ROTATING MACHINERY & CONTROLS LABORATORY

ROMAC Newsletter

To ROMAC Industrial Members,

Fall 2013 Issue

This year has been a particularly exciting year for ROMAC. I am pleased to welcome two new research staff members, Dr. Roger Fittro and Dr. Ya Zhang. Roger joined ROMAC in August as a Senior Scientist. Prior to joining ROMAC, Roger was at GE's Global Research Center, where he led a controls group in the development of new product technologies for applications such as Gas Turbines for Power Generation, High-Speed Compressors, Wind Turbines, Commercial & Military Jet Engines and Diesel-Electric Locomotives. During his 10 years at GE, Roger was also one of the key technology developers and lead project engineer for GE's Joint Strike Fighter (JSF) advanced engine control program, and he led the technology development effort for a new high-speed magnetic bearing supported integrated gas compressor. Ya is a Visiting Professor from the Beijing University of Chemical Technology. Ya will be working in ROMAC until August 2014.

We also have some exciting developments with our software:

- **RotorSol v3.3** was released in October, 2013. **RotorSol v3.4** will be released before the start of 2014.

- **RotorLab+ v3.0** will be available in December, 2013.

- **GearRotor v1.0**, a code for analyzing geared-systems, will also be available in December, 2013, along with a user manual.

There are several new companies that have joined ROMAC in 2013. Our new members are:

- Daikin Applied
- Florida Turbine Technology
- General Atomics
- OKBM

2013 Annual Meeting Summary

The 2013 Annual Meeting, held in Virginia Beach, was very informative for all. The Questionnaire, which was filled out by both those attending and several ROMAC participants who could not attend, gave us insights into future directions, shortcomings, and strengths. The results of the Questionnaire are listed in the table on the next page. The summary of the Questionnaire responses is on the ROMAC website, on a tab in the page for the 2013 Annual Meeting. We have also posted pictures from the Annual Meeting there. As a result of the comments on the questionnaires, we are expanding our faculty and expert input for students and companies. We are working on developing the fluid film bearing test rig, to determine the best way to implement it. Software is being updated, and newly available software with much greater capabilities is now available to students to use for their studies and to help members solve rotor dynamics problems.

With the exception of the presentations, one of the highlights of the gathering was the dinner on Tuesday night, held on the top floor of the Cavalier Hotel, which started off with a dark cloud approaching from the Ocean

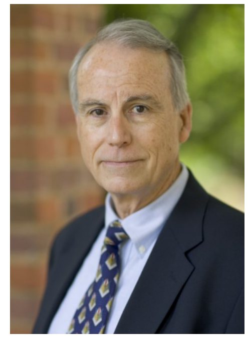
News on Software Releases:

- ***RotorSol v3.3*** *was released in October 2013.* ***RotorSol v3.4*** *will be released before the start of 2014*
- ***RotorLab+ v3.0*** *will be available in December 2013.*
- ***GearRotor v1.0****, a code for analyzing geared-systems will also be available by December 2013 along with a user manual.*

side of the dining room, and turned into a lightning display (with a bit of thunder) and ended with a wonderful rainbow to the south of the room. There is a picture of the rainbow on the web site. This, in addition to great food, and good company, made for an enjoyable night.

We feel that the Annual Meeting is an effective way for members and UVA faculty and students to network and to share problems and information. We enjoy being able to host members and to let everyone know about our research successes over the preceding year and to hear your comments.

In 2014, the Annual Meeting will be held in Charlottesville, from June 23 to 27. We will again start with a reception on Monday night, but may do lab tours and individual work with software on Friday instead of Wednesday afternoon. Please let us know your suggestions for the meeting. This may seem early to be making arrangements, but we have to make hotel commitments soon, and your input is valued. Would you like us to put together a short course the week after the meeting? If so, what would you like it to cover? Would a short course Monday, before the start of the meeting, be a better day for you and your colleagues?



Houston Wood
Professor, Mechanical & Aerospace Eng.
Director of ROMAC
Director of Applied Mathematics

Results of the Questionnaire

Category	Points	Percentage
Fluid Film & Rolling Element Bearings	98	39.2%
Rotor Dynamics	65	26.0%
Seals	46	18.4%
Magnetic Bearings & Automatic Controls	21	8.4%
Optimization of Rotor-Bearing Systems	21	8.4%
Turbomachinery Flows	6	2.4%
Other	3	1.2%

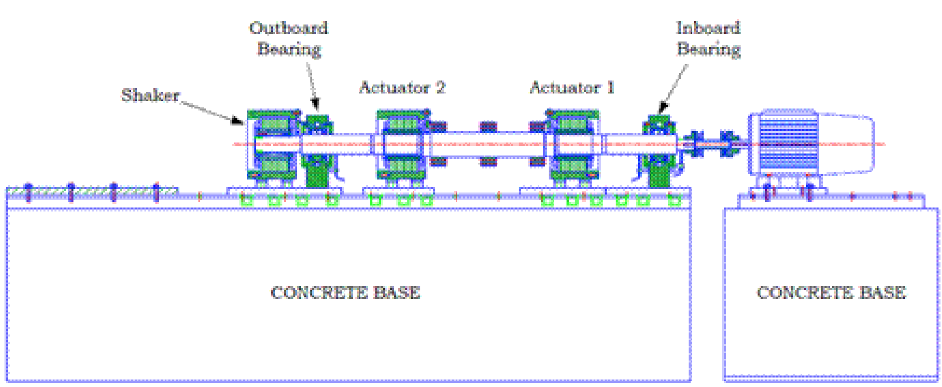


Figure 1: Stability test rig drawing

Summary of Research Projects

Experimental Measurements of Damping Ratios under Starved Bearing Lubrication Conditions

Student: Brad Nichols

An experiment is being developed to observe the effect of reduced flow rate in tilting-pad journal bearings on the overall system damping and stability. Previous studies have shown that reduced lubricant flow rates to bearings can provide significant savings in power loss. These studies do not discuss the impact on the bearings dynamic performance and most importantly, its ability to provide damping to the system.

The primary objective of this study is to provide insight into the power losses that can be achieved by reduced flow, as well as to uncover any potentially negative impacts that reduced flow may have on system damping and stability. The experimental data obtained will be compared with predictions from bearing modeling software such as ROMAC's MAXBRG for bearings operating under starved conditions.

The secondary objective of the study is to investigate different system identification techniques and their relative accuracy of system damping predictions. These techniques included both time and frequency domain techniques and different excitation methods such as unidirectional and bidirectional sine-sweep excitations.

The experiment will be conducted on the previously documented ROMAC "Stability Test Rig." This rig consists of a 61" long flexible rotor with a 3.5" mid-span diameter (Fig.1, 2). The rotor is supported by two tilting-pad bearings with a 2.757" nominal diameter and a 48" span. The rig also contains two mid-span magnetic bearings for the introduction of cross-coupled forces and an outboard magnetic shaker for system identification purposes. System damping will be estimated under fully flooded lubricated conditions, and then subsequently estimated as the oil supply flow rate is decreased through starved bearing conditions. This procedure will be repeated for a number of operating conditions (i.e. speeds and loads). Two bearings with centrally pivoted pads and preloads of 0.3 and 0.1, respectively, will be tested in both load-on-pad and load-between-pad configurations. In addition to estimating system damping, pad temperatures, oil supply and discharge pressure, and flow rates, relative power loss will also be recorded.

The test rig is currently being repurposed to accomplish the tests described above. Models of the rotor/bearing system have been established to predict the behavior of the system under starved bearing conditions. CFD is being considered as another method of predicting the complicated flows that occur in tilting-pad bearings, specifically under starved conditions. It is anticipated that testing will be completed by the end of this calendar year, with results to follow at the ROMAC annual meeting in 2014.

Figure 2: Stability test rig

Gear Code for Rotordynamics: GearRotor

Student: Jason Kaplan

The ability to accurately predict rotating machine resonant frequencies and to assess their stability and response to external forces is crucial from a reliability and preventive maintenance perspective.

Resonant frequencies and forced response become more difficult to predict when additional complicated components such as gearboxes are present in the rotor system.

Gearbox dynamics contain many complex interactions and many of the simplifying assumptions provided in the literature, particularly those concerning the gear mesh stiffness, do not apply to most geared systems. A finite element formulation of the gearbox, which couples the axial, lateral, and torsional degrees-of-freedom of the low and high-speed shafts, has been developed. It has the capability to apply to a wide variety of both spur and helical geared systems and is sufficiently robust to account for arbitrary orientation angles between the parallel shafts. A releasable version of this geared -systems code along with the user manual will be available by December 2013. Beta versions are underway and already include extending these methods to planetary gear trains.

Future work will involve nonlinear and time-transient phenomenon stemming from tooth backlash, time-varying mesh stiffness, mesh phasing, and transmission errors. This work will culminate in a Ph.D. proposal and dissertation.

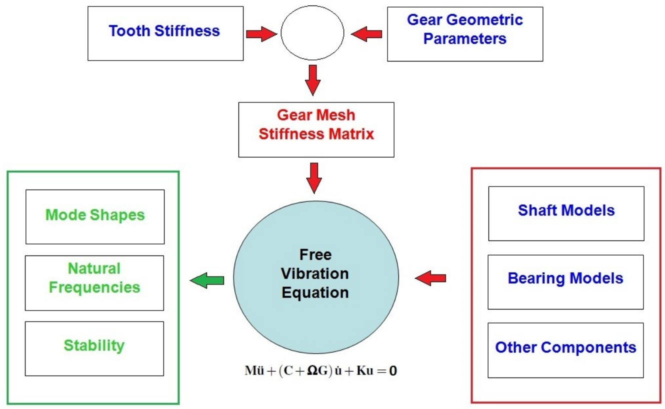


Figure 3: The analysis flowchart

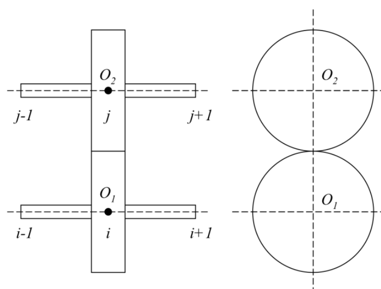


Figure 4: Gear-pinion interaction of nodes i and j

An FEA Based Squeeze Film Damper Software with Inertia Effects, Supply Condition, and Axial Seal Considerations: MAXSFD

Student: Saeid Dousti

For over a half of a century, squeeze film dampers (SFDs) have been the main source of vibration damping in a variety of industrial applications. Despite their simple damping mechanism, their functionality has been proven to be highly variant by their different design aspects and operating conditions which cause large deviations from the simplified bearing models. In this study, a thorough model based on the solution of a two-dimensional Reynolds equation including the inertia effects is developed. The finite element method is employed solve Reynolds equation. A so-called “realistic SFD” geometry that is analyzed in this study is commonly adopted in aerospace applications and contains a relatively shallow supply groove with supply and discharge holes on its circumference. These SFDs are highly pressurized to minimize the cavitation phenomena and its adverse effects. By neglecting the obsolete assumption that the pressure at the supply groove drops to that of the supply condition, clearance is considered axially variant and Reynolds equation valid in the supply groove as well. This design takes advantage of piston ring seals which are incorporated mathematically in the model as the axial boundary conditions. The supply condition is treated with two different models, first by imposing supply/discharge pressures at the supply/discharge holes’ locations and second by following Mamool and Vance’s (1978) inlet and outlet flow model. The inertia effects significance is studied for different design parameters and working conditions. The next generation of SFDs analysis code is under development based on the mentioned hypotheses.

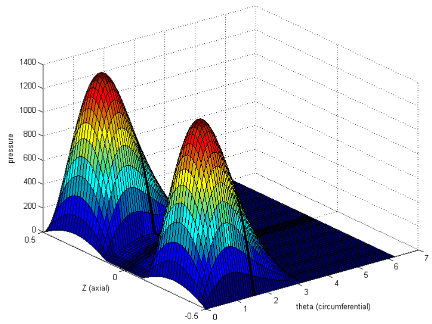
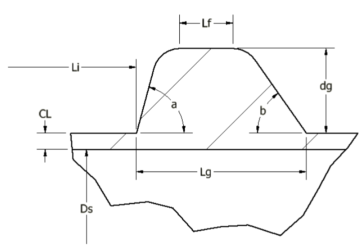


Figure 5: 2D pressure profile of an open end SFD with supply grooves and holes

Optimization of the Static and Dynamic Performance of Annular Seals

Student: Neal Morgan

The objective of this research project is to apply statistical experimental design and optimization methods to the design process of a labyrinth seal. Current progress includes generalized parameterization of a selected water labyrinth seal geometry. This full parameterization is then reduced to a manageable number of variables (Fig.6) to perform optimization of the geometry for minimal leakage. Multiple reduced parameter models are being investigated with multiple optimization routines, such as: multi-island genetic algorithms, pointer algorithms, and simplex algorithms. Future goals of this project are to perform sensitivity studies of leakage rates for the reduced parameter models and to combine a hybrid bulk flow/CFD method with the developed optimization methods for leakage rate to include rotordynamic coefficients.



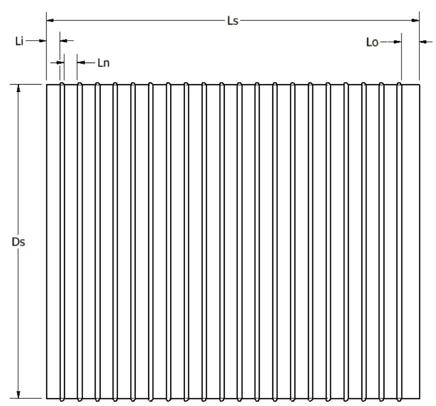


Figure 6: Seal design Variables

RotorSol

Student: Michael Branagan

RotorSol is a time independent rotordynamic solver. It uses the finite element method to solve for models consisting of 12 degrees-of-freedom beam elements. This allows for the analysis of systems which couple the lateral, axial, and torsional degrees of freedom. This is important for analysis of systems with components such as gear boxes, thrust bearings, etc. RotorSol can perform both stability and forced response analysis and can contain a variety of components such as aerodynamic cross coupling, flexible couplings, and tilting pad bearings using the full dynamic coefficients. RotorSol is also being developed to be the main time-independent solver behind RotorLab+, ROMAC's new GUI, going into the future. RotorSol v3.3 was released in October, 2013. RotorSol v3.4 will be released before the start of 2014. Future work on RotorSol will include adding new components such as gears, based on Jason Kaplan's work, and seals, adding more analysis options such as critical speed maps and nonsynchronous analysis, new rotor properties such as internal damping of the rotor and distributed mass models for the rotor and more verification and validation of the program.

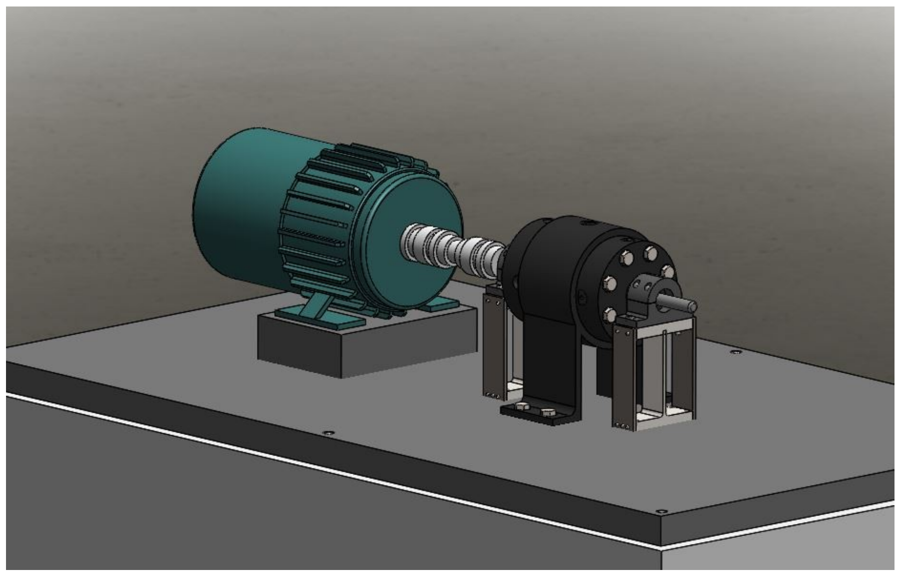
Gas-Expanded Lubricants for Increased Energy Efficiency in Rotating Machinery

Student: Brian Weaver

Lubricants are necessary in rotating machinery to provide separation between solid surfaces and to enable efficient, long-term machine operation. However, they can also contribute to power losses and heat buildup as the fluid is subject to shear forces. Here, tunable binary mixtures called gas-expanded lubricants (GELs) are proposed to overcome these limitations of conventional lubricants. GELs consist of a synthetic lubricant and carbon dioxide under pressure with properties, such as viscosity, that can be controlled dynamically in response to changing environmental or rotordynamic conditions. By controlling the pressure of the mixture, the bulk mechanical and thermal properties of the fluid can be specified in real time. These tunable fluids will enable operators to minimize the efficiency losses that can affect conventionally lubricated systems as well as to control the rotordynamic performance of machines via bearing stiffness control. By lowering the pressure, the original properties of the lubricant can also be restored.

Current work is focused on two key studies. The first study currently underway is the design, assembly, and operation of a test rig aimed at measuring GEL performance in seals, as these will be critical to ensuring proper machine performance under GEL-lubricated conditions (Fig. 7). A systems-level study, also underway, will use bearing and rotordynamic analyses to predict the effects of GELs on the overall performance of full-scale turbomachinery via two case studies.

The results of this work will demonstrate the potential for utilizing this lubrication technique in rotating machinery to increase efficiency and reliability while providing users with rotordynamic control over their machines.



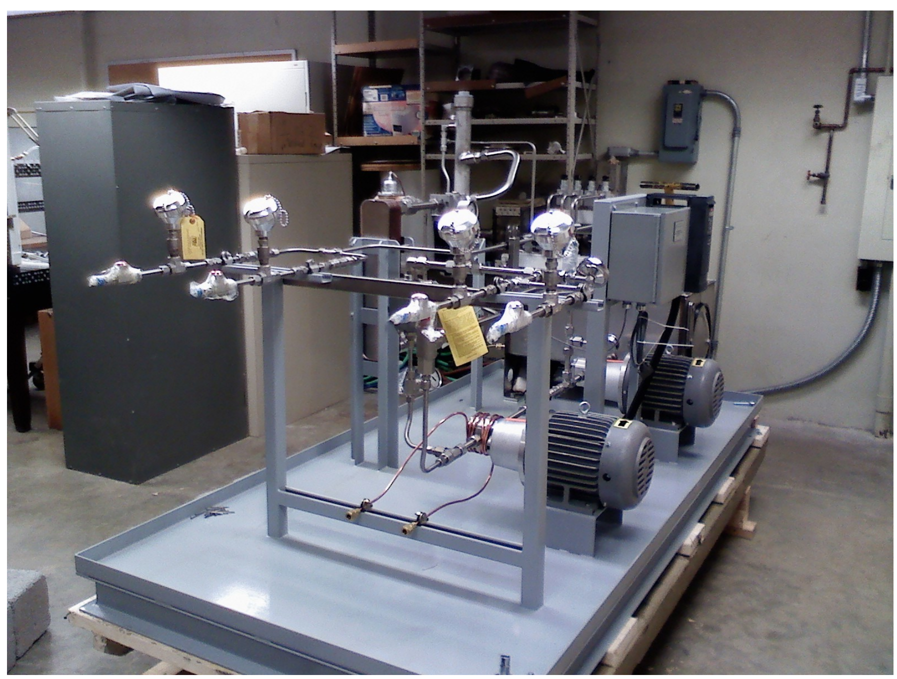


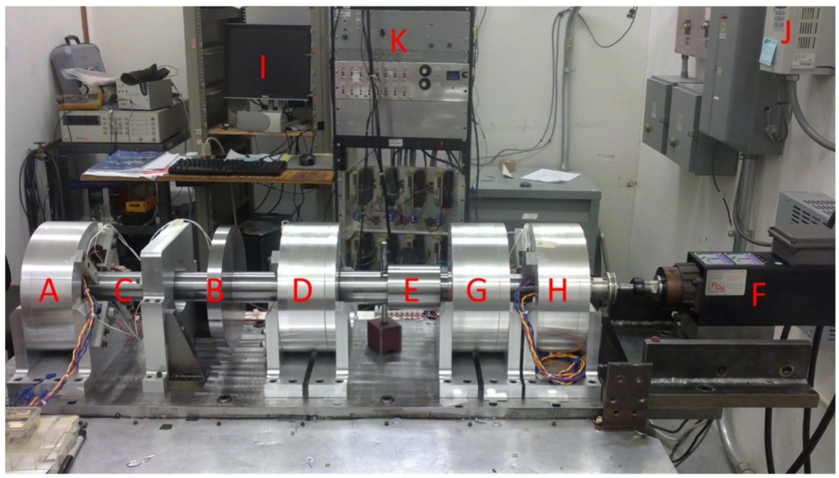
Figure 7: GEL seal test rig will guide seal designs for GEL-lubricated systems

Characteristic Model Based All-coefficient Adaptive Control of a Flexible Rotor Suspended on Active Magnetic Bearings

Student: (Dee) Long Di

The project explores the application of the characteristic model based all-coefficient adaptive control (ACAC) method to the stabilization of a flexible rotor AMB system. The proposed characteristic modeling process significantly simplifies the modeling of a system with high order complex dynamics by analyzing its characteristics and considering the control requirement. A second order time-varying difference equation is able to model the rotor AMB system in a position tracking/keeping scenario. Based on the characteristic model, characteristic model based ACAC has fewer coefficients to estimate and the controller structure is much simpler compared with conventional adaptive control.

Simulation has shown performance improvements over the μ-synthesis robust controller in terms of minimizing the vibration and maintaining a small orbit while using small control signals. Experimental results have also demonstrated some features of characteristic model based ACAC method and shown it is comparable to μ-synthesis in certain measures.



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

Figure 8: Test rig components

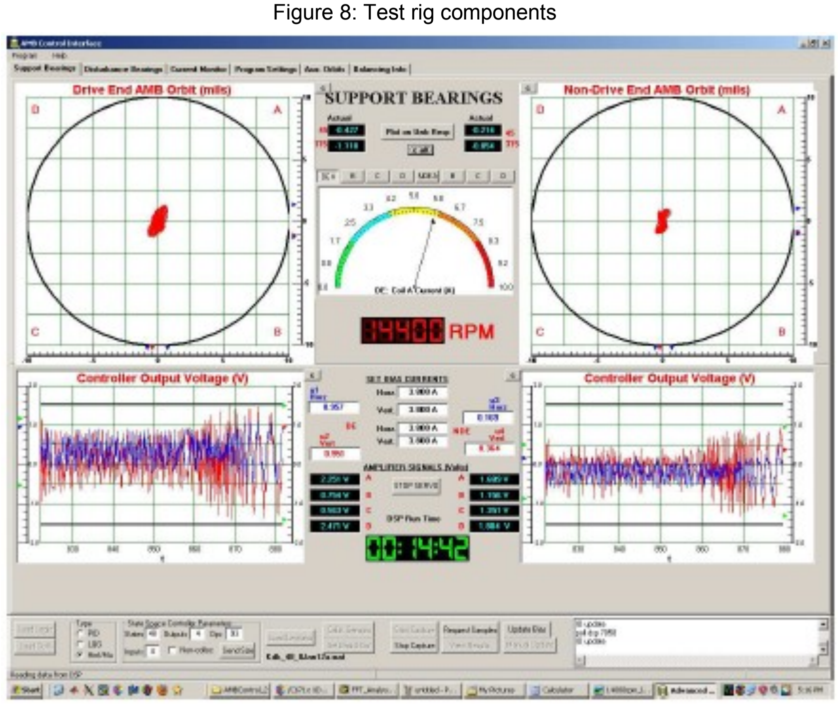


Figure 9 Characteristic model based ACAC performance

Robust Fractional Control for Flexible Rotor supported by Magnetic Bearings

Student: Parinya Anantachaisilp

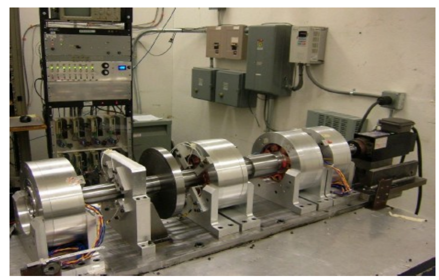
The concept of a differentiation operator with integer order is a well-known fundamental tool of modern calculus. Furthermore, there is an extension to the situation where the order is arbitrary, i.e., fractional order. Recent findings support the notion that fractional-order calculus should be employed where more accurate modeling and robust control are concerned. Specifically, fractional-order calculus found its way into complex mathematical and physical problems. In the field of automatic control fractional calculus is used to obtain more accurate models, to develop new control strategies, and to enhance the characteristics of control systems.

In general, robust control design can be achieved by using loop shaping via frequency domain specifications such as sensitivity function, gain crossover frequency, gain margin, and phase margin. But in most cases it is very time consuming and relies on the experience of the engineer to arrive at a controller that provides performance capa-

Therefore, many researchers began to develop the automatic loop shaping (with known controller structure) which makes the process of finding a controller more effective. With that said, sometimes the automatic loop shaping might not arrive with the satisfying controller. Thus, fractional order controller has a good potential to provide a satisfying controller since it has more space to search for the parameters as well as more flexibility in choosing parameters for the controller.

The ongoing research into fractional order control is being used for the application of active magnetic bearings (AMB) in order to test the capability of fractional order control because this is a very complex system - it is an open loop unstable, non-minimum phase, and multiple input multiple output (MIMO) system. Also, it has uncertainties from frequency and cross-coupling. These combine to create a significant challenge for the fractional order control concept.

The scope of this research includes the fractional order system modeling and identification and the fractional order controller design. Essentially, the applicability and efficiency of fractional order control will be investigated as well as compared to the existing integer order control methods examined on the flexible rotor supported by magnetic bearings test rig shown in Fig. 10.



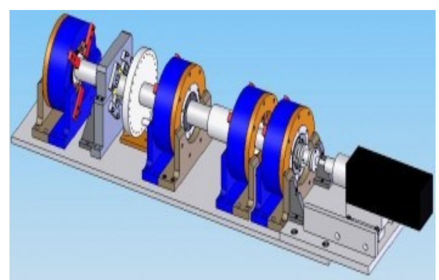


Figure 10: Flexible rotor supported magnetic bearings test rig

Control of Magnetic Bearings with Material Saturation Nonlinearity

Student: Ali Gerami

A nonlinear model and control method for magnetic journal bearings is being designed considering the core material's nonlinear behavior for the first time. The nonlinear modeling makes it possible to operate the existing industrial AMBs with a larger electric current and to achieve larger load capacity. This approach yields a bigger domain of attraction, better transient response, and better disturbance rejection capabilities than that achieved using present industrial practice. As a result of this research, existing industrial AMBs could be tuned to become more resilient in dealing with external disturbances, have safer shutdown and therefore cause less damage to the backup bearings.

Also smaller and lighter AMBs can be designed by using the proposed method.

The most appealing advantage of using the nonlinear model is to increase the disturbance rejection potential. By using the proposed nonlinear model, the system can operate and survive an extra load that is caused by a harsh situation (storm on a wind turbine, turbulences on an offshore drilling rig, etc.).

As a tangible example, consider a balance beam that resembles a thrust magnetic bearing system with a backup ball bearing sitting at 50% of the airgap and an initial offset (40% of the airgap). While the system is operating, a pulse-like disturbance upsets the system. The simulation result is shown in Fig. 11. The top graph is a comparison of the time response of the systems with common linear models and the proposed nonlinear model. The bottom graph in the figure shows the total force exerted on the beam in the linear and nonlinear models alongside the disturbing force. The figure shows the maximum tolerable disturbance by the system with the nonlinear modeling. While the nonlinear design tolerates forces as large as 588N, the linear system became unstable. The force graph shows how the extra force capability helps stabilize the system.

In the former example, the time responses show that in an existing AMB system, by making some adjustments to the controller, the system can tolerate almost twice the disturbance force and, therefore, almost 4 times the disturbance energy.

For experimental proof of the concept, a balance beam test rig was designed. The experimental setup is shown in Fig. 12.

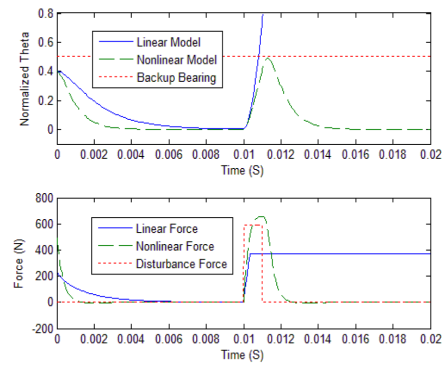


Figure 11: Time response comparison

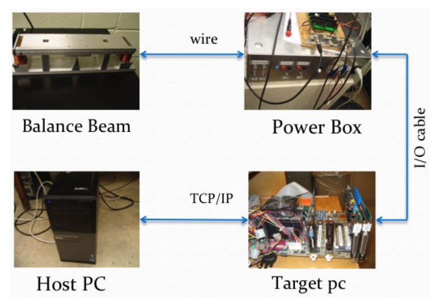


Figure 12: The experimental setup

Dynamic Performance Enhancements for Non-Laminated Magnetic Thrust Bearings

Student: Zackary Whitlow

Due to continually increasing performance demands in the market, the percentage of high-speed compressors supported by active magnetic bearings has grown substantially over recent years. Magnetic bearings enable higher speeds and power-densities than their more traditional bearing counterparts. In addition, significant reductions in overall system footprint and maintenance costs are also enabled by the use of magnetic bearings in high-speed compressors. Magnetic bearing supported compressors have known deficiencies as well – specifically their limited ability to deal with surge events and other similar large amplitude, fast dynamic load events. In addition to radial vibrations, surge events tend to induce large axial vibrations. The ability of a magnetic bearing to deal with these conditions is complicated by system nonlinearities. Non-laminated thrust bearings are especially susceptible to surge events due to limited static as well as dynamic force capabilities.

Taking advantage of the ability to easily modify performance by changing the control algorithm, we will address these problems associated with compressor surge. Feedback linearization using a more accurate nonlinear electromagnetic model will be used to address problems associated with large deviations from nominal operating position. Zhu *et al.* have developed a more accurate model of the current to force relationship of non-laminated actuators that includes eddy current effects.

We are investigating the potential of incorporating these models into the overall control design process to help overcome dynamic deficiencies of magnetic bearings in response to surge. Our controllers will be tested on a 35 pound flywheel rotor supported vertically by a non-laminated thrust bearing and fitted with a shaker to simulate compressor surge.

UNIVERSITY of VIRGINIA

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Faculty

Dr. Houston Wood	Dr. Chris Goyne
Dr. Zongli Lin	Dr. Robert Ribando
Dr. John Knight	Dr. Andres Clarens
Dr. Bob Rockwell	Dr. Roger Fittro
Dr. Alex Untaroiu	Dr. Wei Jiang
Dr. Patrick Migliorini	Dr. Se Young Yoon

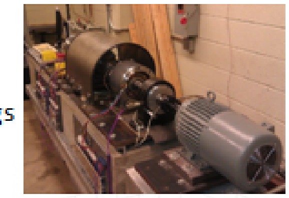
Staff

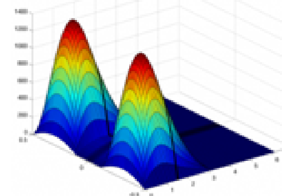
Sara Thacker
Barbara Pilkey
Sean Travis

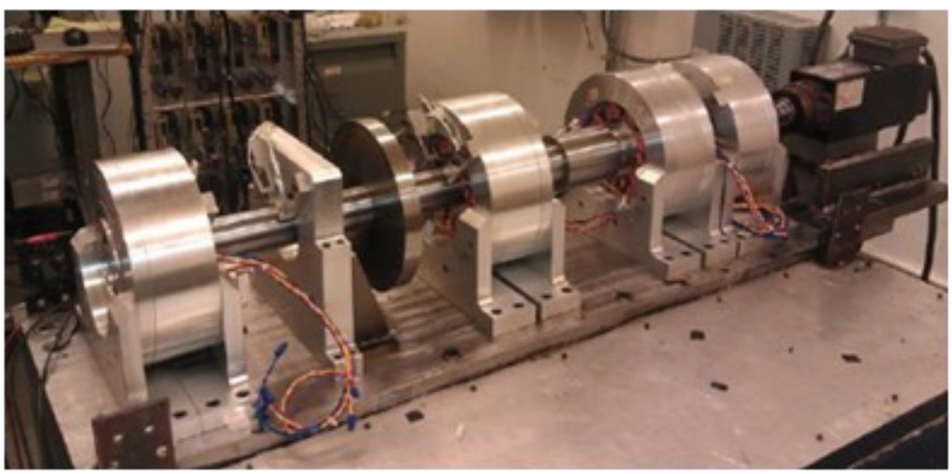
Graduate Students (10+), Undergraduate Students, and Interns

Areas of Expertise and Current Activity

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







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