at the next Annual Meeting to be held June 19 – 23. Meetings notes from each quarterly meeting will also be made available to all members through the ROMAC website.

ROMAC Graduate Students

Harrison Gates joined the ROMAC lab in early June to begin studies for a Ph.D. in MAE. He currently has a Ph.D. in Chemical Engineering from the University of Maine.

Several students have intent to complete their degrees by the end of this year. **Benny Schwartz** will soon finish up his M.S. in Mechanical Engineering. He then plans to pursue his Ph.D. **Long Di (Dee)** successfully defended his dissertation earlier this month and will receive his Ph.D. in ECE. **Brad Nichols** plans to finish his Ph.D. in MAE early next year. **Michael Branagan**, **Neal Morgan, Ben Thomas,** and **Cori Watson** expect to finish their studies for a Ph. D. in Mechanical & Aerospace Engineering during the Spring 2017 semester.

We expect May 21, 2017, Graduation Day to see several ROMAC students having successfully completed their degrees and walk The Lawn, a long-standing honor and UVA graduation tradition.

Cori Watson was selected to participate in the 2016 NextProf Workshop *Changing the Face of Academia* at the University of Michigan in Ann Arbor, Michigan. The workshop took place in late September. Cori was also the recipient of an STLE Early Careerist Award in the student category at the STLE 71st Annual Meeting and Exhibition in May.

Ben Thomas recently learned his paper entitled **Fixed Plant Analysis of Iran's Post-JCPOA Implementation Breakout Potential** that he presented while attending the American Nuclear Society's 2016 Advances in Nuclear Nonproliferation Technology and Policy Conference in Santa Fe, NM, September 25-27, 2016 received a second place award in the student paper competition!

ROMAC Graduate Students – *continued*

Earlier this year we also had students completing their studies and moving on with their careers. **Thomas Gresham** received his M.S. MAE degree in August and is now working with member company Pratt & Whitney in Hartford, CT. **Day Griffin** also finished his M.S. MAE degree and has retuned to work with ROMAC member Pioneer Motor Bearing Co. in Charlotte, NC, where he was employed prior to beginning his studies with ROMAC. Several of our soon-to-be graduates are currently in conversations with potential employers as well, many of them being member companies.

ROMAC Visiting Scholars

As in previous years, ROMAC continues to host several visiting scholars this semester. In addition, the faculty are currently engaged in discussion with others from various university laboratories exploring collaboration and research opportunities.

Dr. Fengxia Lu is an associate professor at the College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics. Her research is in design methodology for high-efficiency double helical gears and design theory and key technology for drive transmissions of heavy lift helicopters. She is here through November 2016.

Qihang Li (Lee) is a visiting graduate student from Beijing University of Chemical Technology. His current research involves rotor dynamic analysis and control of rotating machinery. His appointment is through January 2017.

Dr. Cheng Liu is a returning visitor. His first visit was as a graduate student in September 2012 for one year. He is currently a Research Assistant in the National Key Laboratory of Vehicular Transmission, School of Mechanical Engineering, Beijing Institute of Technology having received his Ph.D. in March 2015. His research interest is torque conversion; his current appointment is through January 2018.

Mr. Tomohiko Tsukuda is a steam turbine engineer within the Turbo Machinery Group of R&D with the Toshiba Corporation in Yokohama, Japan. His research is in fluid dynamics of turbomachinery with an emphasis on steam turbines. His appointment is through October 2017.

Dr. Yunbo Zhou is an associate professor and the vice director at the Nanjing University of Science and Technology, Vehicle Engineering Department. His research involves design and methodology of structures for vehicles and aircraft. His appointment is through February 2017.

We will update the ROMAC website as we welcome new visiting scholars later this academic year.

2017 Five-Day Rotordynamics Short Course

Mark your calendars and save the date. The next ROMAC Five-Day Short Course will be held July 17-21, 2017 at the ROMAC laboratories on the grounds of the University of Virginia, in Charlottesville. As in years past, the course will cover topics in rotordynamics, bearing and seal dynamics, magnetic bearings, and applied dynamics for industrial rotors. Registration information will be available on the ROMAC website in mid-January 2017. If you need additional information prior to that time please contact us at romac@virginia.edu.

2016 Annual Meeting Summary

Late afternoon Monday June 6, 2016 ROMAC members, faculty, students, and invited guests attended a welcome reception at the Holiday Inn – University Area in Charlottesville, VA. Earlier that day, ROMAC offered a one-day short course focusing on Rotordynamics and a course especially designed for our members who are advanced MAXBRG & THRUST users.

On Tuesday morning, Houston Wood welcomed Craig Benson, and Eric Loth. Dean Benson was appointed in July 2015 to lead the School of Engineering and Applied Science (SEAS). Eric Loth began his role as chair of Mechanical and Aerospace Engineering (MAE) in September 2015. Each shared their vision of MAE and SEAS as well as their thoughts on ROMAC as we move forward together. Houston Wood then gave an update on ROMAC. The keynote address was given by ROMAC member, President of Rodyn, and UVA Professor Emeritus Edgar J. Gunter.

The meeting continued through Friday morning. In all there were 64 attendees from four countries. There were 36 talks presented by industry members, ROMAC faculty, and graduate students. Friends and colleagues were reunited, new friendships were forged, and new ideas and research projects were discussed.

2016 Rotordynamics Short Course

Our annual five-day short course on rotordynamics and magnetic bearings was held at ROMAC laboratory at University of Virginia School of Engineering July 11-15, 2016. The course covered topics in rotordynamics, bearing and seal dynamics, magnetic bearings, and applied dynamics for industrial rotors. The course included presentations by University of Virginia faculty and graduate students. In addition, case histories, examples from industry, and other presentations were given by industry experts.

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

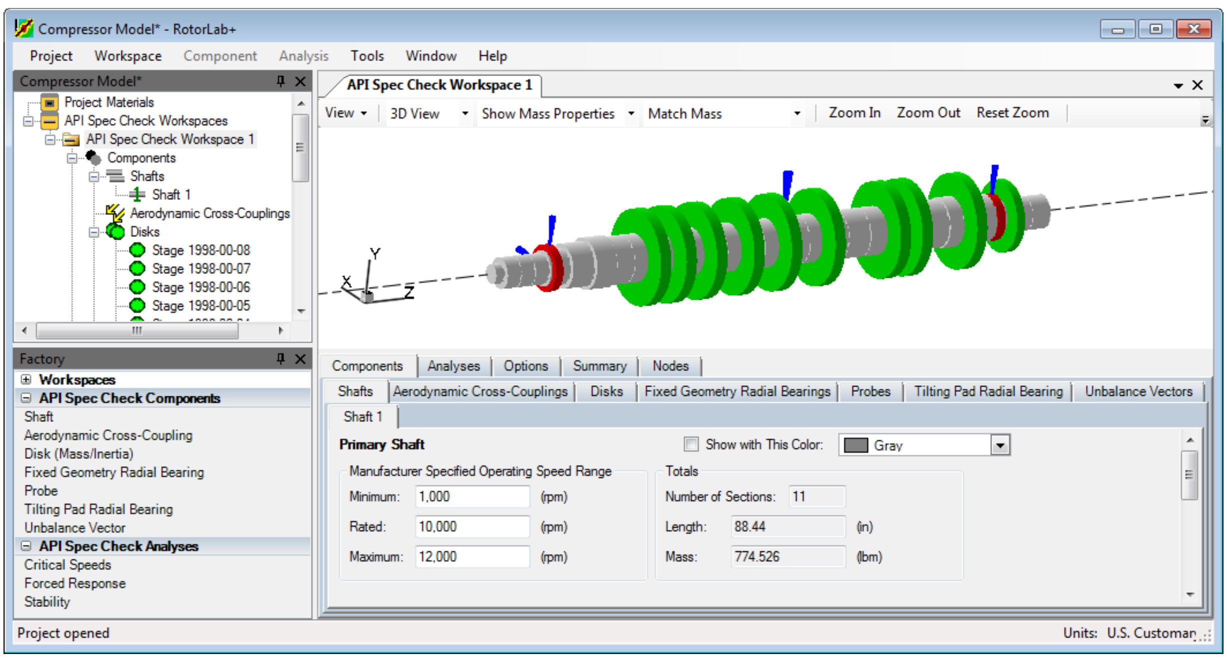
Please contact us at romac@virginia.edu for more information.

Software Updates

This year saw a number of developments in our software program, the biggest being the release of RotorLab+ 4.0 in April. This latest version of our primary software suite comes with a number of new features, the details of which can be found on the ROMAC Software website. Along with other sections of our website, the Software section has seen significant updates in the last year including an updated *Descriptions of Recommended Analysis Codes* page for members seeking out the best software solutions for their projects.

Our software team is currently working on multiple planned releases for this Fall and Winter. The first is an update to our RotorLab+ suite, version 4.1, which will include new materials for rotordynamics projects, enhancements to various plots within the Assembly and API Workspaces, as well as fixes to any bugs that have been reported since the 4.0 release. A second planned release is an update to our legacy RotorGui interface. In addition to RotorLab+ 4.0, this version of RotorGui will provide users with access to an updated version of MAXBRG that cuts run times in half when compared to previous versions. This update will also provide GUI access to THRUST v5.30, and updated TORTRAN3 with an increased node limit to accommodate larger models, a 64-bit version of DAMBRG2, and user manual updates. The final release planned for this year will be MAXSFD, a new code that solves a 2D extended Reynolds equation for squeeze film dampers along with other theoretical advances including a new effective groove model.

Please contact our Software Engineer Brian Weaver at bkw3q@virginia.edu with any software- related questions.



RotorLab+ 4.0 Interface

Summary of Research Projects

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

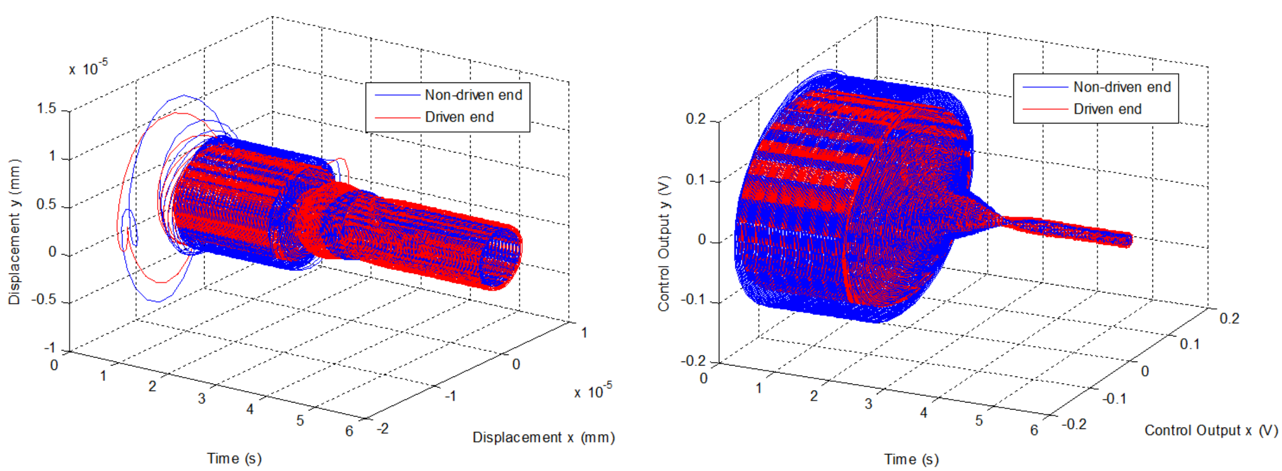
Autobalancing of AMB Systems Using a Differential Regulator Based Output Regulation Approach

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

High speed rotating machines are subject to unbalance forces caused by residual imbalance weight. When the rotor's axis of geometry and its principal axis of inertia are not aligned, unbalance forces synchronous to the rotational speed cause the rotor to deflect from the geometric center and enter a whirling motion. To reduce the effects that the rotor unbalance has on high speed machines supported by AMBs, the conventional approach has been to either generate counteracting bearing forces or to shift the rotating axis in such a way that the shaft is rotating force-free or performing auto-balancing.

In this research, a differential regulator based output regulation approach is presented to address the autobalancing problem of AMB systems for varying rotational speeds. The problem of output regulation is to design a controller for disturbance rejection and/or reference tracking, while the disturbance or reference signal is generated by a known dynamic system called an exosystem. After formulating the output regulation problem based on a time-varying exosystem, it is observed that the compensator gains can be obtained based on the solution of a differential regulator equation (DRE). Since AMB systems are of non-minimum phase, to ensure the boundedness of the compensator gains, the original normal form is reformulated and a unified gradient method is adopted to guarantee the residue error in the output regulation is minimized. Then the compensator gains are continuously generated to closely approach the output regulation objective with a small error in the regulated output. To apply output regulation to AMB systems for autobalancing, the unbalance force is modeled by the exosystem and the AMB force defines the error to be regulated. When the rotational speed varies, the exosystem becomes time-varying, and the proposed differential regulator based output regulation approach is adopted to generate the desired bounded compensator gains that minimize the AMB control force to achieve autobalancing.

The proposed method is verified in simulation for autobalancing with both varying and constant rotational speeds on a flexible rotor AMB test rig. The vibration levels under both cases are similar while the control voltage is significantly reduced with the differential regulator.



Simulated control voltages and rotor displacements with differential regulator off/on.

Fluid Film Bearing Test Rig

Students: Benstone Schwartz, Paul Gancitano
Expected Graduation Dates: May 2017

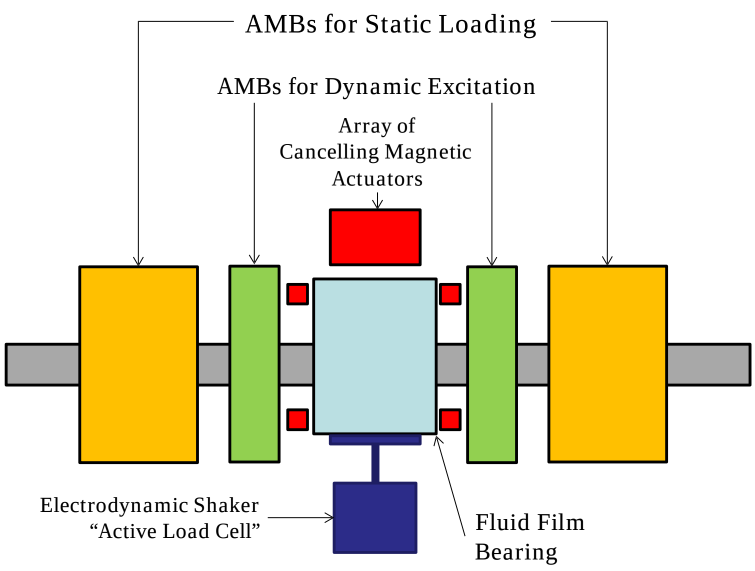
Fluid-film bearing applications continue to push the envelope on operating speed, specific load, and performance, requiring bearing technologies to keep pace. Modern applications commonly involve bearing operation in the transition and turbulent flow regions. Little data, especial with high accuracy, is available for the dynamic properties of bearings in this range. The Fluid Film Bearing Test Rig (FFBTR) aims to make these measurements possible.

Additionally, the FFBTR will provide additional validation of ROMAC codes including THPAD and MAXBRG. The development of an improved test rig with higher performance capability will lead to continued development and refinement of ROMAC bearing analysis tools for years to come.

Recently a comprehensive analysis of predicted uncertainty in measured dynamic coefficients was completed and the results indicated that the original 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 designed and developed.

An “Active Load Cell” test bed is being developed in parallel with the FFBTR to validate the concept and ensure the best accuracy possible for bearing force measurements. This test rig will utilize electrodynamic shakers and a control algorithm to accurately identify fluid-film bearing forces. The determination of these forces are critical to understanding the stiffness and damping coefficients of a fluid-film bearing, particularly at high frequencies.

All of the design concepts are being simulated using a high-fidelity Simulink model in an attempt to fully validate all aspects of the final design before test rig manufacturing and assembly commences. In Spring 2016 a great deal of progress was made in the development of the high-fidelity simulation, and some preliminary results were presented in the summer at the annual meeting. Presently, the high-fidelity simulations are being finalized, with a plan to present the results at both the Annual Meeting, as well as at the 2017 Turbo Expo in Charlotte, NC.



Proposed redesign of the FFBTR.

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

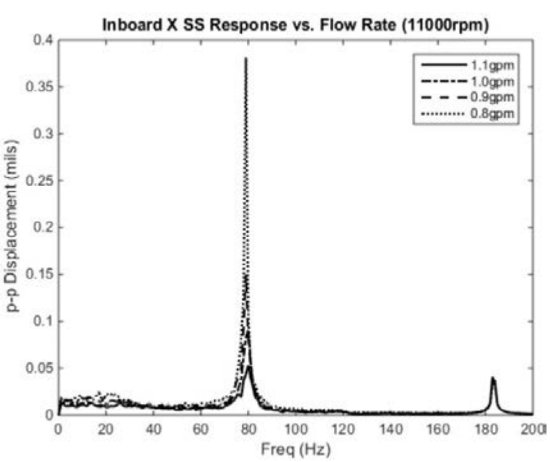
Student: Brad Nichols
Expected Graduation Date: May 2017

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 related to decreased forces. While machine efficiency may be improved with reduced lubricant flow, little experimental data on its effects on system stability and performance is presently available in the literature.

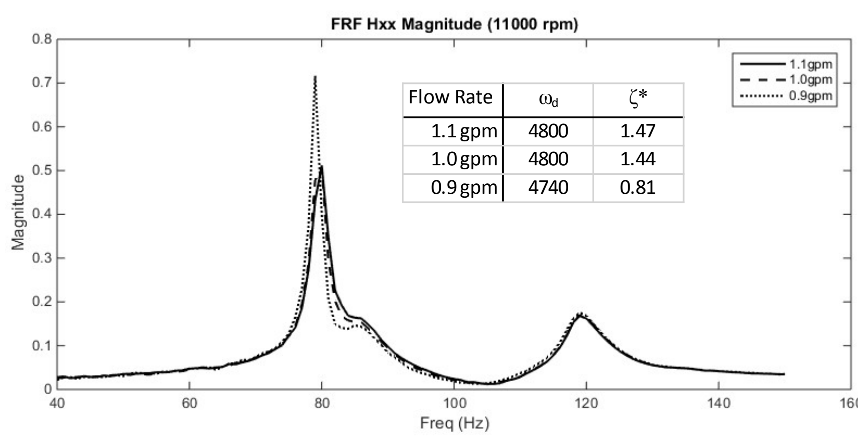
Data collection was completed this spring for an experimental investigation designed to study the effects of incrementally reduced oil supply flow rates on both steady-state bearing performance and overall system stability. The test rig used in this study was designed to be dynamically similar to a high-speed 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.

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 the figure below, 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. The second figure below shows the FRFs obtained under three different flow rates at 11,000 rpm and a bearing load of 18 psi. A full dissertation, journal paper, and ROMAC 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.



Sub-synchronous vibrations vs. oil supply flow rate.



**Obtained using half-power estimation method*

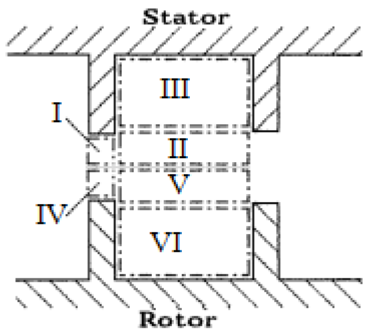
Experimental FRF, 11,000 rpm, 18 psi bearing load.

Helical Groove Seal Analysis Tools

Student: Cori Watson
Expected Graduation Date: May 2017

This project expands ROMAC's computational analysis methods to include helical groove seals, which are non-contacting annular seals with continuous grooves on the surface of the rotor and/or stator. The initial code has been developed as a three control volume bulk flow code for helical groove seals with either grooves on the rotor or grooves on the stator. This code numerically solves the continuity and conservation of momentum equations in each control volume using three key concepts. The first is that the turbulence can be modeled as shear stress momentum loss terms, which is the basis of bulk flow theory. The second is the assumption that the rotor has a small eccentricity with a circular orbit. The final principle used is a Jacobian transformation to the characteristic flow patterns, which are the axial flow and the groove flow.

Currently, this code is being expanded to a six control volume method for helical groove seals with grooves on both the rotor and the stator. Methods of modeling the interactions of the two sets of grooves are being explored.

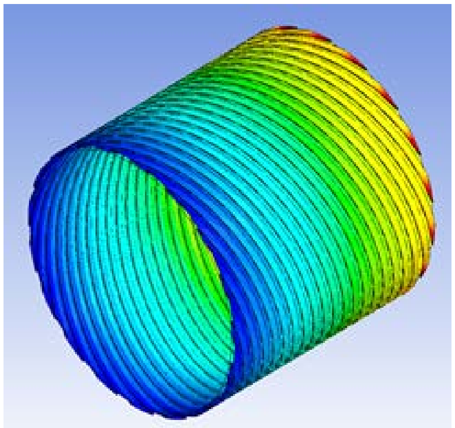


Optimization of Helical Groove Seals

Student: Cori Watson
Expected Graduation Date: May 2017

ANSYS CFX modeling is being used to develop optimized helical groove seal designs for a variety of configurations and operating conditions. The goal of this project is threefold. First, the optimization can be used to explore the performance of helical groove seals. Second, the computational data can be used to calibrate helical groove seal codes currently being developed. Third, comparison of the results to that of the helical groove seal bulk flow codes will allow for error mapping to quantify the accuracy of the computational method throughout the design space.

The initial phase of this project has been to optimize high pressure helical groove seals with grooves on the stator for use in an impeller stage. Additional work compares the performance helical groove seals with grooves on the rotor versus helical groove seals with grooves on the stator. The next phase of this project is to perform ANSYS CFX simulations to calculate rotordynamic coefficients and optimize for maximum effective damping. Finally, similar optimization studies will be performed for helical groove seals with grooves on both the rotor and the stator.



Pressure Profile for Helical Seal from ANSYS CFX Simulation.

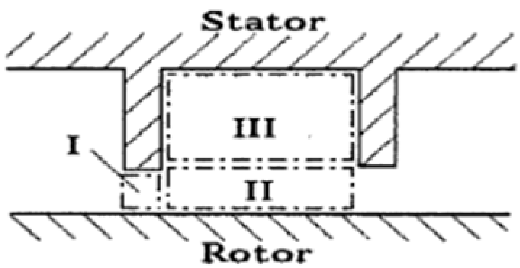
Improvements to ROMAC Seal Codes

Student: Cori Watson
Expected Graduation Date: May 2017

A number of ROMAC's existing labyrinth seal codes are more than twenty years old and were therefore developed in a time where computational resources were much more limiting. This project seeks to expand the capabilities of current labyrinth seal codes to use a three control volume method, which will allow for improved accuracy and analysis of labyrinth seals. Other improvements being considered are:

1. Allowing the inlet boundary condition used to be chosen between inlet velocity or inlet pressure depending on the application of the user.
2. Increasing the order of the perturbation method to allow for eccentricities greater than 10%.
3. Incorporating multistage seals such as smooth-labyrinth or brush-labyrinth seals.

Additionally, calibration and error analysis of the codes is planned so that quantification of the accuracy of the numerical methods are available in the user manuals.



Gas Centrifuge Modeling

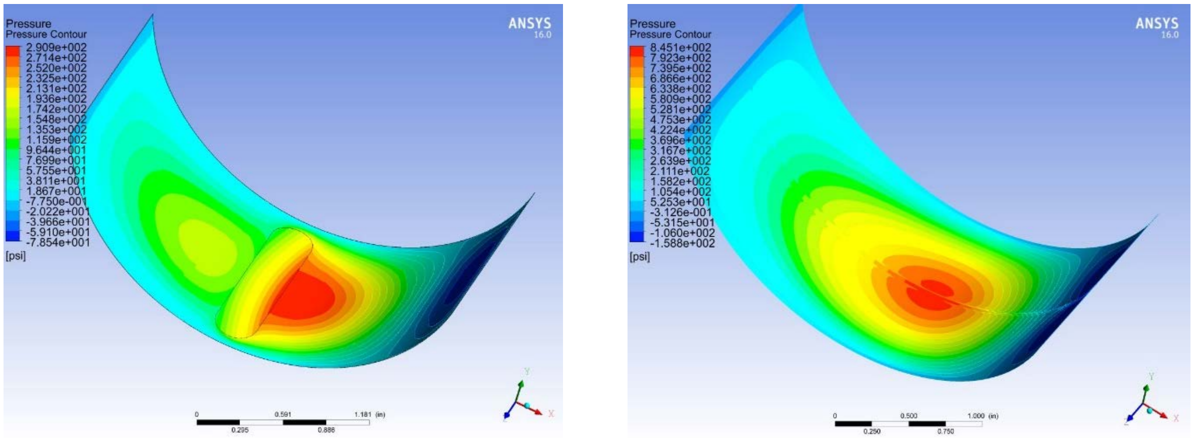
Student: Ben Thomas
Expected Graduation Date: May 2017

Development of a computational model that better predicts the performance of small, low-speed gas centrifuges based on the Onsager Equation with Carrier-Maslen end conditions. The linearized sixth-order partial differential equation is solved using a finite element algorithm to describe the flow in the centrifuge. The velocity profile described by the flow solution is then used to obtain a numerical solution of the isotopic diffusion to predict the transport of uranium hexafluoride molecules. A centrifuge performance map describing the separative performance over a range of feed and product rates is then generated for use in cascade modeling software packages to more accurately predict the separative performance potential of existing gas centrifuge enrichment plants (GCEP) subjected to traditional and off-normal operating conditions.

Influence of Surface Irregularities on Bearing Operation

Student: Michael Branagan
Expected Graduation Date: May 2017

Fluid film bearings serve a crucial role in many rotordynamic systems, contributing both supporting stiffness and the majority of the system damping. Being able to understand and successfully capture the behavior of these bearings is vital to ensuring machine reliability and improving rotordynamic performance. Irregularities on the bearing surface can have a noticeable effect on bearing operation. These surface irregularities can be either intentional, such as lift pockets, or accidental, such as scratches. CFD will be utilized in order to better understand the effects that these can have on bearing operation. Models of both scratches and lift pockets will be generated and compared to cases without such features. Using the CFD results, a simplified model will be generated in order to couple it with more simplified Reynolds equation solvers. A new 3D Reynolds equation solver will then be developed which is able to accurately model bearing with these types of bearing irregularities.

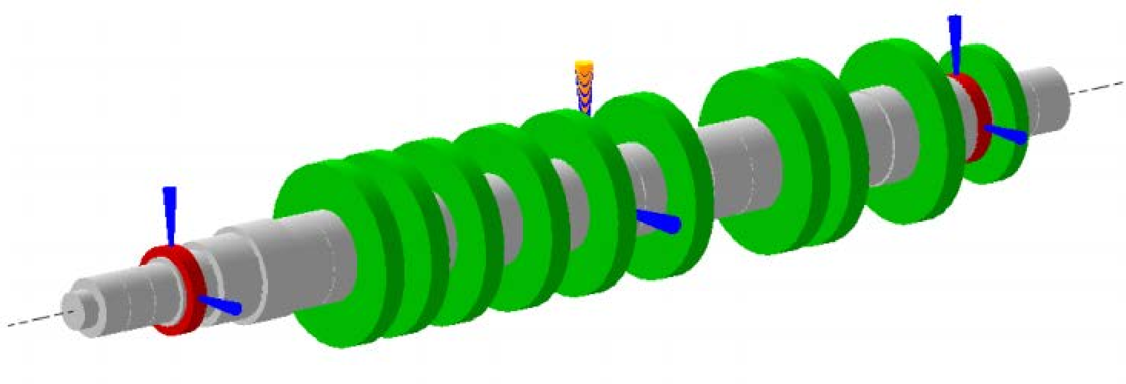


The effects of a lift pocket and circumferential scratch on pressure profiles.

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 for modeling support structures.

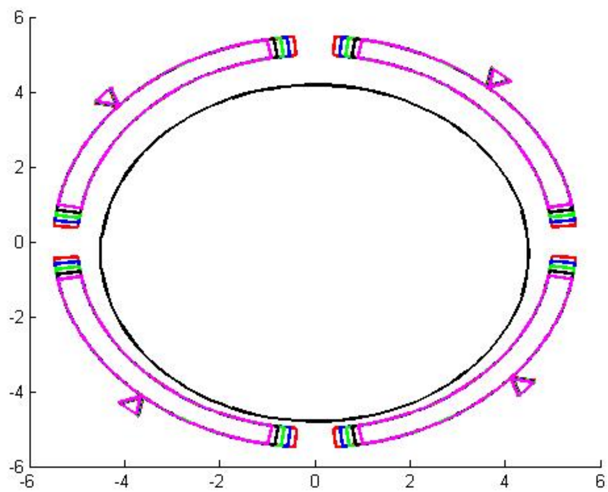


RotorSol finite element model.

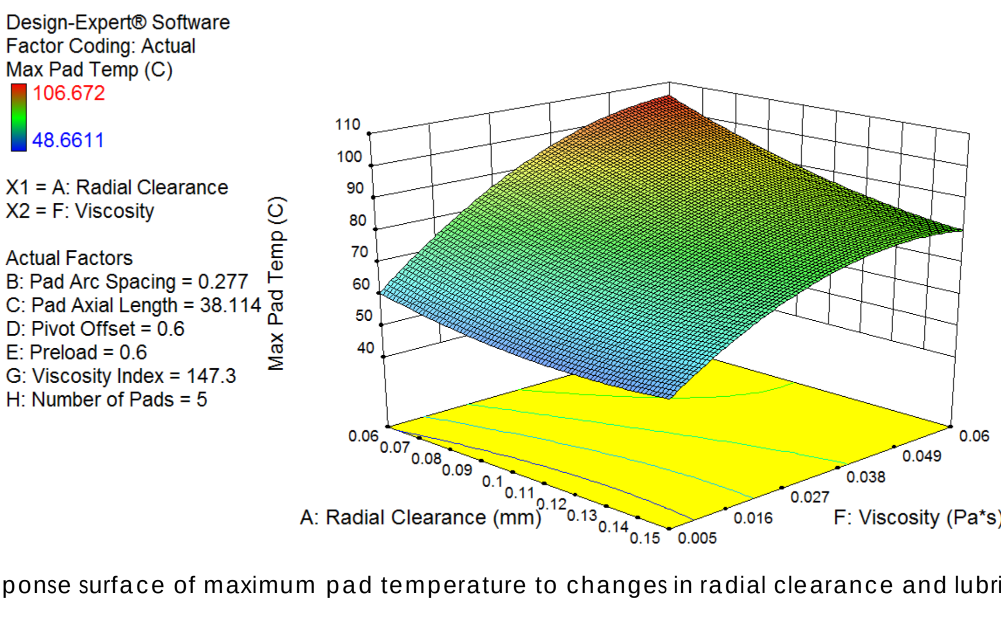
Numerical Optimization by Experimental Design of Tilting Pad Bearings

Students: Michael Branagan, Neal Morgan
Expected Graduation Date: May 2017

Bearings provide a critical supportive function in rotating machinery and are thus commonly designed to operate within a set of design constrictions. This makes optimization a powerful tool for use in bearing design. Design of experiments is a useful method which enables intelligent data point selection in order to create simplified models using a minimum number of data points. This project uses design of experiments coupled with MAXBRG to generate simplified bearing models. The optimization of these simplified models enables the minimization of various bearing operation parameters while maintaining others. In phase I of this project, tilting pad bearings from an eight-stage centrifugal compressor are examined individually. The bearing power loss and maximum pad temperature are minimized while maintaining a minimum film thickness to ensure film integrity and a maximum film pressure to prevent damage to the bearing structure. The optimization will be performed with varying weights on the maximum pad temperature and power loss to examine the tradeoffs that one can achieve. In phase II of the project, the bearing model will be coupled to the compressor model and a similar design of experiments will be performed. The design will be performed in order to generate simplified models for both the bearings individually, as well as for the full rotor/bearing system. In this phase, the optimization will be performed in order to minimize key bearing parameters while maintaining safe rotor and bearing operating conditions.



Bearing design variables include pad arc length, radial clearance, preload, offset, and others.

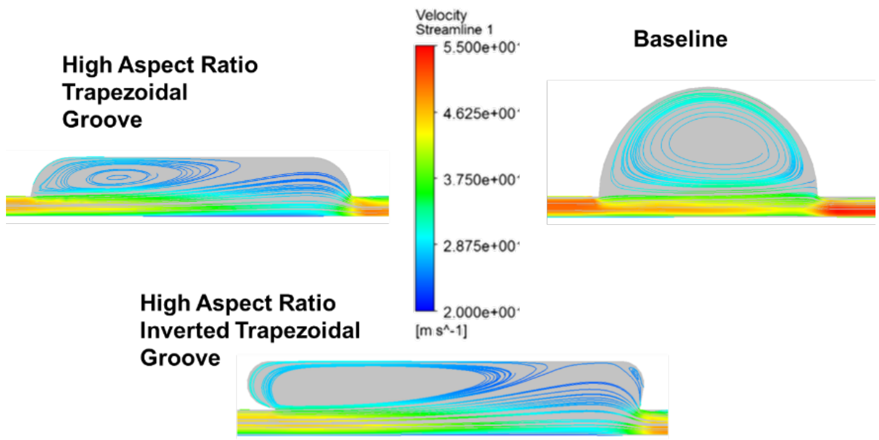


Model response surface of maximum pad temperature to changes in radial clearance and lubricant viscosity.

Analysis of Labyrinth Seals by Computational Numerical Methods

Student: Neal Morgan
Expected Graduation Date: May 2017

The objective of this research project is to develop new software and new analysis methods for annular seals of both traditional and non-traditional geometries. In traditional analysis methods such as the analytical perturbation approach known as bulk flow analysis, these expansion and recirculation grooves are commonly rectangular or semi-circular because it simplifies the analytical analysis. Recently, computational fluid dynamics (CFD) work has been performed on the geometric optimization of these groove shapes to minimize leakage through example seals. This work has conclusively demonstrated that non-traditional groove shapes can improve leakage response in the simulated seals. Unfortunately, CFD simulations require increased engineer and computational time in comparison to traditional bulk flow methods.



Semicircular groove flow vs. high aspect ratio trapezoidal groove flow.

A numerical analysis technique is under development to apply alternative numerical techniques to a set of simplified Navier-Stokes Equations representing a steady viscous potential flow. These assumptions are less strict than those of bulk flow and will allow for detailed flow characterization throughout the annular seal. The flow will be modeled with the vortex formulations of the Navier-Stokes equations and solved numerically by boundary element methods. Boundary element methods reduce the dimensionality of a full 3D seal to 2D, significantly reducing mesh sizes and increasing solution speed. The method will be developed for use with generalized, parameterized grooves first, with geometry import and a similar method using the Euler equations for gases for future development steps.

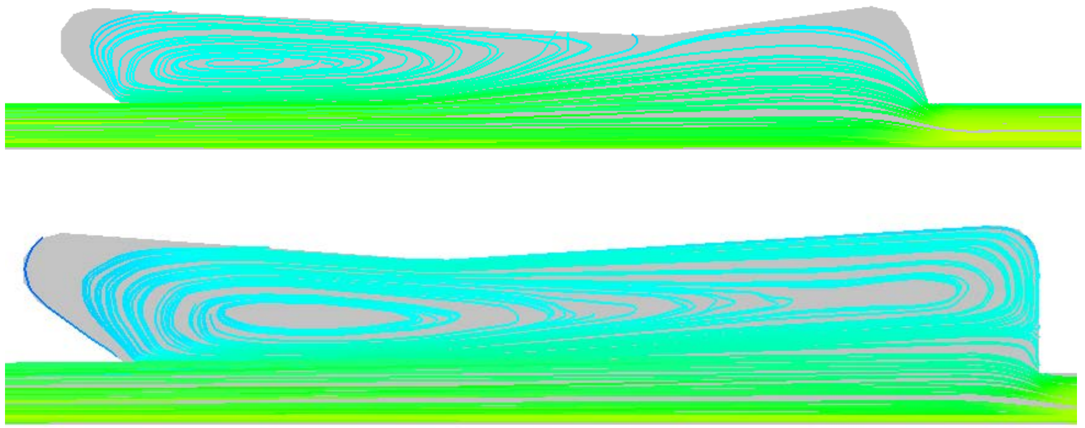
The developed analysis method aims to fully characterize the seal flow and rotordynamic response with solution times at least one order of magnitude faster than a commercial CFD package for a full 3D seal analysis. This will offer more accurate solutions than traditional bulk flow methods for novel annular seal geometries at reasonable computational cost. Accurate and computationally inexpensive modeling tools that allow for large seal geometry variation will prove invaluable to design optimization of turbomachinery flow paths.

Groove Shape and Labyrinth Seal Geometry Optimization

Students: Neal Morgan, Harrison Gates
Expected Graduation Dates: May 2017, May 2021

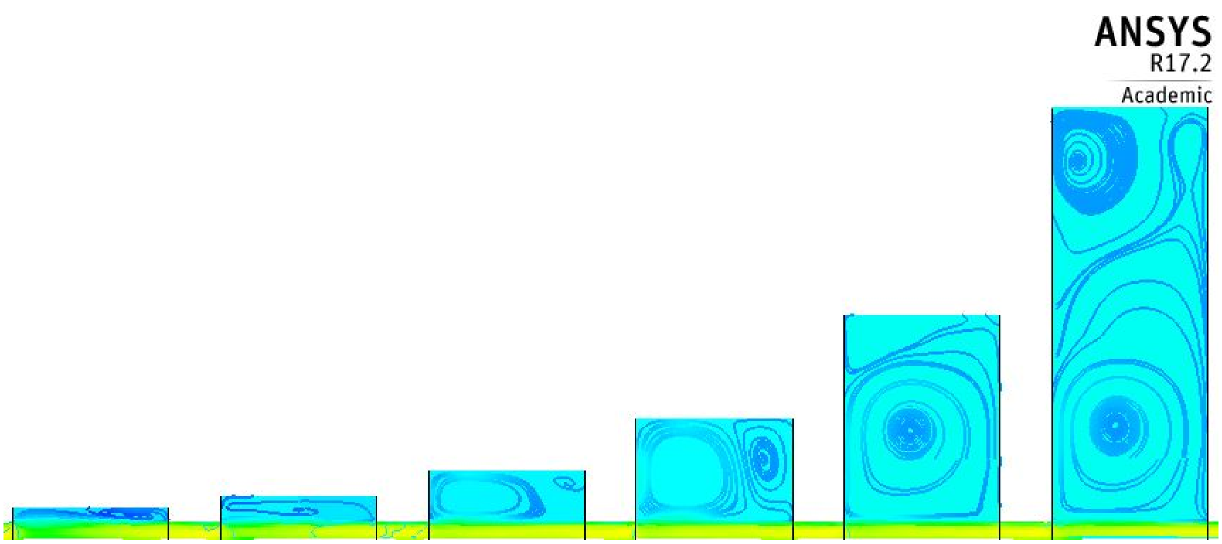
Two studies are in progress to investigate new parameterizations for labyrinth seal geometries. These studies are investigating the effects of groove shape and the effects of non-uniform grooves of patterned size and shape on labyrinth seal flow and rotordynamic characterization.

The first study continues previous work by investigating a repeated pentagonal groove shape applied to a full 3D CFD model of a 20-groove balance drum labyrinth seal with a working fluid of water. The grooves are parameterized by inlet and exit angle, front depth, back depth, and the x and y location of a vertex inside the groove. This allows for concave and convex pentagonal groove shapes that manipulate the anchoring and size of the in-groove vortices generated by the pressure and shear-driven flow. These vortices have a significant impact on seal leakage and rotordynamic performance.



Pentagonal groove flow examples.

The second study investigates the same nominal full 3D CFD model of a 20-groove balance drum labyrinth seal with a parameterized model consisting of 10-60 traditional rectangular grooves. These grooves vary axially in width and depth according to quadratic functions representing groove aspect ratio and percentage of available width (per groove). This will allow for the investigation of the effects of number of grooves and converging and diverging groove profiles on seal leakage and rotordynamic performance.



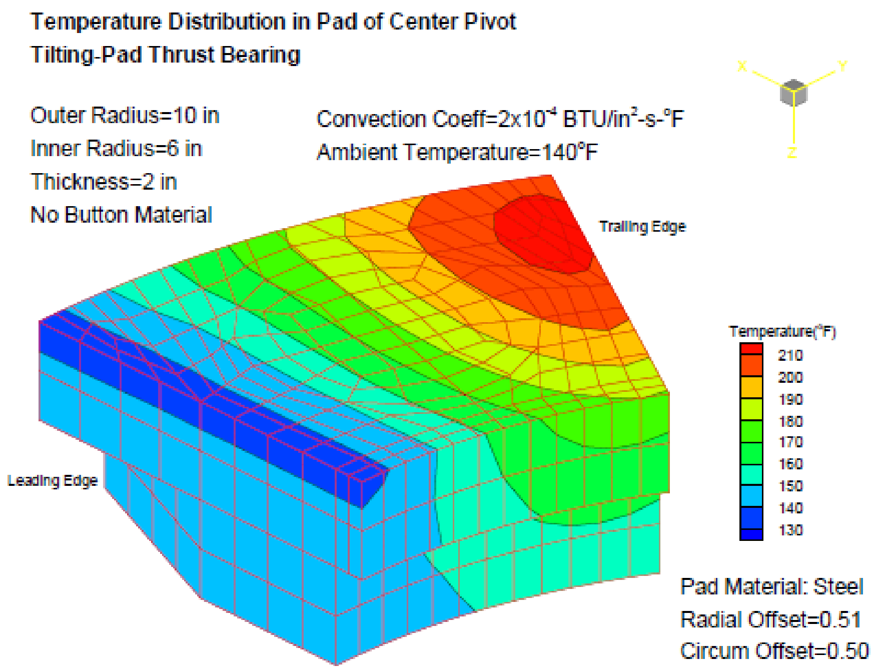
Non-uniform groove flow example.

Both studies are performed with experimental design methods to reduce the number of CFD simulations and develop a response surface map of seal design parameters against seal performance responses. A multi-objective optimization will be performed with a range of weighting parameters to obtain seals with minimum leakage and maximum effective damping properties.

Thrust Bearing Modeling Tools

Student: Xin Deng
Expected Graduation Date: May 2020

The focus of this project is on developing a new fluid film thrust bearing code that performs comprehensive thermoelastohydrodynamic (TEHD) analysis. Like the current ROMAC code for thrust bearings (THRUST), the lubricant would be incompressible and the operation would be steady state. However, this new code would address the weaknesses of THRUST in areas including turbulence modeling and numerical robustness. It would also expand the capabilities to model some geometries that cannot be modeled by THRUST. Moreover, this new code would be flexible enough to allow future improvement of various theoretical models, for example, groove mixing and direct lubrication. To achieve all of these goals, modifying the existing THRUST code would not be cost effective because some equations must be reformulated and various iteration loops must be restructured. A better approach is to develop a new analytical software tool utilizing advanced techniques only available in recent years.



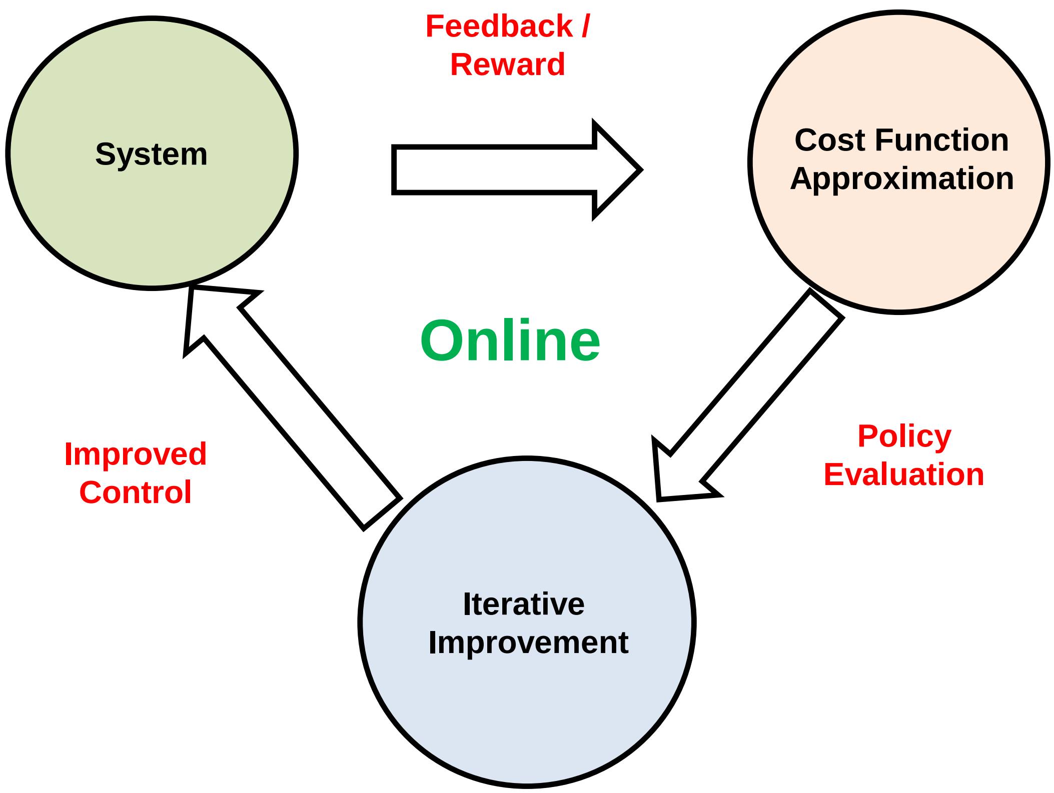
Investigation of Reinforcement Learning-Based Control and its Possible Application in Rotating Machines

Student: Syed Ali Asad Rizvi
Expected Graduation Date: May 2020

Over the years many control methods have been proposed towards controlling rotating machines such as PID control, state-space control, robust control, and optimal control. These methods have proven their performance when a good mathematical model of the machine is available. However, extracting model information is generally challenging and also involves uncertainties in the identified model. Learning-based techniques come into picture when accurate models are not known in advance.

Reinforcement learning is new in line of modern adaptive control techniques which aims to design control systems that are both adaptive and optimal. These controllers can be considered as direct optimal adaptive controllers in which an optimal controller is designed without heavily relying on system models. The controller interacts with the system and modifies its control policy based on some reinforcement signal. The process involves online iterative approximation of optimal cost function and optimal control.

The theory of reinforcement learning control is however still new, and more results are needed for it to be feasible in practical control applications. In this project, we are investigating some reinforcement learning algorithms and seeking to extend the theory in order for it to be applied in rotating machines. In the future, such advanced control techniques are expected to require more computational capability, therefore we are also considering upgrading our existing control system hardware for our test rigs. High speed control and data acquisition boards comprising of modern embedded systems such as multi-core processors, DSPs or FPGAs are currently in consideration.



Big-Picture Overview of Reinforcement Learning Control

2016 ROMAC Reports

In 2016 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 2016 is included below. These papers and past reports have been made available on the ROMAC Reports website as part of a major update completed this Fall.

Zhou, J., Di, L., Cheng, C., Xu, Y., and Lin, Z., "A rotor unbalance response based approach to the identification of the closed-loop stiffness and damping coefficients of active magnetic bearings", Mechanical Systems and Signal Processing, Vol. 66-67, pp. 665-678, 2016.

Weaver, B., Kaplan, J., Clarens, A., and Untaroiu, A., “Transient Analysis of Gas-Expanded Lubrication and Rotordynamic Performance in a Centrifugal Compressor,” Journal of Engineering for Gas Turbines and Power, Vol. 138, pp. 042504-1-042504-8, 2016.

Yoon, S., Anantachaisilp, P, and Lin, Z., “An LMI Approach to Control of Exponentially Unstable Systems Subject to Saturation and Time-Varying Delay in the Input,” Recent Results on Nonlinear Delay Control Systtems, Advances in Delays and Dynamics Vol. 4, pp. 367-384, 2016.

Yoon, S., 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, Vol. 24, Iss. 6, pp. 2182-2189, 2016.

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, Vol. 33, pp. 146-160, 2016.

Yoon, S.Y., Di, L., and Lin, Z., "Unbalance Compensation for AMB Systems with Input Delay: an Output Regulation Approach", IFAC Control Engineering Practice, Vol. 46, pp. 166-175, 2016.

Gunter, E.J. and Weaver, B., "Kaybob Revisited: What We Have Learned About Compressor Stability From Self-Excited Whirling," Proceedings of the Vibration Institute 40th Annual Training Conference, pp. 1-22, Asheville, NC, June 13-17, 2016.

Gunter, E.J. and Waite, J., "Dynamic Analysis and Field Balancing of 100 MW Utility Gas Turbine-Generators," Proceedings of the Vibration Institute 40th Annual Training Conference, pp. 1-38, Asheville, NC, June 13-17, 2016.

Yu, Y. Saadat, M., Untaroiu, A., Thomas, B., and Wood, H., "Prediction of Turbo Air Classifier Cut Size Based on Particle Trajectory," Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, Paper No. GT2016-57903, pp. V006T21A010-1-V006T21A010-11, Seoul, South Korea, June 13–17, 2016.

Mu, H., Wei, W., Untaroiu, A., and Yan, Q., "Study on Reconstruction and Prediction Methods of Pressure Field on Blade Surfaces for Oil-filling Process in a Hydrodynamic Retarder," International Journal of Numerical Methods for Heat & Fluid Flow, Vol. 26, Iss. 6, pp. 1843-1870, 2016.

Gresham, T., Weaver, B., Wood, H., and Untaroiu, A., "Characterization of Brush Seal Permeability," Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, Paper No. GT2016-57910, pp. V05AT15A031-1-V05AT15A031-9, Seoul, South Korea, June 13–17, 2016.

Watson, C., Untaroiu, A., Wood, H., Weaver, B., Morgan, N., and Jin, H., "Response Surface Mapping of Performance for Helical Groove Seals with Incompressible Flow," Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition, Paper No. GT2016-57945, pp. V07BT31A036-1-V07BT31A036-7, Seoul, South Korea, June 13–17, 2016.

Watson, C., Wisher, P., Wood, H., and Weaver, B., "Quantifying the Linearity of the Fluid Dynamics for Noncontacting Annular Seals," Proceedings of ASME International Mechanical Engineering Congress & Exposition, Paper No. IMECE 2016-66804, pp. 1-6, 2016.

Watson, C. and Wood, H., "Optimizing a Helical Groove Seal Using Computational Fluid Dynamics," Proceedings of EDF-Pprime 2016, Paper NO. EDF-Pprime-2016:112151, pp. 1-10, 2016.

Di, L., Chen, C.Y., Lin, C.H., and Lin, Z., "Characteristic Model Based All-Coefficient Adaptive Control of a High-Speed Desorption Pump Supported by AMBs," Proceedings of the 15th International Symposium on Magnetic Bearings, pp. 1-8, Kitakyushu, Japan, August 3-6, 2016.

Di, L., Yoon, S., and Lin, Z., "Autobalancing of AMB Systems Using a Differential Regulator Based Output Regulation Approach," Proceedings of the 15th International Symposium on Magnetic Bearings, pp. 1-8, Kitakyushu, Japan, August 3-6, 2016.

Branagan, M., Griffin, D., Goyne, C., Untaroiu, A., and Wood, H., "Compliant Gas Foil Bearings and Analysis Tools," Journal of Engineering for Gas Turbines and Power, Vol. 138, No. 5, pp. 054001-1-054001-8., 2016.

Gerami, A., Fittro, R., and Knospe, C., "Modeling and Control of Magnetic Bearings with Nonlinear Magnetization (Simulation vs. Experiment)," Proceedings of the 15th International Conference on Magnetic Bearings, Japan, August 2016.

Kurvinen, E, Fittro, R., and Maslen, E., "Advanced Control Performance in Compressor Surge," Proceedings of the 15th International Conference on Magnetic Bearings, Japan, August 2016.

Whitlow, Z., Fittro, R., and Knospe, C., "Dynamic Performance of Conventional and Segmented Active Magnetic Thrust Bearings," IEEE Transactions on Magnetics, submitted April 2016.

Kurvinen, E, Fittro, R., and Maslen, E., "Improving Compressor Surge Performance with Advanced Control," Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, May 2016.

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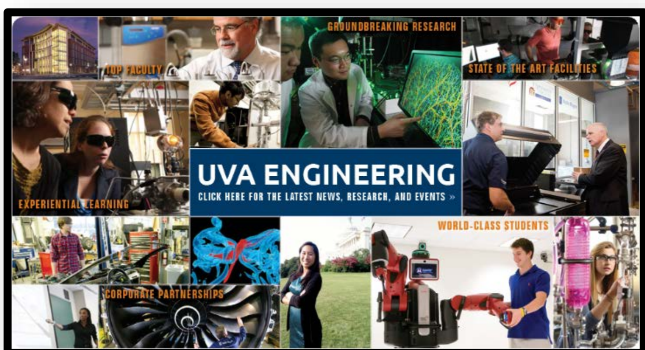
- Magnetic Bearings and Controls
- Optimization of Rotor-Bearing Systems
- Experimental, Computational, and Theoretical Studies



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