From our Director

It is hard to believe the 2017 Fall semester ends this week. With the onset of it way back in August we welcomed three new graduate students this academic year: Jeffrey Bennett, Madeline Carlisle Collins and Wisher Paudel. Read more about each of them on page four.

As always the summer semester was a busy time for ROMAC students and faculty with our annual meeting and short course, as well as many students attending and presenting at conferences. Many of us were able to enjoy a little time away from the lab as well.

Our students are busy with their research projects, studying for qualifying exams, writing papers, designing test rigs, studying for exams and preparing to defend dissertations. You will find their updated project summaries on the following pages.

My ROMAC colleagues and I are very pleased to announce that Dr. Minhui He, has joined the ROMAC faculty as a part-time senior scientist. Minhui has been active with ROMAC for many years, first as a graduate student, a ROMAC software engineer, and then as an active member through BRG Machinery Consulting. Please see more about Dr. He on the following page.

ROMAC 2018 membership invoices have been sent out. Please take advantage of the 5% discount and ensure your payment is received by March 31, 2018.

During the last year our main lab space received some TLC. MEC 105 was painted, the lighting was replaced, as well as the ceiling grid and tiles. This work has gone a long way to freshen up our space and was fully funded by UVA Facilities and Maintenance, with funds put aside for spaces that had not received physical improvements for years. We will continue to make updates to labs and student work areas as we can.

Please log on to the ROMAC website periodically for up to date information. If you have a research project suggestion, or need, please let us know how we can help by contacting us at romac@virginia.edu.
**ROMAC Honors Ed Memmott**

ROMAC honored long time member Dr. Edmund Memmott at dinner on Tuesday evening during the ROMAC Annual Meeting. ROMAC industry members, faculty and students honored Ed upon his retirement from Dresser Rand—A Siemens Company in the field of rotordynamics with over 44 years of service. Ed retired in September 2017.

Ed has been an active participant in the ROMAC Consortium for a long time. In Ed’s own words, “I have been coming to UVA since sometime in the 1970s.” Dr. Memmott, has attended numerous ROMAC annual meetings, and has participated as an industry member instructor for the ROMAC Five Day Short Courses. He has already offered to continue in that role. In addition to sharing his expertise in rotordynamics over the years, Ed has functioned as the unofficial photographer for ROMAC events.

The inscription on the plaque reads: *With appreciation and gratitude to Ed Memmott upon his retirement from Dresser Rand—A Siemens Business for decades of membership, support and dedication to the Rotating Machinery and Controls Consortium. ROMAC 2017.*

We wish Ed and his wife, Theresa many enjoyable and relaxing years of retirement.

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**Minhui He Joins ROMAC Lab**

We are very pleased to announce that Dr. Minhui He has joined the ROMAC Laboratory at the University of Virginia, School of Engineering and Applied Science as a part-time Senior Scientist. His responsibilities include conducting research in the fields of fluid film bearings, annular seals and rotordynamics. He will direct graduate students on their research projects, as well as assist in the selection and definition of future research.

Dr. He received his BS degree in Chemical Machinery Engineering in 1994 from Sichuan University. From 1996 to 2003, he conducted research on fluid film journal bearings in the ROMAC Laboratories, receiving his PhD in Mechanical and Aerospace Engineering in 2003. Dr. He is also a Machinery Specialist with BRG Machinery Consulting LLC, in North Garden, Virginia, where his responsibilities include vibration troubleshooting, rotodynamic analysis, as well as bearing and seal analysis and design. He is a member of ASME and on the advisory committee for the Texas A&M Asia Turbomachinery and Pump Symposium.

Many of you know Minhui through your participation with ROMAC over the years. We are pleased to welcome him in to his new role as senior scientist. Dr. He can be reached at mh9n@virgininia.edu.

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*Houston Wood presents Ed Memmott a commemorative plaque*

*Minhui He
ROMAC Senior Scientist*
Downtown Staunton, VA was the location for the 2017 ROMAC Annual Meeting held June 19-23. Over 35 ROMAC members from the US and five countries made their way to the Shenandoah Valley to attend. During the meeting nearly 40 industry talks were presented by industry experts, ROMAC faculty and graduate student researchers. Evenings were filled with opportunities to relax, collaborate, and network.

2017 ROMAC Annual Meeting

Meeting attendees prepare for the next talk.

The ROMAC Advisory Board

On Monday afternoon prior to the start of the 2017 ROMAC Annual Meeting the Advisory Board, and ROMAC faculty met with Eric Loth, Chair of the Mechanical and Aerospace Engineering Dept. As well as SEAS, Susan Barker, Sr. Director of Research Development and John Ralston, Director of Corporate Relations. There were several areas of valuable discussion. ROMAC members can view the minutes through the ROMAC Advisory Board page on the website through this link here. As members of ROMAC you may contribute agenda items by sending your requests to Lori Mohr Pedersen and/or directly to one of the Advisory Board members.

2017 Summer Short Course

The ROMAC Laboratory held their annual Rotordynamics and Magnetic Bearing Five Day Short Course July 17-21, 2017. The course was attended by six participants from ROMAC member companies, as well as two of our new graduate students. This course is open to both ROMAC members and non-members. A wide variety of topics are taught by industry experts, ROMAC faculty, researchers, and PhD students. The 2018 Five Day Short Course will take place July 9-13, 2018. More detailed information will be posted on the ROMAC website as it becomes available.

Pictured are six of the seven members from the Beijing Institute of Technology who attended.
New Graduate Students

**Wisher Paudel** is a PhD student in Mechanical & Aerospace Engineering. He received his BS in Mechanical Engineering from UVA in May 2017. During his 3rd & 4th years he worked with ROMAC as an undergraduate research assistant. He presented a paper, co-authored with Cori Watson and Houston Wood: “Mixed Helical Labyrinth Seal Optimization Using Computational Fluid Dynamics” at the 2017 ASME Turbo Expo. Wisher began his graduate studies during the summer semester. He is currently on a fellowship from the Nuclear Regulatory Commission.

Madeline Carlisle Collins is a PhD student in Mechanical & Aerospace Engineering. She received her undergraduate degree in Mechanical Engineering with a minor in Math from Louisiana Tech University. Madeline was recognized and received the academic award for the “Outstanding Senior” in Mechanical Engineering. She is a UVA School of Engineering Distinguished Fellow.

Jeffrey Bennett is a PhD student in Civil & Environmental Engineering and is a UVA School of Engineering and Applied Sciences Distinguished Fellow. Jeff received his undergraduate degree in Mechanical Engineering from Virginia Tech and a joint M.Sc. Degree in Turbomachinery Aeromechanics from Royal Institute of Technology, Stockholm, Sweden and the University of Liege, Liege, Belgium. Prior to his acceptance at UVA he worked as a research engineer with ROMAC member company, Southwest Research Institute.

Students Graduating in December

**Brad Nichols** defended his PhD dissertation “Experimental measurements and modeling of tilting-pad bearing performance and system stability under reduced oil supply flow rates.” in early December.
ROMAC Visiting Scholars

The ROMAC faculty, students, and staff are currently hosting three visiting scholars with a variety of backgrounds.

**Dr. Cheng Liu** has been with us since January 2016. He is currently a Research Associate 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 centers on torque conversion. Cheng has been an active and valued member of the ROMAC lab. His appointment is through early-January 2018.

**Dr. Hui Liu** is a professor and the Director of the Vehicle Engineering Department at the Beijing Institute of Technology where she received her education, completing her Ph.D. in 2003. Her research is focused on the design method and theory of vehicle transmission and noise, vibration and harshness technology of chassis. Dr. Liu’s appointment is through mid-March 2018.

**WeiQi Bai** received his BS in Engineering in 2013 from Beijing Jiaotong University and continues his studies as a PhD student in the State Key Laboratory of Rail Traffic Control and Safety at BJTU. His research interests are: Modeling and collaborative control of high-speed train; Energy-saving optimal control; High-speed railway systems and Fault diagnosis. His appointment is through October 2018.

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**Dates to Remember in 2018**

- **ROMAC 2018 INVOICES DUE**
  - March 31, 2018

- **ROMAC ANNUAL MEETING**
  - June 4-8, 2018
  - CHARLOTTESVILLE
  - DOUBLETREE HOTEL

- **2018 FIVE DAY SHORT COURSE**
  - July 9-13, 2018
We are pleased to announce multiple software releases for the latter half of 2017. A number of code releases were announced at the 2017 Annual Meeting including a new 2D squeeze film damper code MAXSFD, MAXBRG v5.3 (a higher-speed version originally released as part of RotorLab+ 4.0), TORTRAN3 v2.0 (which allows for larger shaft models), and a 64-bit compatible DAMBRG2. Additional code releases now available to members include the following:

**THRUST v5.4:** This version includes multiple enhancements to improve accuracy, convergence, and control for more complex geometries and fluid environments including water lubrication. New inputs provide for greater control over cross-film nodes for turbulence modeling, circumferential nodes for heat flux calculations, and the method used for eddy viscosity calculations. New outputs include RMS values for the turbulence solution and improved error reporting when convergence is not achieved. Multiple iteration loops within the program have also been modified for improved convergence.

**SFDNL:** New guidance to enhance the usefulness of this code has been added to the Software Catalog including an SED file for using the code with RotorGUI and an input file listing for manual editing.

**RotorLab+ 4.2** is also anticipated to be released this winter, with a number of enhancements being made to the program including:

- Multi-level shaft capabilities for critical speed analysis, forced response, and FORSTAB stability analysis
- New multi-level shaft example project
- Mode tracking and log dec vs. cross-coupled stiffness plots will be available in the Assembly Workspace
- Auto-meshing will now be optional
- User manuals added for all built-in analysis codes
- Bug fixes and improvements to overall program stability

Stay tuned for this and other upcoming software releases including RotorGUI 2.0, MAXBRG v5.4, TORTRAN3 v2.1, Seal4, GearTran, and BrushSolve. Please contact our software engineer Brian Weaver at bkw3q@virginia.edu with any software-related questions.
Many applications of computational fluid dynamics (CFD) for rotating machinery components require multiple reference frame models in order to model dynamics in steady state. For example, in double surface helical groove seals, because both the rotor and the stator are not circumferentially symmetric, either a multiple reference frame model must be used or the mesh will deform. The fluid domain can be broken into sections with different reference frames as shown in Figure 1.

This multiple reference frame approach is also needed to calculate the rotordynamic coefficients of helical groove seals, hole pattern seals, and impellers. One open question is which interface model is the best for specific applications. The two most common interface models are frozen rotor and staged interfaces. The frozen rotor interface works by fixing the relative position of the rotor and stator and simulating that moment in time. Then the relative position can be changed through the rotational offset, as shown in Figure 2, and the component simulated at a new moment in time. The staged interface works by circumferentially averaging the pressure to approximate the relative motion of the rotor and stator.

This project will look at two problems: double surface helical groove seals and the vibration of axial impellers. The best multiple reference frame interface model will be determined. We then hope to produce a general result or method of determining the best interface model to use in general simulations of rotating machinery components.
Evaluating Configurations of Double Surface Helical Groove Seals using Computational Fluid Dynamics

Student: Cori Watson

In multistage pump design, it is now common to use helical groove seals with grooves on both the surface of the rotor and stator where the grooves are opposing in direction. That is, where the grooves on the rotor pump towards the inlet, but the grooves on the stator pump towards the outlet. Despite this being the industry standard, no data in the literature exists suggesting that this design is better than helical groove seals with grooves in the same direction, i.e. both pumping towards the inlet (Figure 1).

This project examines the conditions in which opposing grooves are a better configuration than helical groove seals with grooves both pumping towards the inlet. To accomplish this, simulations are run using ANSYS CFX for a variety of operating conditions for each configuration. The baseline design of this study is a model that has been validated against experimental results of an opposing groove seal design from the literature. Finally, this study presents discussion and conclusions of the preference to opposing direction helical groove seals based on the flow mechanisms of the two seal configurations.

This work will form the basis of future work optimizing double surface helical groove seals and designing computationally efficient analysis tools for these designs, which are already widely in use but lack computational analysis tools.

Analyzing the Rotordynamic Performance of Helical Groove Seals using Computational Fluid Dynamics

Student: Cori Watson

The rotordynamic performance of helical groove seals has yet to be analyzed using computational fluid dynamics (CFD). One reason for this is that in order to model the eccentric performance of helical groove seals in steady state, the model must be separated into multiple reference frames as shown in Figure 1.
Analyzing the Rotordynamic Performance of Helical Groove Seals using Computational Fluid Dynamics

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In this approach, the rotor and stator regions are separated into two domains with a domain interface connecting them. Then, both the rotor and stator walls are specified as no-slip stationary and the domains are prescribed to rotate at the wall velocities. The domain interface is modeled as a frozen rotor.

In the first stage of this project, the rotordynamic coefficients of helical groove seals calculated in CFD are compared against experimental results by Iwatsubo et al (1990). This validates that CFD - and specifically the setup with multiple reference frames and a frozen rotor interface - is an accurate method to model the rotordynamic forces of helical groove seals.

Next, the helix angle of the helical groove seal is optimized to maximize the effective damping of the system and the physical mechanism of this optimal point is explained in terms of the force balance between the pumping force of the rotor and the pressure differential force acting on the fluid within the grooves.

Finally, this project seeks to develop a formula for approximating the helical groove seal design parameters which will produce maximum effective damping. This will serve as a starting point for industry engineers to use as a baseline design before running analysis codes for a more in-depth study of helical groove seal performance.

Finalizing and Releasing New ROMAC Seal Codes

Student: Cori Watson

Over the prior year, work has been done to develop and validate new codes for incompressible helical groove and labyrinth seals. Initial comparisons of these codes to experimental results are promising and the next step of this project is to extensively calibrate the codes to minimize the average error and to be able to quantify the accuracy of these methodologies.

Thus far, computational fluid dynamics (CFD) has been validated against experimental results for labyrinth and helical groove seals. Next, a range of simulations will be run in CFD and these results will form the data set against which the new bulk flow codes will be calibrated. The calibration is done by choosing the empirical friction factors that maximize the accuracy of the codes by reducing the average error between the CFD and bulk flow results across a range of operating conditions and design parameters.

Comparison of the CFD and ROMAC codes’ results can also be used to produce error maps that can be used to approximate the accuracy of the codes at given operating points. We hope to include these in the new user manuals so that the end user will have a sense as to the accuracy of the codes in his or her application.
Experimental Measurements and Modeling of Tilting-Pad Bearing Performance and System Stability under Reduced Oil Supply Flow Rates

Student: Brad Nichols

Graduation Date: December 2017

High-speed rotating machines such as pumps, compressors, and turbines across a wide range of industries rely on tilting-pad, fluid-film journal bearings to provide static support to the shaft while introducing stabilizing damping forces into the system through the development of a hydrodynamic film wedge. These bearings depend on a constant flow of fresh oil to keep bearing temperatures low while providing sufficient oil to support the shaft. Traditionally, oil is supplied at an adequate flow rate to flood the bearing pads, producing a fully developed film layer over all pad surfaces. Reduction of the oil supply flow rate may cause cavitation, or lack of a fully-developed film layer, over one or more of the pads. This condition is commonly referred to as starvation. The extent of bearing starvation is heavily dependent on the oil delivery method, housing design, and operating condition. Numerous experimental studies have looked at the effects of reduced oil supply flow rate on steady-state bearing performance for various bearing designs and operating conditions. It is well-documented that reduced oil supply flow rates result in decreased operational power losses at the expense of increased operating temperatures. While these effects are widely known, fewer studies have been published that focus on the effects of flow rate on dynamic bearing performance or system stability.

A series of experimental studies were conducted in order to observe the effects of oil supply flow rate on steady-state bearing performance as well as dynamic performance and system stability. All measurements were performed on the Stability Test Rig consisting of a flexible shaft supported by two tilting-pad bearings in traditional, flooded housing designs. Under a number of operating speeds and bearing load conditions, the oil supply flow rate to the two supporting bearings was systematically reduced while collecting data at each condition. Pad temperatures, sump temperature, journal operating position, and input power were all measured for the study on steady-state bearing performance. Vibration measurements under various operating conditions were measured to observe the effects of flow rate on substantial subsynchronous vibration patterns observed in the shaft during supercritical operation. Finally, vibration measurements were recorded during shaft perturbations produced with a magnetic actuator to identify modal properties, specifically damped natural frequencies and damping ratios. All experimental data was compared to TEHD modeling results obtained from MAXBRG. Both flooded and starved bearing flow assumptions were considered in an effort to validate the starvation model under reduced flow rate conditions. As shown in Figure 1, the starved bearing model predicts upper pad cavitation that increases in severity with decreasing flow rate, lessening the load carried by the bottom pads.

Figure 1: Pressure profiles vs oil supply flow rate, 10,000 rpm, 124 kPa specific load.
Similar results were also observed in the starved model predictions with increasing speed for a given flow rate. The progressive unloading of the upper pads and redistribution of pad pressures seen in the starved model corresponds to a drastic increase in the amplitude of subsynchronous vibration occurring at the first bending mode of the shaft, as shown in Figure 2.

As seen in Figure 3, subsequent identification of the damping ratio associated with this mode shows a decrease in system stability with each decrease in oil supply flow rate.

The trends predicted by the two bearing models produced some unexpected results. Both models predict an increase in system stability with decreasing oil supply flow rate. Additionally, the starved bearing model consistently predicts higher damping ratios than the flooded model across all operating conditions. Predicted pressure profiles and dynamic coefficients were investigated to help explain these results. Based on good correlation with measured journal operating position and damped natural frequencies, it was concluded that the pressure profiles and predicted stiffness values of the starved model were reasonably accurate and an improvement over the flooded model in reduced flow rate conditions. It was also concluded that the starved model tends to over-predict bearing damping, resulting in the observed trends. While the starved model produces more accurate predictions of critical speeds, the flooded model consistently provides a more conservative approach when determining the stability margin.
Computational Modeling of Pad Surface Irregularities in Fluid Film Bearings

Student: Michael Branagan
Expected Graduation Date: May 2018

Predicting the response of bearings is a vital part of rotor system design as bearings are used to support and stabilize the system. Fluid film bearings are commonly used bearings that can be found in many applications today. As operating loads and speeds increase, there is an increased importance in accurately predicting the bearing behavior. Surface irregularities can occur accidentally, such as the case with scratches, or can be machined into the bearing as is the case with jacking pockets. CFD models are being developed in order to better understand the physics that occur in the vicinity of these surface irregularities. Simpler models will be developed that will be compatible with the Reynolds equation. CFD and available experimental data will be utilized in order to validate the model. A software tool is being developed that will be capable of accounting for a three dimensional pad surface and the resulting phenomena.

Axial Dynamic Similarity of Groove Flow in Labyrinth Seals

Student: Neal Morgan
Expected Graduation Date: May 2018

Traditionally, annular seal flow is modeled with bulk flow methods for simple geometries in cases for which experimental data is available, or with computational fluid dynamics (CFD) when the groove geometry is non-rectangular or when empirical friction factors from prior test data are unavailable. Computational models of fully three-dimensional labyrinth seals often consist of many millions of volume elements and thus require significant computational resources to solve. This study proposes a set of simplified numerical models for seal analysis by which the flow pattern in a single groove can be taken as representative of each groove of identical geometry at different axial locations along the seal. For both liquid and gas working fluids, the velocity components were normalized for each groove cavity and the immediately adjacent jet flow region.
Axial Dynamic Similarity of Groove Flow in Labyrinth Seals

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The normalized velocity components were then used to establish dynamic similarity relationships between grooves as a function of normalized axial position and the seal boundary conditions. Based on the boundary conditions and these normalized velocity components, semi-empirical models were generated to represent the seal flow parameters. The simplified analysis method was then tested by simulation of the first few labyrinth grooves, and adjacent jet flow segments which were used to predict the total seal flow. The generated models allow for prediction of the seal pressure, density, and velocity component profiles prior to bulk flow or computational simulation. The rotordynamic forces can also be predicted for new whirl speeds from the outcomes of one or two computational simulations depending on the working fluid. This approach offers significant savings in engineer time and computational cost over established CFD methods alone by improving the initial values for the simulation, or reducing the size and number of simulations needed. Further analysis and understanding of the flow similarity mechanism and behavior also provides insights into the unique fluid dynamics of rotating fluids in small annular clearances.

Figure 2: Liquid seal (above) and Gas seal (right) groove vortex streamline visualization.

Figure 3: Gas seal comparison of circumferential velocity and tangential force component profiles for 0 whirl frequency.
Application of Boundary Element Methods to Tubomachinery Flows

Student: Neal Morgan

Optimizing the design of annular seals by controlling the geometry of the seal to change the leakage, pressure drop, and rotordynamic reaction forces is the forefront of current seals research to improve machine efficiency and stability. These optimization studies often require non-standard groove geometries for which a bulk flow code is insufficient to accurately predict groove flows and seal behavior, thus much of the emerging seal geometry research is performed with CFD simulation studies. As the geometries become more complex and the demands for efficiency increase, larger mesh sizes and more simulations will be required to properly explore the geometric design spaces of interest. With the increasing number of elements and with an increase in geometric parameters to vary, the total time and computational cost for the optimization studies will grow exponentially. This necessitates investigations into alternative numerical methods for seal analysis that are computationally cheaper. The simplest method to reduce the computational cost of a CFD-type model is to reduce the mesh size. The proposed approach, Boundary Element Analysis, does this by reducing the dimensionality of the problem by one. Numerically, the method is similar to Finite Element Analysis (FEA), as both methods use elements represented by a system of weighted residual equations constructed through the Galerkin method. However, the Boundary Element Method (BEM) only involves integration over elements on the boundary of the domain rather than inside many 3D elements throughout the domain. This is accomplished by rewriting the governing equations as boundary integrals only and selecting weighting functions as fundamental solutions to the divergence equation. The final solution is obtained by approximation through shape functions and solution of a matrix inverse as with FEA. As only elements on the boundary of the domain are needed, the method requires less memory and reduced solution time. Additionally, when the fundamental solutions input as weighting functions are chosen well, BEM can converge more rapidly than typical FEA as these solutions automatically satisfy the partial differential equations involved. BEM is also well suited to problems involving discontinuities or singularities, allowing for more complex geometries and operational parameters. The primary disadvantage of BEM is that developing the fundamental solutions and boundary integral equations for a new application requires more expertise and mathematical effort than a similar FEA or finite volume method. The goal of this work is to develop a BEM analysis tool for ROMAC that solves the 3D incompressible Navier-Stokes equations for a generalized seal geometry. This method can then be compared to traditional CFD and bulk flow techniques for accuracy and computational cost.
Gas Centrifuge Modeling

Student: Benjamin Thomas

Expected Graduation Date: May 2018

Based on the Onsager Equation with Carrier-Maslen end conditions, a linearized sixth-order partial differential equation describing the flow in the volume of the rotor of a gas centrifuge is solved using a finite element (FE) algorithm. The countercurrent flow in the centrifuge is generated as a result of gas feed and withdrawal, mechanical scoop interaction, and a rotor wall temperature gradient. These drive mechanisms are modeled by mass, momentum, and energy sources/sinks. The FE results are compared to results from the Pancake code, an existing code employing an eigenfunction expansion solution technique to solve the Onsager equation. Due to proprietary concerns and the potential sensitive nature of separation applications, two fictitious (yet feasible) centrifuge designs, the Rome centrifuge and the Iguacu centrifuge, have been accepted by the international community to enable collaboration and information sharing. Good agreement is demonstrated between the FE and Pancake solutions for each drive mechanism as well as the overall mass flux profile for both the Rome and Iguacu designs.

The axial mass flux derived from the hydrodynamic solution is used in a finite differencing (FD) scheme to obtain a numerical solution of the diffusion equation to predict the transport of uranium hexafluoride molecules. The set of governing equations is not readily solvable using analytical means, and different solution methods have been developed to arrive at approximations for both the axial concentration gradient and overall concentration profile. The generally accepted method of approximation describes the axial variation of the radially averaged concentration. The newly developed 2-D FD approximation allows for separative performance calculations at all points along the radial direction.

Finally, centrifuge performance maps describing the separative performance over a range of feed rates and cut values have been generated for use in cascade modeling software packages to more accurately predict the separative potential of existing and theoretical gas centrifuge enrichment plants (GCEP).

Figure 1: Results of 2-D Finite Difference Isotope Transport Model. Shown above are continuous surface plots representing the normalized mole fraction of the light isotope in a 2-D representation of the axisymmetric rotor volume. The radial coordinate scale heights 'x' represent the local atmosphere as "e-foldings" of density in the rotor where 0 is on the rotor wall and 15 is nearer to the axis. The Z/a represents the axial height given in radii. The Iguacu machine is shown at the left, with a radius of 6 cm and rotor height of 48 cm. The Rome machine is shown to the right, with a radius of 25 cm and a height of 500 cm. The results shown are simulations at a wall speed of 500 m/s.

subjected to traditional and off-normal operating conditions. These new performance maps are currently in use in a case study to compare GCEP output with that derived from performance maps created using a semi-empirical method based on the Pancake code and radially averaged separation calculations for separative performance. Cascades of centrifuges designed for both the Rome and Iguacu machines are modeled and compared to existing models.
Fluid Film Bearing Test Rig

Student: Benstone Schwartz

Expected Graduation: May 2020

The advanced Fluid Film Bearing Test Rig (FFBTR) project aims to measure component-level bearing dynamic properties (stiffness and damping coefficients) at high frequencies and minimize the uncertainty of the experimental measurements. Comprehensive uncertainty analysis has been driving the design of the test rig. Figure 1

The latest results of uncertainty analysis performed on the FFBTR design were presented in 2017 at the ROMAC Annual Meeting and the ASME Turbo Expo in Charlotte, NC. The results showed that it may be possible to develop the FFBTR with piezoelectric load cells rather than the Active Load Cell concept initially proposed. The members expressed interest in the concept utilizing piezoelectric load cells as presented at the annual meeting. Parallel uncertainty analyses were developed for the two concepts for comparison.

While the Active Load Cell concept offers the best performance in terms of minimizing uncertainty, using piezoelectric load cells allows for comparable uncertainty while resulting in a simpler design which would be faster to design, build and commission. Presently, the uncertainty analyses for the FFBTR are being further improved by developing support structure models in ANSYS. This allows for realistic support structure models that include cross-coupling between axes of measurement and cross-coupling between subsystems such as the AMBs and the fluid-film bearing being tested. Inclusion of bearing shell compliance is also being investigated.

The ultimate goal of the uncertainty analysis is to develop an understanding of the effect of measurement error on our ability to identify dynamic coefficients and also how assumptions such as the choice of modeling paradigm for the support structure can affect the identification results for the actual test rig. By performing this analysis, aspects of modeling that significantly increase uncertainty can be identified and mitigated.

In conjunction with the uncertainty analysis, detailed designs of components of the test rig are making steady progress. Currently the rotor design is being finalized with the help of an undergraduate student under Benny's guidance. The present plan is to begin the process of procuring manufactured components during the spring of 2018.
Thrust Bearing Modeling Tools

Student: Xin Deng

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 presently be modeled by THRUST. Moreover, this new code would be flexible enough to allow for the future improvement of various theoretical models (ex. groove mixing and direct lubrication). To achieve 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.
Turbulence Input Parameters Correction Methodology in Water Lubricated Thrust Bearings

Students: Xin Deng, Harrison Gates

A non-dimensional wall distance for a wall-bounded flow can be defined by $y^+$. Boussinesq hypothesis is given by Reichardt’s formula and fitting the velocity profile with experiments having a $y^+$ in the range of 0-1,000, which results in Ng-optimized Reichardts constants $k = 0.4$ and $\delta_i^f = 10.7$. Armentrout and others developed an equation for $\delta_i^f$ as a function of the pivot Reynolds number, which in this work has been further improved by expanding the range of Reynolds numbers considered in the benchmarking performed.

For typical turbulence models, it can be assumed that if the $y^+$ is fixed to that of a standard oil bearing for which the modeling tool THRUST was validated against, the proposed formulation can be used to adjust the mesh number $N$ to allow for convergence with other fluids like water which THRUST was not designed for. Specifically, the kinematic viscosity can be varied for different fluids assuming the rotational speed, diameter, and fluid film thickness are within reason for the THRUST validation experiments. By fixing $y^+$ to a constant value, an equation for the required number of elements $N$ across the film for turbulence can be generated.

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![Figure 1: Comparison of minimum film thickness between benchmark code and THRUST with and without modified cross-film element numbers.](image1)

![Figure 2: New approximation for delta+](image2)
Model-Free Optimal Linear Quadratic Regulation Control Using Output Feedback Q-Learning

Student: Syed Ali Asad Rizvi

Expected Graduation: May 2020

This work deals with the exploration of reinforcement learning control methods and their application to electromechanical systems. Recently, we have solved the Linear Quadratic Regulation (LQR) optimal stabilization problem using a model-free output feedback Q-learning method, and this work has been accepted in the premiere control conference, 56th IEEE Conference on Decision and Control, to be held in Melbourne, Australia in December, 2017. Also, we are glad to announce that our work has received 3rd prize in the University of Virginia ECE Poster Competition held in August 2017.

In this work, we are focusing on the LQR controller that has been successfully applied in many real world applications including Active Magnetic Bearings (AMBs). The optimal control methods like LQR and many other optimal control techniques that we have seen in the literature are all model-based designs. The classical model-based control theory relies on the availability of accurate system models which can be difficult to obtain owing to the increasing complexity of systems and an ever presence of modeling uncertainties. This basically means that the effectiveness of such controllers is directly dependent on the model accuracy that we obtain from modeling tools. Modeling is a complex process and generally involves inaccuracies which ultimately affect the controller design as well. This motivates this research in which we are interested in designing optimal controllers without requiring any model information. This is where machine learning control comes into the picture.

We have obtained some preliminary simulation results using the proposed method for an AMB-supported balance beam system as shown in Figure 1.

It can be seen in Figure 2 that the balance beam system has been stabilized without requiring model knowledge. Figure 3 shows that the controller parameters also converge to the optimal LQR parameters which correspond to the nominal model of the system.

Currently, we are investigating robust optimal controllers such as H-infinity controllers which could be designed using a similar model-free approach.
Hot Oil Carry-Over in Fluid Film Bearings

Student: Harrison Gates

Fluid film bearings are essential to the reliable operation of high-speed rotating machinery. Oil-based bearing lubricants typically have a reduced viscosity with increased temperatures, which in turn reduces the load capacity of the bearing. As a result, the correct thermal model is necessary for accurate predictions of bearing flow behavior, load capacity, and stiffness and damping forces applied to the shaft.

The term “hot oil carry-over” describes the fraction of hot oil transferred from the trailing edge of the previous pad in a bearing to the leading edge of the next pad, and is considered by bearing manufacturers to be a significant source of uncertainty in modern bearing analysis tools. In this study, computational fluid dynamics is used to study this important flow parameter by evaluating current methods recommended for its estimation. The effects of bubbly flow as a result of cavitation will also be considered.

Variable Labyrinth Seal Groove Design Parameterization

Students: Harrison Gates, Cori Watson and Neal Morgan

Labyrinth seals have been demonstrated to be very effective in limiting leakage of the working fluid out of a rotary system. These seals typically consist of a series of equally spaced rectangular grooves of fixed size, used to impede working fluid escaping from the jet stream region between stages where a pressure differential exists. Annular seals are also known to have significant rotodynamic effects. Thus, the rotodynamic coefficients of the seal must be calculated, particularly the cross-coupled stiffness which results from the pressure wedge created by the eccentricity and rotor’s angular velocity.

Previous researchers have focused on minimizing the leakage by adjusting the width, depth, and number of grooves in a uniform manner. In this study, experimental design methods were applied to uniquely optimize the labyrinth seal for leakage and rotor dynamic stability over various numbers of grooves, whirl speeds, and parabolic distributions of groove aspect ratio and widths. A 7-factor, minimum simulation, resolution V composite study is generated to explore the variable design space of parabolic distributions of seal groove aspect ratios and scales for different groove densities. This experimental design was repeated at five distinct whirl speeds to allow for least-squares regression calculation of rotodynamic coefficients for the seal geometries. Response surface maps are developed from results to show the effect of design parameters (independently and coupled) on seal pressure differential. These maps allow for visual and analytical analysis of the direct and interaction effects of each design variable on a desired response.
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An ANSYS CFX CFD model of a labyrinth seal was developed to solve the Navier-Stokes equations with finite volume methods. A mesh independence study was then performed to minimize solution time and verify the mesh independence of the finite volume solver. Y+ values satisfying the k-\(\varepsilon\) turbulence model were verified and models were validated against experimental results in the literature. An in-house three control volume bulk code (Seal4) was compared to the ANSYS CFX results in terms of leakage and rotodynamic coefficients. Comparison of the bulk flow code results against ANSYS CFX simulations allow for evaluation of the effectiveness of bulk flow methods at predicting flow behavior for varied and high aspect ratio groove geometries. A multi-objective optimization function for leakage and rotodynamic response was developed and is discussed. This analysis method allows seal manufacturers to tailor seals to specific design applications, improving the efficiency of processes by reducing leakage and increasing the pressure gradient across the seal.

Investigating the Flow Phenomena of Mixed Helical and Labyrinth Grooved Seals Using Computational Fluid Dynamics

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This project focuses on mixed helical groove and labyrinth non-contacting annular seals with an application to multi-stage pumps and other liquid applications. These seals have helical grooves on either the rotor or stator surface and labyrinth grooves on the other surface.

The first stage of this research, completed in 2016, was to analyze the leakage of these seal configurations using computational fluid dynamics, specifically ANSYS CFX. The leakage of a seal at a given pressure differential is directly correlated to the power loss of the machine and thus is an important parameter to determine and optimize. The results showed that seals with helical grooves on one surface and labyrinth grooves on the other have an approximately 45% lower leakage than an optimized helical groove seal with grooves just on the stator.

The next stage of this project is to determine the interaction between helical and labyrinth grooves and the source of the reduction in leakage. The current hypothesis is that the labyrinth grooves improve the circumferential velocity which adds to the pumping mechanism of the helical grooves.

The final stage of this project is to analyze the rotordynamics of mixed helical and labyrinth grooved seals. The increase in circumferential velocity that improves the leakage performance of this seal type may make these seals less stable than traditional helical groove seals, but they could still be more stable than labyrinth seals. We also hypothesize that mixed helical groove and labyrinth seals will perform favorably in both performance metrics at a higher range of rotor speeds than helical groove seals which could make them an ideal choice in applications that experience a wide range of operating conditions.
Areas of Expertise and Current Research

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

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