UVA

SCHOOL *of* ENGINEERING
& APPLIED SCIENCE
Department of Mechanical and
Aerospace Engineering
Rotating Machinery and Controls Laboratory

ROMAC NEWSLETTER

FALL 2018

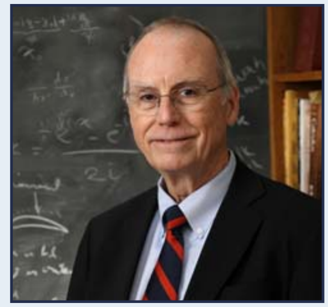
SPECIAL POINTS OF INTEREST

- **ROMAC Graduates, Promotions, New Students and an Extended Visiting Scholar Appointment**
- **Looking Back**
- **New Levels of Membership**
- **Looking Ahead**
- **Student Research Projects**
- **ROMAC Software Update**
- **Awards and Recognitions**
- **Additional ROMAC Research**

Have you seen the ROMAC Video ?

Click Here

From our Director



Houston Wood

I'm in my sixth year as director of ROMAC, with each new academic year I see excited students, and faculty who have new ideas, and research work that bring challenges and successes, as well as a growing membership. These factors together add up to a stronger ROMAC Consortium and very active ROMAC students and faculty.

In May, Brad Nichols and Cori Watson proudly walked the lawn and graduated. New Ph.D. student, Pedro Herrera joined us in June, some of you had to opportunity to meet him at the annual meeting or the short course in July.

The annual meeting was well attended and from the comments received it was an enjoyable and successful meeting. We had presentations from our industry members, graduate student researchers and ROMAC faculty. July brought eleven participants to the ROMAC Lab for our short course. Students and faculty traveled to ASME Turbo in Norway, and the ASME Fluids Engineering Summer Conference in Montreal, Canada.

Zongli Lin and Roger Fittro represented ROMAC as a Gold Sponsor at the ISMB 16 conference in Beijing, China in August.

Zongli Lin, a General Chair of ISMB 16 conference in Beijing, China, at the ROMAC booth there.

We've welcomed new members, Beijing Jiaotong University, Refrigeration Engineering International, Nanjing University of Aeronautics & Astronautics, Rolls Royce Marine Powered Operations and Gulf Coast Bearing & Seal, Inc.

ROMAC and our colleagues at the Beijing Institute for Technology will be conducting an International Conference on Rotating Machinery Transmission and Controls, July 19 –23, 2019 in Beijing China. This event is in addition to our ROMAC Annual Meeting, which is scheduled for June 10—14, 2019 in Charlottesville.

Membership invoices went out in mid-October. Paying your membership fee on time is important to the ongoing strength of ROMAC. We are offering the same incentive for paying on time as last year. Your invoice will reflect your on time payment discount.

2018 ROMAC Graduates

Brad Nichols, Ph.D.

In late November 2017, Brad defended his dissertation entitled: "Experimental measurements and modeling of tilting-pad bearing performance and system stability under reduced oil supply flow rates". He is currently an assistant professor at Virginia Commonwealth University in the Department of Mechanical and Nuclear Engineering.

Cori Watson, Ph.D.

In early April Cori defended her dissertation: "Computational Modeling of Helical Groove Seals ". As a research associate with ROMAC, Cori continues her research, is teaching a class for MAE, is developing a short course on CFD, and mentoring ROMAC students.

New Faculty Position

Roger Fittro
Assistant Research Professor
Mechanical & Aerospace Engineering

We are pleased to announce and congratulate Roger Fittro for his recent promotion to Assistant Research Professor. After four years of leadership within ROMAC as Associate Director and five years of service since joining ROMAC as a Senior Research Scientist, Roger was promoted to the position of Assistant Research Professor (effective May 2018). In his new appointment, Roger's efforts will continue to remain focused on his work, leadership and service within ROMAC. In addition, he will be taking on increased graduate student mentoring and advising responsibilities as well as pursuing ROMAC technology related external funding.

New Graduate Student

Pedro Herrera joined ROMAC as a Ph.D. student in June. He earned his degree as a Mechanical Engineer from the Universidad Industrial de Santander in Bucaramanga, Colombia and received the degree of "Master in Rotating Machinery" from Universidad de Zaragoza in Spain.

Mr. Herrera has various industrial experience, having worked as a Manufacturing Engineer in the auto-parts industry, a Maintenance Engineer working with pumps and compressors, and has been a Project Engineer in the selection, installation, and commissioning of rotating machinery. His primary technical interests are turbomachinery, rotordynamics and fluid film bearings.

Visiting Scholar Appointment Extended

Weiqi Bai received his B.S. 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. Mr. Bai is working with Prof. Zongli Lin. His appointment is through October 2019.

ROMAC Advisory Board Update

Since the inception of the ROMAC Advisory Board (RAB) in 2016, it has been the intent to rotate members of the board on rolling basis, so as to get varied input and also to help reduce the burden on any single individual.

The RAB appreciates the service of original members: Lorenzo Naldi, GE Oil & Gas, and Balaji Venkataraman, Solar Turbines, who have rotated off. Kris Altiero, Bechtel Plant Machinery, Inc. and Christoph Hentschke, RENK, will remain on the board for another year. And we welcome Phil Johnson, Daikin –Applied and Bruce Fabijonas, Kingsbury, Inc. who begin their new term.

2018 ROMAC Annual Meeting

ROMAC member company representatives gathered in Charlottesville, June 4-8 for the ROMAC Annual Meeting. The meeting was well attended by industrial members, with six giving presentations. The remaining 26 talks were given by ROMAC faculty and graduate research assistants on topics such as seals, rotordynamics, fluid film bearings, modeling and validation, fluid analysis, system modeling & magnetic bearings, and updates on ROMAC test rigs.

Tuesday evening after a tour of the ROMAC Labs and a brief walking tour of the Grounds, we dinned in the Dome Room of The Rotunda. We were joined by Mr. Tom Pitts, as Mr. Thomas Jefferson, who entertained us all with information and stories of a different time.

Houston Wood discusses ROMAC with Tom Pitts as Thomas Jefferson.

Photo Credit: Jack Cofer

During the Annual Meeting our members approved the proposed Tiered Membership Levels which are designed to give prospective small and medium sized companies interested in joining ROMAC the ability to do so more easily. The three levels of membership are detailed on the following page.

Seven specific research proposals were suggested, of those three were new. The top three were the newly introduced projects: Validation and Calibration of ROMAC Codes, One Equation Turbulence Modeling in MAXBRG, and Starvation: Film Shape in Bearing Codes.

2018 ROMAC Short Course

This summer we had eleven attendees at our Short Course, the largest group in recent years; seven were from non-member companies. Presentations were given by ROMAC faculty, graduate research assistants, and industry members with expertise in their fields: Rich Armentrout, Curtiss-Wright, Scan DeCamillo, Kingsbury and Ed Memmott, API 684 Task Force and Hunter Cloud and Minhui He, BRG Machinery Consulting, Inc.

ROMAC Introduces New Levels of Membership

At the annual meeting in June, ROMAC members approved the proposed tiered levels of membership designed to give small and medium sized companies interested in joining ROMAC the ability to do so more easily. The three levels of membership are:

Standard Membership

- Initiation Fee: $27,000
- Annual Membership Fee: $28,500
- Two (2) Company representatives may attend the ROMAC Annual Meeting at no cost
- Additional attendees may participate for nominal fee
- Company representative is eligible to serve on the ROMAC Advisory Board

*Small & Medium-sized Enterprise (SME) Membership (< 250 employees)

- Initiation Fee: $10,000
- Annual Membership Fee: $20,000
- One (1)Company representatives may attend the ROMAC Annual Meeting at no cost
- Additional attendees may participate for a nominal fee
- Eligible to serve on the ROMAC Advisory Board
- Proportional Research Project Voting

*Small Business Membership (< 50 employees)

- Initiation Fee: $5,000
- Membership Fee: $13,500
- One (1) Company representative may attend the ROMAC Annual Meeting at no cost
- Additional attendees may participate for a nominal fee
- Not eligible for membership on the ROMAC Advisory Board
- Proportional Research Project Voting

*USA Government Definition: Ownership structure, Revenue, Number of Employees

If you would like additional information regarding membership

under these newly established guidelines

contact us at

(434) 924-3292 | romac@virginia.edu

Looking ahead

2019 ROMAC membership fees are due March 31, 2019

ROMAC Annual Meeting
June 10-14, 2019
OMNI Charlottesville Hotel | Charlottesville, Virginia

Rotordynamics and Magnetic Bearings
Short Course
Summer 2019 Exact Date to be Decided
University of Virginia | ROMAC Lab

Computational Fluid Dynamics of Machine Components
Short Course
Summer 2019 Exact Date to be Decided
University of Virginia | ROMAC Lab

International Conference on Rotating Machinery Transmission and Controls
July 19 – 23, 2019*
Beijing, China

Hosted by the Chinese Mechanical Engineering Society (CMES)

Sponsors:
Fluid Power Transmission & Control Institution (FPTCI)
Beijing Institute for Technology (BIT)
National Key Laboratory of Vehicular Transmission (NKLVT)
Rotating Machinery and Controls Laboratory (ROMAC)

If you are interested in attending please let us know.
This will assist with planning.

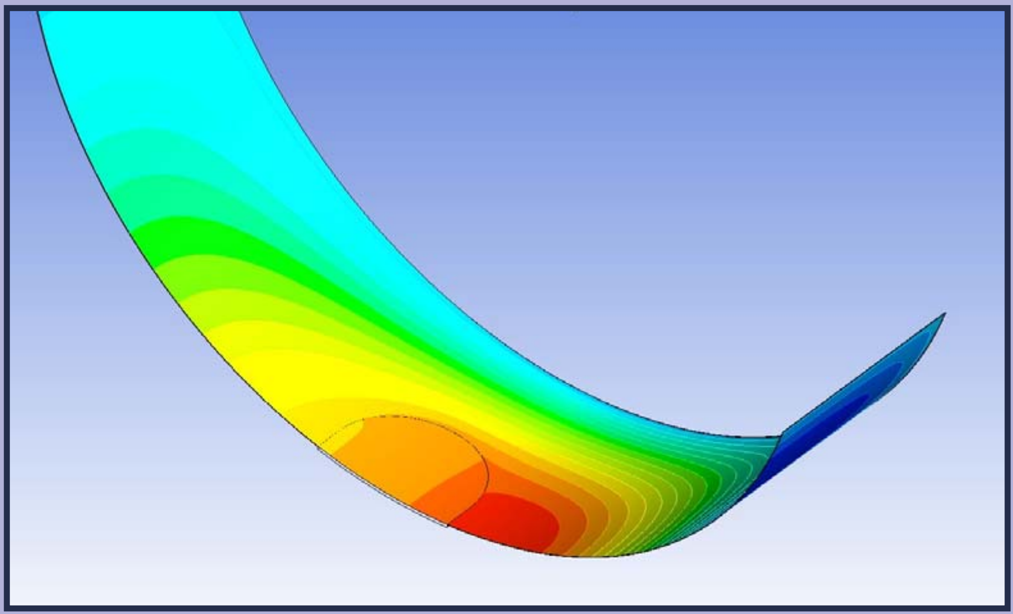
** We are in the early stages of planning the event the opening date is confirmed, however, the end date is not yet established. It will depend on number of speakers and presentations.*

Graduate Student Research Projects

Computational Modeling of Pad Surface Irregularities in Fluid Film Bearings

Student: Michael Branagan
Expected Degree: Ph.D. May 2019

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. Simplier 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, MAXBRG3D, is being developed that will be capable of accounting for a three dimensional pad surface and the resulting phenomenom. This code will couple together the 2-dimensional Reynolds equation with full 3-dimensional energy and elasticity equations.



Fluid Film Bearing Test Rig

Students: Benstone Schwartz and Pedro Herrera
Expected Degree: Ph.D. May 2019 and Ph.D. May 2023

The advanced Fluid Film Bearing Test Rig (FFBTR) project will measure component-level bearing dynamic properties (stiffness and damping coefficients) at excitation frequencies between 10 Hz and 500 Hz with detailed uncertainty analysis performed to understand the accuracy limits of the experimentally identified coefficients. The design of the test rig has been driven by comprehensive uncertainty analysis and the current design of the test rig is shown in Fig. 1.

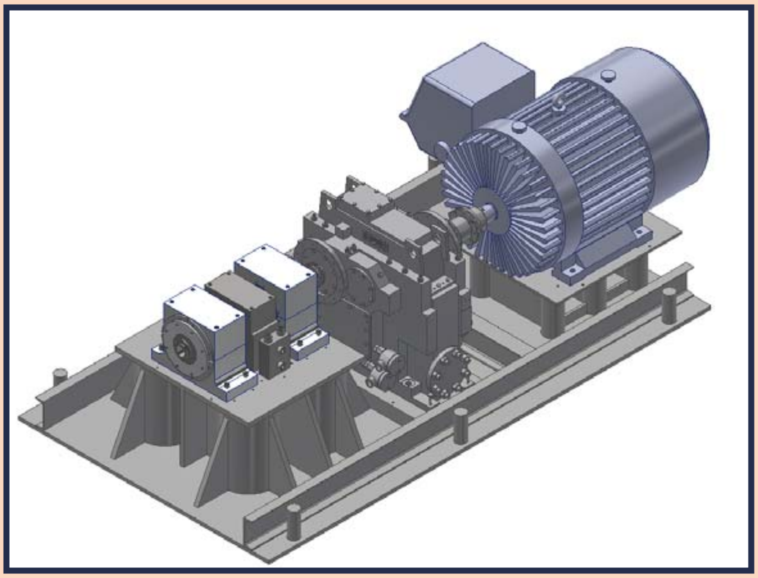


Figure 1: 3-D Model of FFBTR
(Note: detail design in-progress)

In 2017, two concepts were shown: a test rig based on an “Active Load Cell” concept and a test rig with piezoelectric load cells. Based on rigorous uncertainty analysis, it was determined that the design with piezoelectric load cells was suitably accurate in the desired excitation frequency range. This test rig design would be faster to design, build, and commission. At the 2018 ROMAC Annual Meeting, the results of the uncertainty analysis and the latest design updates were presented to the industry members. The models analyzed for the 2018 Annual Meeting included finite-element models of the substructure, bearing housing and shell, and AMB housings. These higher-fidelity models supported an advanced uncertainty analysis that allowed for determining the effects of compliance on the identified coefficients.

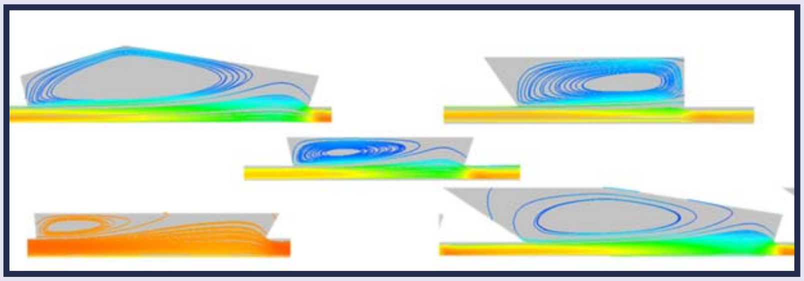
With positive feedback received at the Annual Meeting, ROMAC is moving ahead with the construction of the test rig by working on the detailed design of remaining components and subsystems. Steady progress is being made on the detailed design with additional feedback from BRG Machinery regarding the design of the bearing test section. The current plan is to begin procurement of purchased parts and obtain quotes for manufactured parts in Spring 2019.

A new Ph.D. student, Pedro Herrera, is assisting with the detail design of the test rig and will help with procurement and manufacture. Pedro is presently being brought up to speed on the design of the test rig, and he will continue to work with the test rig after construction and be the lead student in charge of commissioning the test rig and running the initial bearing coefficient identification tests.

Application of meshless numerical PDE solution methods to turbomachinery flows

Student: Neal Morgan
Expected Degree: Ph.D. May 2019

Optimization of designs for annular seals by varying the seal geometry allows for tuning of leakage, pressure drop across the seal, and rotordynamic reaction forces. Current research on annular seals is focused on improving machine efficiency and stability for specific systems, rather than finding a generalized “ideal” seal. These optimization studies often obtain better results when testing non-standard groove geometries. These non-standard geometries require more complex computational modeling techniques than a simple one or three control volume bulk-flow code for smooth and rectangular grooves. Additionally, the bulk flow models do not adequately predict flow characteristics and seal behavior for many cases, thus many modern optimization studies are done with CFD simulations. As the geometries become more complex and the demands for performance efficiency increase, larger mesh sizes with more complex boundary layers and more simulations will be required to adequately explore a potential geometric design space of interest. As the boundary layers increase in complexity more mesh elements are necessary and more geometric parameters will be employed in an investigation. With these factors increasing, the computational time and expense will increase geometrically and the engineer time required to setup the computational models and ensure mesh independence will also increase rapidly. This suggests a need for investigations into alternative numerical methods for seal analysis that reduce requirements on mesh size and complexity without greatly sacrificing detail from the results. The simplest method to reduce computational cost of a CFD simulation is to reduce the mesh size. The proposed approach, Boundary Element Analysis, does this by reducing the dimensionality of a given problem by one. Numerically, the Boundary Element Method (BEM) is similar to Finite element analysis, as both methods use elements represented by a system of weighted residual equations constructed through the Galerkin method. However, BEM takes the Galerkin method one step further in order to integrate only over the boundary of the fluid domain. This study aims to reduce the simulation size further by combining the perturbation analysis used in bulk flow methods with a 2D axial-radial cross-section of the seal flow modeled using the BEA techniques. This is necessary due to the non-sparse matrices employed by BEM that grow very quickly in computer memory requirements in three dimensions. The BEM equations for the two dimensional flow region are obtained by rewriting the Navier-Stokes equations in terms of the Laplace equation and non-linear forcing terms. The BEM is then applied to the Laplace side by expressing the solution in terms of boundary integrals and selecting weighting functions as fundamental Green’s function solutions to the Laplace equation. The non-linear forcing terms are then approximated by radial basis functions and expanded in terms of those same fundamental solutions, in a method called Dual Reciprocity BEM (DR-BEM). The final solution is obtained by iterating the fluid velocities and pressure from an initial condition. As only the elements on the boundary are explicitly integrated, this method can require less computational expense and is less dependent on mesh quality. BEM belongs to a category of numerical techniques called “meshless methods” because the solutions are not particularly sensitive to the internal mesh node locations. Thus the nature of DR-BEM is suited to complex geometries, non-continuous flows, and varying boundary layers. 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 DR-BEM software package for ROMAC that solves the 3D incompressible Navier-Stokes equations for a generalized 2D seal geometry cross-section. This method can then be compared to traditional CFD and bulk flow techniques for accuracy and computational cost.



Model-Free Reinforcement Learning for Discrete-Time H-infinity Control Using Output Feedback

Student: Syed Ali Asad Rizvi
Expected Degree: Ph.D. ECE May 2020

This work extends our model-free Q-learning based linear quadratic regulator (LQR) method to solve the H-infinity control problem. Compared with our previous LQR design, this method is also able to handle external disturbances, and thus, improves the robustness of the controller. The design process remains completely online and model-free, which neither involves any knowledge of the system dynamics nor requires access to the internal state of the system.

We are glad to announce that this work has been recently published in the premier control journal Automatica, Rizvi, S. A. A. and Lin, Z., “Output feedback Q-learning for discrete-time linear zero-sum games with application to the H-infinity control.” Automatica, 95, 2018, pp. 213-221.

The summary of the work is as follows. Reinforcement learning techniques usually rely on the feedback of the measurement of the complete state, which is generally not available in practical situations. In this work, we present an output feedback Q-learning algorithm towards finding the optimal strategies for the discrete-time linear quadratic zero-sum game, which encompasses the H-infinity optimal control problem. A new representation of the Q-function in the output feedback form is derived for the zero-sum game problem and the optimal output feedback policies are presented. Then, a Q-learning algorithm is developed that learns the optimal control strategies online without needing any information about the system dynamics, which makes the control design completely model-free. The proposed algorithm converges to the optimal solution obtained by solving the game algebraic Riccati equation (GARE). Unlike the value function based approach used for output feedback, the proposed Q-learning scheme does not require a discounting factor that is generally adopted to mitigate the effect of excitation noise bias. It is known that this discounting factor may compromise the closed-loop stability. The proposed method overcomes the excitation noise bias problem without resorting to the discounting factor, and therefore, converges to the nominal GARE solution. As a result, the closed-loop stability is preserved. An application to the H-infinity autopilot controller for the F-16 aircraft is demonstrated by simulations.

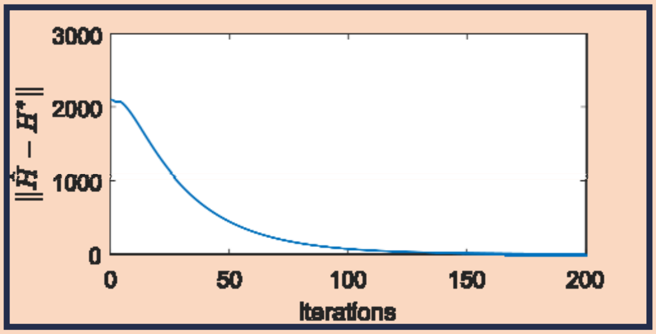


Figure 1: Convergence of the H-infinity controller parameters

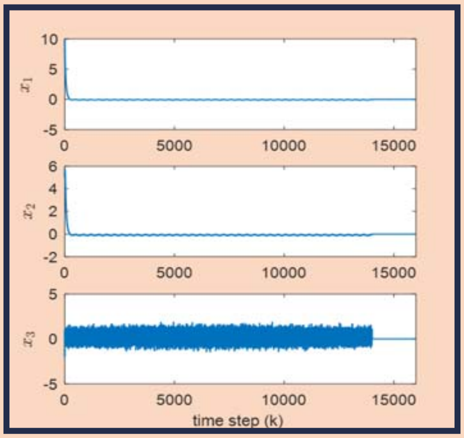


Figure 2: State trajectory of the closed-loop system under output feedback Q-learning H-infinity control

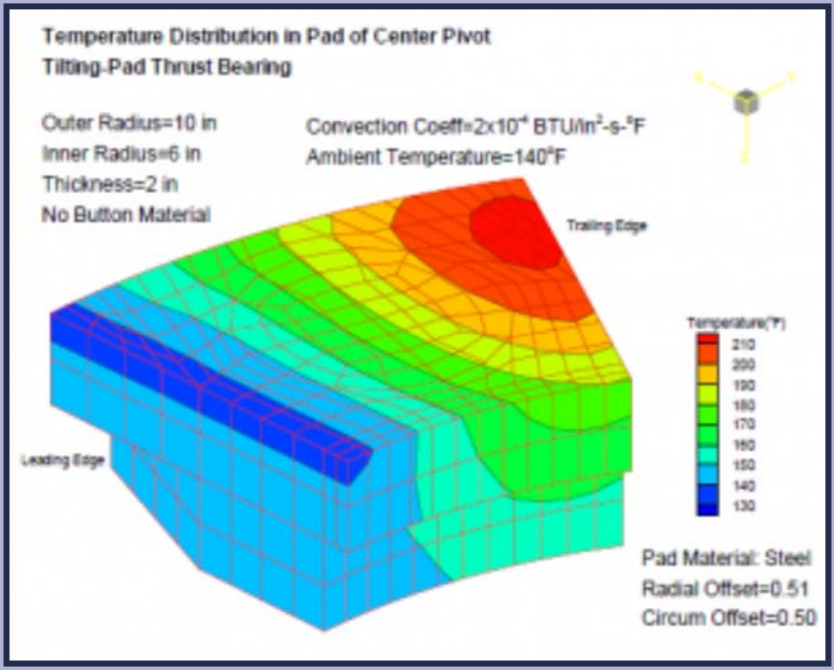
It can be seen in Figure 1 that the controller parameters converge to the nominal H-infinity control parameters corresponding to the actual model of the system. Figure 2 shows that the system has been stabilized even in the presence of external disturbances without requiring the information of system dynamics, but only using output feedback.

Future plans for this work include generalizing the current full-information H-infinity algorithm to systems such as magnetic bearings for which disturbances may not be directly measurable.

New Thrust Bearing Modeling Tools

Student: Xin Deng
Expected Degree: Ph.D. 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 a 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 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.



The solution of the Reynolds equation portion of the code is currently being developed. In order to complete coding of this portion, the general process of FEA modeling of thrust bearings, including structure, mesh, FEA equations, boundary condition and solver need to be achieved. Starting from a flat pad case, a preliminary code is nearly completed and tested. This will serve as a strong foundation and one of the hard parts for the new thrust bearing code development.

The goal is to finish the Hydrodynamic (HD) portion of the new Thrust bearing, then the Thermoelastohydrodynamic (TEHD) part, and then take a couple of months to improve the performance of the new thrust bearing code. The final goal is to get a complete new thrust bearing code.

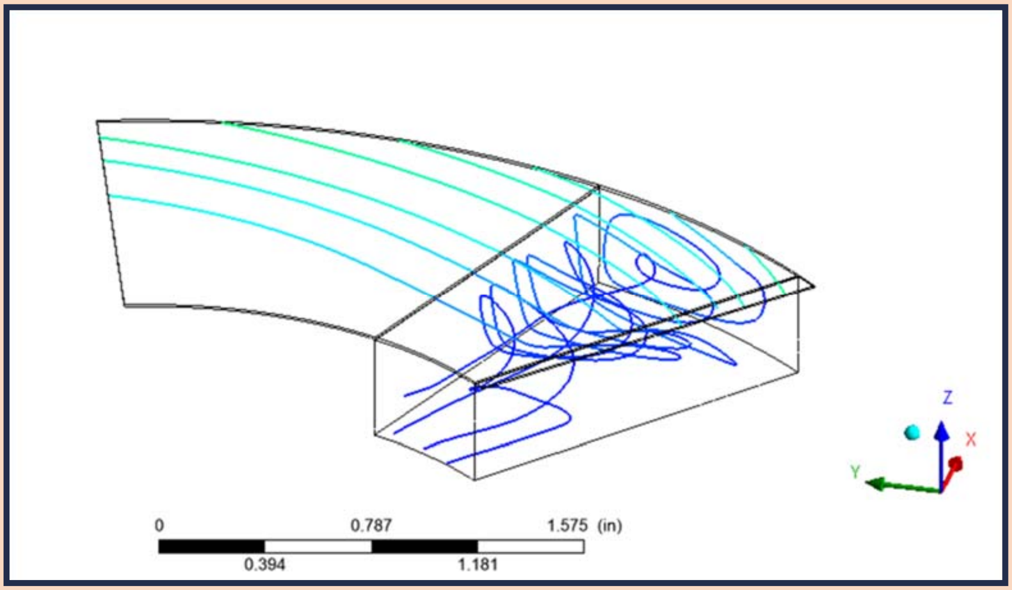
CFD Analysis of Groove Mixing and Development of Thermal BC Predictions for TEHD

Student: Harrison Gates
Expected Degree: Ph.D. 2020

As performance requirements are continuously increased, high-speed industrial rotating machinery, such as centrifugal compressors, are forced to operate closer to their temperature and stability limits. Therefore, more accurate prediction of bearing characteristics are increasingly necessary to prevent i) instability issues in the field or ii) overly conservative bearings designs. Fluid-film bearing thermal boundary conditions are important because they influence viscosity through adjusting isotherms across the thin film, pad, and rotor, and therefore significantly affect the prediction of the bearing's steady-state operating conditions as well as the associated rotordynamic coefficients. The objective of this work is to investigate the fundamental physics involved in the transfer of heat between pads and across the bearing groove and apply this understanding to develop improved thermal boundary conditions for TEHD bearing models.

A literature review was the first step to determine the present state-of-the-art of mixing models. Next, CFD verification techniques for mixing coefficient prediction have been developed using a simplified slider bearing for a variety of operating conditions including: supply temperature, aspect ratio, and rotor speed as well as a variety of thermal boundary conditions including: isothermal, adiabatic, and Conjugate Heat Transfer (CHT) conduction. Additionally, this research includes an investigation of the impact of turbulence on the mixing model within the turbulence transition region and beyond. CFD results have been benchmarked against MAXBRG.

The next step is to extend this initial CFD analysis to thrust bearings, using experimental data for a number of bearing designs reported on in the literature to validate the results.



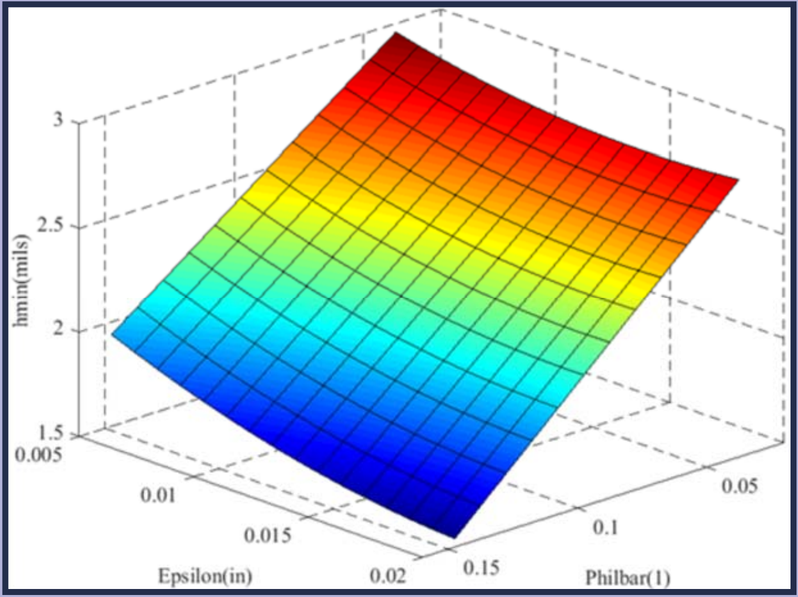
Response Surface Mapping and Multi-Objective Optimization of Crowning and Tapers in Water-Lubricated Thrust Bearings

Student: Xin Deng
Expected Degree: Ph.D. May 2020

Due to different viscosity properties between oil and water, the low viscosity of water decreases film thickness significantly. Crowning and tapers are two main ways to maintain the film thickness requirements in water lubrication, but no studies about the influence of these parameters on the film thickness in water-lubricated bearings have been reported. Therefore, further understanding of the relative performance associated with optimizing the bearing design with different weighted performance metrics and their relationships to bearing design variables would be invaluable to design engineers.

This study explores the impact of three crowning and taper design variables on the performance of one tilting pad thrust bearing using the design of experiments techniques applied to a thermoelastohydrodynamic (TEHD) bearing model. The bearing design variables analyzed in this study include the height of the ground-in crown, taper circumferential angle offset, and the vertical taper distance at the inner and outer radii. Each of the design variables is first varied over five levels, each in central composite design. The outputs from the TEHD numerical simulations used as performance measures for each bearing design point were the minimum film thickness, the film thickness at the pivot location, maximum film pressure and power loss.

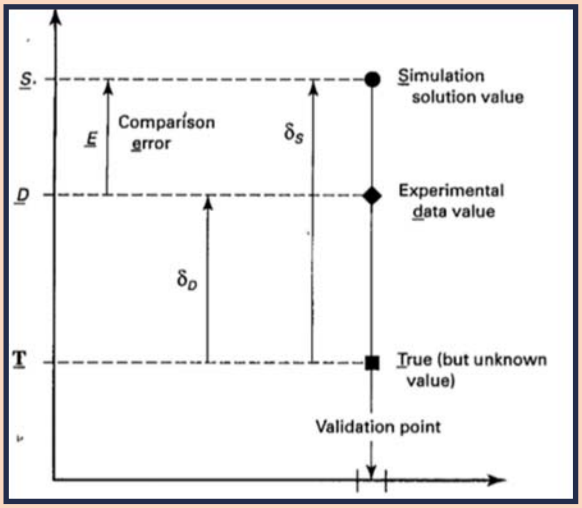
Multi-objective optimization methods were performed. A range of weighting parameters were selected for the optimization functions to find a bearing design that maintains the minimum film thickness criteria while minimizing power loss. The resulting optimum design points allowed for a comparison between the design optimization at different weightings. This study demonstrates how designers can use these approaches to view the relationships between design variables and important performance metrics to design better bearings for a wide range of applications.



Verification and Validation of ROMAC Modeling Tools Considering Sparse Experimental Data and CFD

Student: Madeline Collins
Degree Expected: Ph.D. May 2022

This project will introduce an emerging field of research called validation and verification (V&V) to rotating machinery component modeling. V&V aims to develop mathematical methods for calibrating and quantifying the reliability of computational models. This process will improve ROMAC modeling capabilities and quantify the codes' reliability.



Traditionally, experimental data is required to validate software prediction capabilities. Rotordynamic measurements require high precision and costly instrumentation; therefore, little experimental data is available, and experimental uncertainties are relevant. The scarcity of data introduces a "small sample" statistics problem. To fill this data gap, ROMAC has recently begun to use computational fluid dynamics simulations (CFD) as a supplementary resource for validation. For each software model, CFD provides the opportunity to simulate data for an infinite set of conditions. Unfortunately, CFD simulations are extremely time-consuming, so our software developers must select a finite set of CFD simulations for model validation. CFD also introduces user-input, systematic, and numerical uncertainties.

This research requires two components to work in parallel: (1) calibration: adjusting empirical parameters in the model to agree with sparse experimental data and CFD simulations, and (2) validation: quantifying the uncertainty of ROMAC software output. Once this V&V method is developed, future students in ROMAC will apply it to our existing and future models.

As a result, ROMAC software will produce more accurate and statistically reliable rotordynamic predictions for engineering design. Accurate prediction enables engineers to prevent machine failure and downtime thus saving money and improving safety. Knowledge of model uncertainty enables engineers to design machinery closer to operating limits and thus achieving higher efficiencies.

The first phase of this research is to develop a method for determining the statistic uncertainty of ROMAC codes. This method will be demonstrated on a simple case, a smooth, incompressible seal code, but will be broadly applicable to all of the numerical methods developed at ROMAC.

The Impact of Adding a Labyrinth Surface to an Optimal Helical Seal Design

Student: Wisher Paudel
Expected Degree: Ph.D. May 2022

This research is an extension of the work on mixed helical-labyrinth seal designs that was completed in the fall of 2016. The non-contacting mixed helical-labyrinth groove seals are primarily used in multi-stage pumps or other liquid applications. These seals have helical or continuous grooves on one surface and labyrinth or circumferential grooves on the other surface. The initial design study was conducted for high pressure application where it was discovered that these mixed seals could reduce leakage by approximately 45% compared to seals with grooves on just one surface.

In order to further investigate the reasons behind such reduction in leakage as well as quantify the associated power loss of these seals, this study was conducted at low pressure differential of 1 MPa. The objective was to compare the high pressure results against low pressure and investigate whether there were positive benefits of adding a labyrinth surface to an optimal helical seal. Thus, this time the helical surface was kept constant based on the optimal design obtained from a previous study at the same pressure differential, and the labyrinth surface was optimized. The results showed that the optimal mixed seal at low pressure reduced leakage by 194% compared to the seal that only had a helical surface. The power loss increased by 26% compared to the helical only seal. These results can be explained by the higher circumferential velocity observed for these mixed seals. Because of the ability of mixed helical-labyrinth seals to achieve zero leakage, they could be implemented in a machine as bearing end seals or even for sealing supercritical CO_2 applications, thus making the environment cleaner.

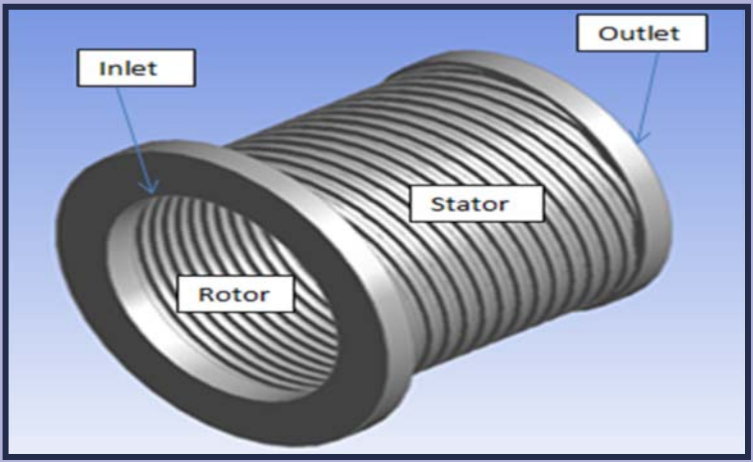


Figure 1: Fluid domain of a helical groove stator labyrinth rotor seal

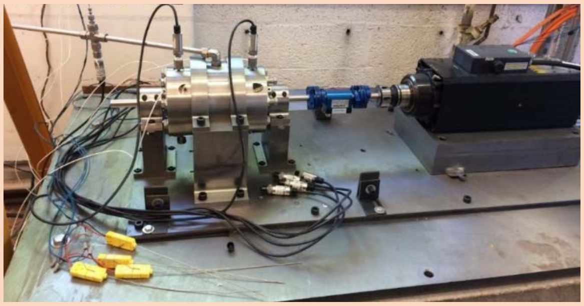
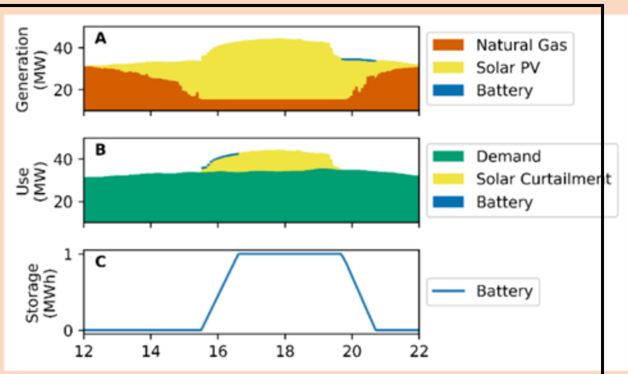
The final stage of this project is to calculate the rotordynamic coefficients of mixed helical-labyrinth groove seals. Preliminary studies show that while these seals could be less stable than helical only seals, they will not result in concerning machine instability as long as the inlet circumferential velocity is less than three times the rotor speed. Thus, a more comprehensive stability analysis could show that these seals can become an ideal choice in applications incorporating wide range of operating conditions.

Seal Test Rig Update + Solar Load Balancing Research

Student: Jeff Bennett
Expected Degree: Ph.D. May 2023

Seal Test Rig

We are continuing to work towards getting the seal test rig operational with air. Since the annual meeting, we have focused on re-evaluating the seal clearance due to difficulties achieving alignment and troubleshooting the proximity probe system which has not been functioning properly. The rig features 2” diameter seals, and was originally machined with a 1-mil clearance. The 1-mil clearance presented operational difficulties and was not comparable to other tests in literature. Therefore, we reviewed the impact of increasing the seal clearance on leakage, thermal growth, and clearance and found that although leakages will be higher, it will be safer to operate. Comparing with other tests in literature, we found that a 4-mil clearance would be more comparable. Currently, the seals are being re-machined to increase the clearance to 4-mil. The proximity probe system which was taken from a previous project was not working. After spending some time troubleshooting, we sent it back to the manufacturer for evaluation. It was found that the combination of power electronics and probes that we had did not work. We are currently working with the manufacturer to determine whether the existing system could be upgraded, or if a new system will be required.

	
Instrumented Seal Test Rig	Control scheme to balance solar generation with natural gas and a battery: A) Electricity generation by source, B) Electricity consumption by use, C) Battery charge level

Solar Load Balancing

As solar power continues to grow, the operation of power plants is changing. UVA has agreed to purchase power from two solar farms coming online this fall, totaling 32 MW in generation, which is quite significant compared to the peak demand of UVA being just over 50 MW. We are evaluating the dynamic capabilities required for power plants to balance the solar power load, with a focus on evaluating supercritical carbon dioxide power cycles. We are simulating operation of natural gas fired power plants using 1 year of demand and solar generation data collected by UVA facilities, and comparing standard open cycle and combined cycle gas turbines with a supercritical carbon dioxide plant in combined cycle.

ROMAC Software Update

We are pleased to announce the release of RotorGUI 2.0 and several exciting developments in progress for RotorLab+.

RotorGUI 2.0 Released

With the release of RotorGUI 2.0, all ROMAC graphical user interfaces require a license file to run. The license file can be obtained from the download page from both RotorLab+ and RotorGUI 2.0. Additionally, legacy codes that have been supplanted by newer codes have been removed from the interface. Other significant updates include:

- Newest version of THRUST included – the new version (THRUST V5.4) has improved convergence, eddy-viscosity modeling with Reichardt's formula, and the ability to increase the number of cross-film elements
- Newest version of MAXBRG included – the runtime has been decreased by approximately 50%
- Newest version of TORTRAN 3

RotorLab+ Updates

In an upcoming version of Rotor Lab + (to be released soon) an automated iteration between squeeze film dampers and Forced Response analysis will be available. Presently, this analysis requires manual iteration by the user.

We have been hard at work improving RotorLab+ and the biggest upcoming update is including Rotorsol as the primary rotordynamic solver in RotorLab+. This will set the foundation for including torsional and axial analysis capability in ROMAC's primary graphical user interface for rotordynamic analysis.

Other Updates

Stay tuned for updates in the coming months including new seal codes and new features for RotorLab+.

Houston Wood and David Green receive SEAS Seed Grant

Professors David Green and Houston Wood were recently awarded a seed grant from the UVA School of Engineering and Applied Science to develop springy nanoparticle lubricants that present remarkable opportunities for huge savings through energy conservation, increased productivity, and reduced maintenance, impacting a wide variety of industries (e.g., automotive, marine, chemicals, power generation, etc.). The objectives of the work are to synthesize the nanofluids and quantify the resulting reduction in nanoscale friction and wear. They are performing the work and hope to attract the interest of a ROMAC partner who can help position the nanoparticle lubricant platform for external funding from government and industry.

ROMAC Awards and Recognition

We are pleased to call your attention to the realization that since 2016 the various awards our ROMAC students have received has doubled. In addition it is worth noting, this was the first year ROMAC students have won more awards than the number of current students, with 11 students and 14 awards this current calendar year.

Spring 2019 Awards

Benny Schwartz

- UVA MAE Distinguished Fellowship

Fall 2018 Awards

Wisher Paudel

- Nuclear Research Counsel Fellowship (*continuing)*
- IMECE Young Engineer Paper Contest Finalist

Neal Morgan

- UVA MAE Distinguished Fellowship

Benny Schwartz

- UVA SEAS Teaching Internship Fellowship

Xin Deng

- Virginia Engineering Foundation Graduate Fellowship
- ASME IGTI Scholarship

Jeff Bennett

- ASME IGTI Scholarship

Summer 2018 Awards

Cori Watson, Ph.D.

- ASME Turbo Young Engineer Participation Travel Award

Xin Deng

- ASME Turbo Student Advisory Committee Travel Award

Wisher Paudel

- ASME Turbo Student Advisory Committee President

Ali Rizvi

- IEEE ACC 2018 Travel Award

Spring 2018

Cori Watson

- UVA MAE Outstanding Graduate Student Award
- Women in Aerospace Workshop Participation Funding

Xin Deng

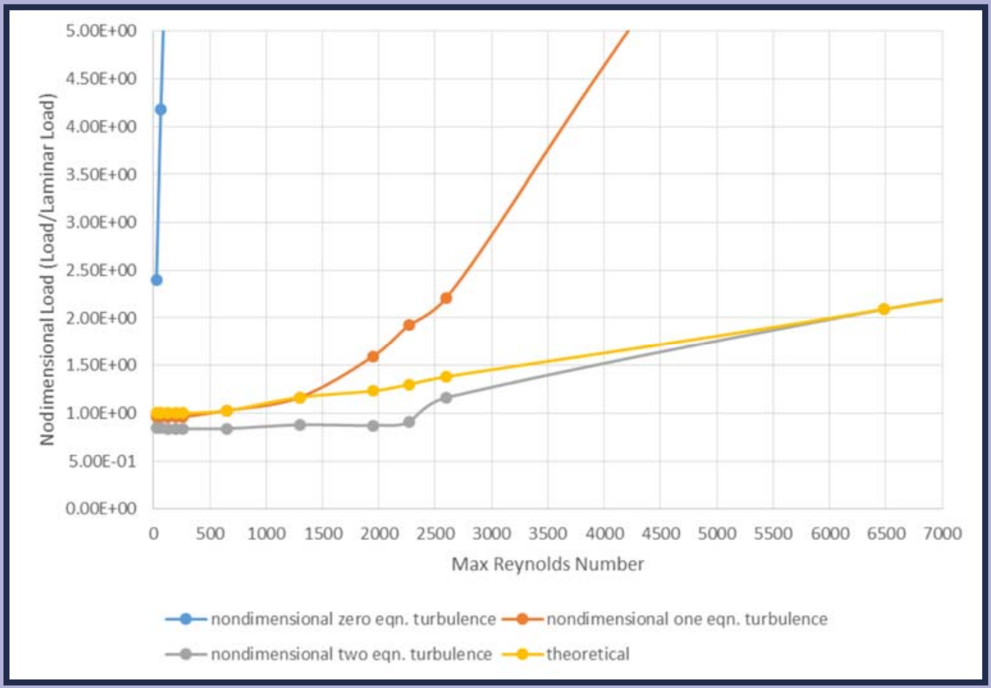
- Runner-up in Graduate Engineering Student Council's 14th Annual University of Virginia Engineering Research Symposium

Additional ROMAC Lab Group Research Projects

Incorporating New Turbulence Models into ROMAC Thermoelastohydrodynamic (TEHD) Codes

Turbulence affects bearing performance by increasing the effective viscosity of the fluid and accurate modeling of turbulence is necessary to correctly predict important bearing performance parameters. Recent CFD work by Michael Branagan and Cori Watson has shown that for Reynolds numbers between 100-1600, 1-equation turbulence models—where the turbulent kinetic energy is calculated using a PDE and the eddy viscosity and turbulent dissipation of energy are found algebraically—are better at predicting turbulence within a bearing than algebraic turbulence models traditionally used in TEHD codes, such as Reichart's formula, or 2-equation turbulence models popular in CFD software such as k-epsilon or SST turbulence models. This is shown in the Figure below. Implementation of a one-equation turbulence model into ROMAC bearing codes has two main advantages. First, the new turbulence implementation will be more accurate across a wide range of cases because it lacks the empirical constants of the algebraic turbulence models. Second, the current TEHD codes have cut-off Reynolds numbers to determine the onset of turbulence, which are unknown values required to be entered by the user, whereas the 1-equation turbulence model does not need these cut-off Reynolds numbers.

This project has three steps. First, the 1-equation model will be implemented into a slider bearing hydrodynamic solver for verification of the numerical method. This allows testing by comparison with CFD results. Second, the 1-equation model will be implemented into MAXBRG. Finally, the new Thrust code being developed by Xin Deng will also incorporate this method.



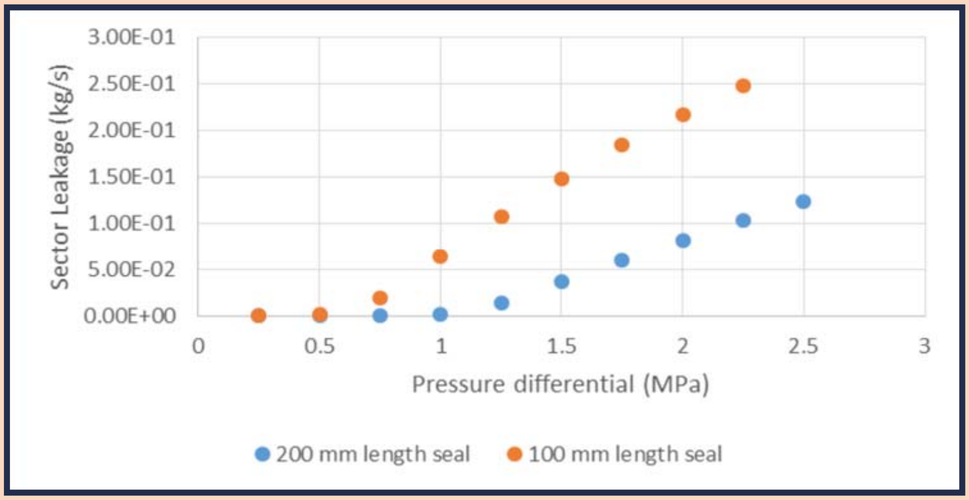
Designing a No-Leakage, Non-contacting Annular Seal

Helical groove seals are a type of non-contacting annular seals that have spiral cut grooves on either the surface of the stator and/or rotor. Prior work has shown that helical groove seals can have zero leakage despite having a radial clearance of 0.1-1 mm where fluid could hypothetically escape. This is due to the pumping action of the helical grooves which displaces fluid back towards the high pressure region as it is dragged with the rotor. However, in the no leakage scenario, the entire gap between the rotor and the stator for the helical groove seal is not filled with lubricant; instead, it is a mixture of lubricant and air.

Initial multiphase CFD analysis found that zero leakage can be achieved for helical groove seals with a clearance of 0.5 mm (20 mils) and a pressure differential of 1 MPa (145 psi) as seen in the figure below. Better results are expected for mixed helical-labyrinth seals based on recent work by Wisher Paudel.

Possible application of this seal design would be the sealing of oil systems for bearings, particularly in vertical axis machines. Additionally, experimental work has shown that helical groove seals have negative cross-coupled stiffness, i.e. that they can be stabilizing to the rotordynamic system. This work will perform CFD and experimental testing on the lubrication system of a bearing to measure the decrease in flow rate compared to the existing labyrinth seal design and will also measure the possible increase in vibrational log decrement (if it is significant enough to be measured). CFD analysis will be performed prior to testing for the combined bearing-seal system to determine the effects of the no leakage seal on steady-state performance characteristics of the bearing such as load capacity, peak temperature, and power loss. Additionally, CFD analysis of the dynamic performance will be performed using the multiphase method to find the dynamic coefficients of the helical groove seal zero leakage situation.

Another application being considered is sealing of sCO_2 turbines in place of dry gas seals. Initial CFD testing has shown that a pressure ratio of up to 5 could be supported with zero leakage for an annular seal with a clearance of 0.1 mm (4 mils). This is substantially above the current pressure ratio that sCO_2 turbine's dry gas seals are design for, which is 2-3, and the clearance is an order of magnitude greater, reducing the risk of machine failure.

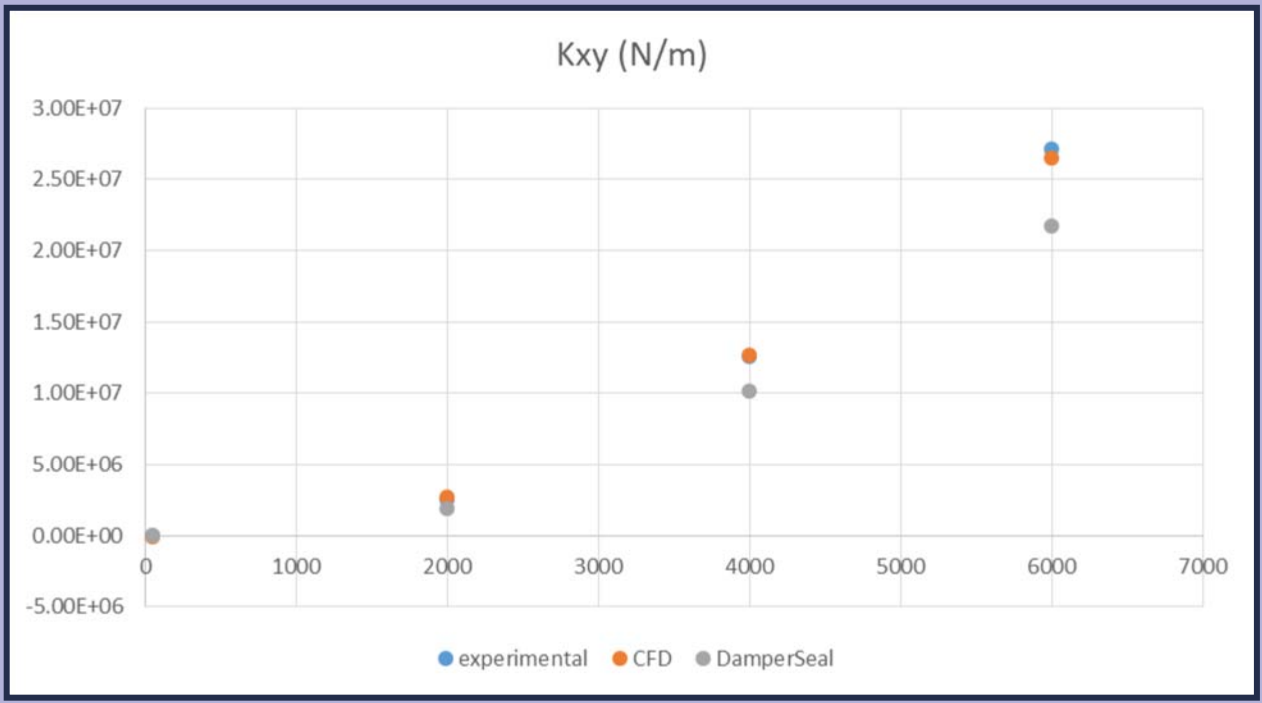


Validation and Updating ROMAC Seal Codes with Analytical Changes and Experimental Comparison

The objective of this project is to go through the existing seal modeling codes at ROMAC to experimentally validate the performance for a variety of annular seal types and improve the performance where needed by making analytical changes to the theory of the codes. The existing experimental data in the literature has been collected and organized by fluid (compressible/incompressible) and seal type (smooth, labyrinth, etc.). We are now systematically comparing seal code results to experimental data for each seal type and making changes where feasible to improve the performance of the codes.

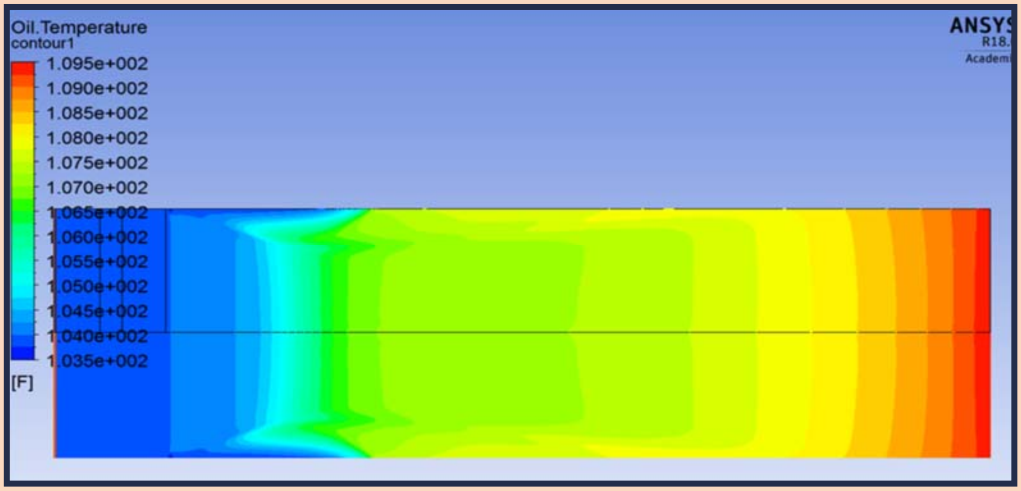
CFD calculation of leakage and rotordynamic coefficients are also being performed for all cases to provide some sense of the accuracy we can hope to achieve. For example, in the figure below, the CFD results match strongly with the experimental data, but the DamperSeal results are off by up to 25%, so it is reasonable to try to improve DamperSeal. However, if the error of the code is the same magnitude as the error for the CFD, then the error may be from experimental uncertainty and no code updates would be necessary.

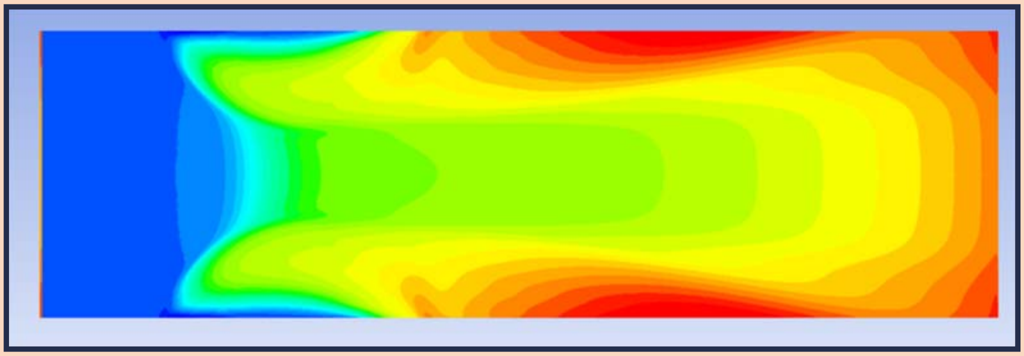
The result of this project is three outcomes: more comprehensive validation of the codes, code updates that improve the accuracy, and a list of what code to use for each seal category. We also plan to remove outdated and inaccurate codes, so that the codes available in RotorGUI and RotorLab+ will cover all seals with only the best codes for each seal type.



Experimental and CFD Analysis of Journal Bearing Starvation

Starvation occurs when not enough oil is supplied to the bearing, causing the film to not support load near the leading edge, despite the region being a converging film. CFD analysis was conducted at ROMAC to analyze the multiphase performance of a slider bearing with starvation. It was found that as starvation increases, the highest temperature point on the pad is no longer at the trailing edge of the pad, but along the axial end as shown in the figure below. Strikingly similar results were obtained by Kingsbury while testing a five-pad tilting pad bearing. In these tests, it was the upper, starved pads which exhibited this behavior. Additionally, the results of both the CFD and Kingsbury experiments showed that the shape of the starved region does not match the assumption made in current bearing codes.





To follow up on this work, ROMAC and Kingsbury are collaborating to run CFD analysis of the exact bearings Kingsbury tested so that direct comparison between the numerical and experimental results can be made. The CFD procedure will use multiphase modeling and fluid-structure interaction (FSI) to find the film shape by iterating on the journal location within the bearing. Deformation will initially be ignored in the CFD analysis, so a low load case was selected by Kingsbury for initial comparison. The end goal of this research is to develop a better starvation model for MAXBRG, which will help improve the overall accuracy of the code.

Kingsbury, Inc.

ROMAC
Consortium in Action

University of Virginia
ENGINEERING
Department of Mechanical and Aerospace Engineering
Rotating Machinery and Controls Laboratory

UNIVERSITY of VIRGINIA

ENGINEERING

Department of Mechanical and Aerospace Engineering

Rotating Machinery and Controls Laboratory

Areas of Expertise and Current Research

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

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