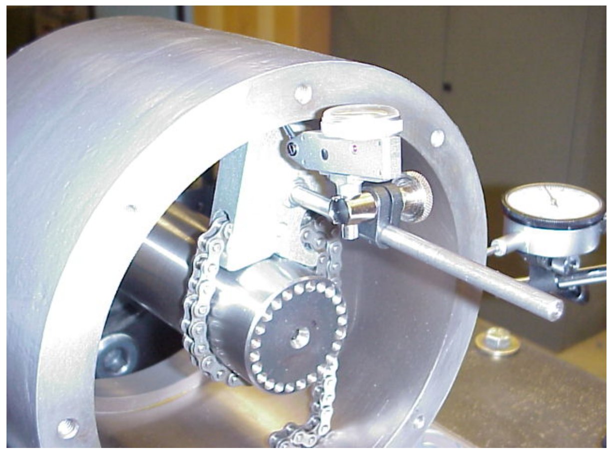
ROTATING MACHINERY AND CONTROLS LABORATORY

2004 ROMAC NEWSLETTER



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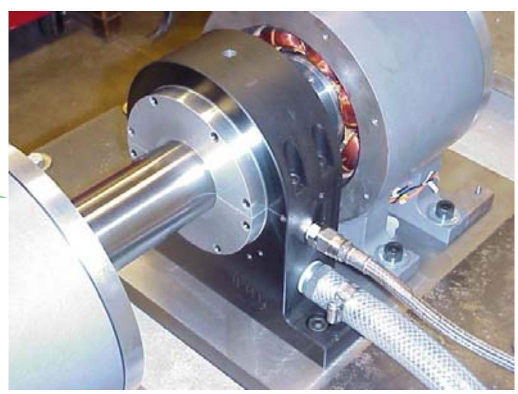
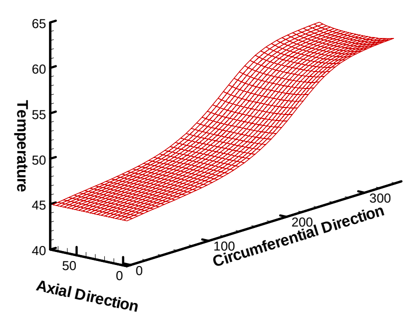
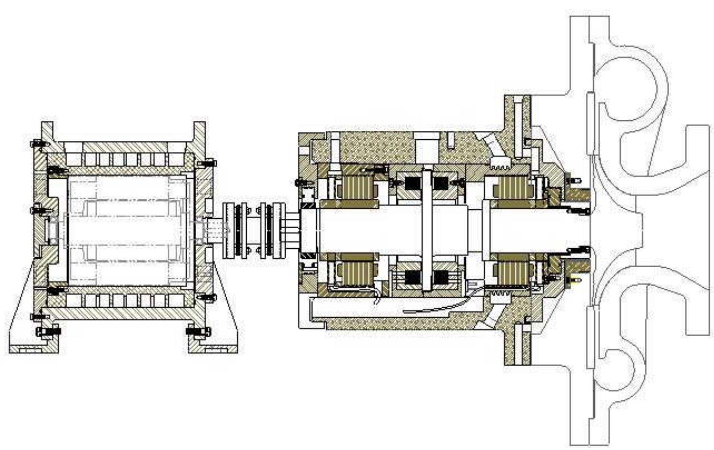




Special points of interest:

- 2005 Meeting in Charleston, SC
- ROMAC welcomes new members
- New computer modeling programs being developed



MESSAGE FROM DIRECTOR

ROMAC NEWSLETTER - ANNUAL MEETING SUMMARY

The 24th Annual ROMAC Meeting was held on June 6-9, 2004. The meeting was very successful with much interaction between the industrial members and ROMAC faculty, students and staff. A number of companies were not able to attend so we are sending out this newsletter to help inform those companies, as well as the ones that attended, about ROMAC activities.

ANNUAL CURRENT MEMBERSHIP AND MEETING ATTENDANCE

We would like to thank you all for being long term members of the Rotating Machinery and Controls Industrial Research Program at the University of Virginia, as well as a welcome back to Kingsbury. We now have 28 industrial members, a slight increase over last year. The companies are AC Compressor, Bechtel, Boeing, Concepts, GE Conmec, Cooper, Curtiss-Wright, Siemens Demag, Dow Chemical, Dresser Rand, Dupont, ExxonMobil, Framatome, Flowserve, KAPL, Kingsbury, Kobe Steel, Mechanical Solutions, Mitsubushi Heavy Industries, Petrobras, Pratt & Whitney, Rockwell, RMT, Rolls Royce, Solar Turbines, Hamilton Sundstrand, TCE, and Waukesha Bearings. Several other companies are considering membership.

This is our first increase in membership in a number of years following a number of mergers and acquisitions over the past 5 or 6 years which resulted in a net reduction of our membership.

There were 29 industrial attendees at the annual meeting representing 20 companies.

ROMAC FACULTY STATUS AND CHANGES

The ROMAC Director is Paul Allaire. There have been significant changes in ROMAC faculty over the past year or so. These were also discussed at the annual meeting. After many years as a ROMAC faculty member, Director, and main line researcher, Ron Flack is in the process of retiring. He has his house on the lake and is going fishing (at least he has given up engineering). Carl Knospe has left ROMAC after 14 years as a faculty member, primarily due to the change in ROMAC research interests away from magnetic bearings.

That left only Paul Allaire, Lloyd Barrett, Eric Maslen, and George Gillies with the main research burden being carried by only a few faculty. We felt that we needed another faculty member and recruited a long term UVA Mechanical Engineering faculty member, Pradip Sheth. He has a strong background in multibody dynamics, machinery, and mechatronics. He also worked at Allis-Chalmers Advanced Technology Center for eleven years in Engineering Development and Computer Applications for industrial machinery.

ANNUAL FEES AND FINANCIAL POSITION

Our membership fee of $16,000 per year is unchanged for 2005. The total income to ROMAC is estimated to be $448,000 in cash or equivalent services or equipment. UVA takes 15% overhead or $67,000 as overhead leaving $381,000 as actual income to ROMAC, again subtracting some cash for services or equipment with a few companies. The approximate yearly spending rate is $145,000 for students including stipends and tuition, $140,000 for faculty and staff including salaries and fringe benefits. We had higher than usual test rig expenses of approximately $30,000 primarily related to the compressor rig, $30,000 for the hydrostatic bearing computer code, and some computer update expenses of

Message from Director, cont.

$27,000. The rest was small, miscellaneous items. We also wish to thank Petrobras very strongly for a $36,000 contribution to the rotor stability testing project and to ExxonMobil for their main support of this project. Thanks also to Kobe Steel for their contributions to the compressor rig.

We have been overspending a bit in the last two years. Thus, we will have to cut back on some faculty and student support this year. Practically speaking, this means that we will be graduating many of our current students. These students have been around for quite a while and it is time for most of them to finish up their work, give the results to the ROMAC members and get a job. Some of these existing students have also been placed on Teaching Assistantships funded by the University to save money. Only a few new students will be brought in this year. Also, we need to move some faculty and staff expenses off to other funded research projects – which are in progress of being secured.

FUTURE RESEARCH

Companies at the annual meeting completed questionnaires regarding desires for future research. The overall results are shown in the chart below.

PROJECT RESULTS AND FUTURE DEVELOPMENTS

We have developed several new computer modeling programs, associated manuals, experimental results as well as several theses and published papers. A series of articles in this newsletter highlights the progress on the various topics and expected developments. We have included both projects directly supported by ROMAC and other projects related to rotating machinery but not funded by ROMAC. If a project is funded directly through ROMAC funds, it is so stated at the beginning of the article or, if it is not, that is also stated.

Paul Allaire, Wade Professor of Mechanical and Aerospace Engineering and Director of ROMAC

Topic	2004 Rating	2003 Rating	2002 Rating
Fluid Film Bearings	35%	32%	29%
Rotordynamics	34%	31%	18%
Seals	14%	22%	18%
Magnetic Bearings & Controls	10%	8%	15%
Turboflows	7%	7%	17%

New Fluid Film Bearing Stiffness and Damping Measurement Test Rig

Student: Tim Dimond

Advisors: Paul Allaire, Pradip Sheth

Funding: ROMAC

There has been a desire from the ROMAC companies for a high speed fluid film bearing test rig to measure stiffness, damping, temperature rise and other parameters. The previous test rig had an upper speed limit of 7840 rpm due to it's design. The shakers on that rig have a limit of 4900 rpm due to overheating and other limitations. Many bearings today operate at a higher speed level that that. Thus there is a project in place to replace this rig with a more advanced rig.

"There is a project in place o replace this rig with a more advanced rig."

The specification of typical bearings to be tested has been under discussion for some time with RMT and we would welcome input from other ROMAC member companies. At this time we are considering fluid film bearings in the range of 4 to 8 inch diameter and L/D ratio with a rotation of up to 13,000 rpm (436 ft/sec surface speed) and static loads of up to 9,600 lbf (800 psi loading). John Nicholas of RMT has characterized such a rig as THE RIG for the next 20 years.

There have been a number of changes in personnel working on this project. Ron Flack is in the process of retiring from UVA. Eric Maslen and Lloyd Barrett have decided not to pursue it so Paul Allaire and Pradip Sheth have taken over. A new Ph. D. student, Tim Dimond, will start on this project in June, 2005 and other ROMAC staff such as Research Scientists will work on this project as well.

The design configuration being developed is one with twin magnetic bearings on each side of the fluid film bearing, similar to the smaller scale test rig at the University of Darmstadt. The rig would likely be driven by a high speed electric motor with variable frequency drive. The magnetic bearings would likely be used to apply both the test static and dynamic bearing loads. However, magnetic bearings do not have very high load capacity so some alternative means are under consideration for the application of large static loads, as often taken by fluid film bearings. A significant issue is the inertia of the shaft which will have overcome by the magnetic bearing forces during dynamic testing.

A component analysis will be carried out for the magnetic bearings (bearing design and lamination stacks, controller, computer interface boards), fluid film bearing system (split housing, test bearings, oil seals), drive system (high speed motor, variable frequency drive, high speed coupling), lubrication system (lube oil supply pump, heater, shell and tube heat exchanger, flow meter), instrumentation (proximity probes, Hall sensors, thermocouples, A/D boards, etc).

This project will be a large scale effort over a number of years. Strong input will be solicited from interested companies. Several companies have already made suggestions. Financial support and "donations" by very interested companies will be necessary to complete this project.

Labyrinth Gas Seal Code/Program Development

Student: Jie Zhou
Advisor: Paul Allaire
Project Start Date: Sept 2000
Funding: ROMAC

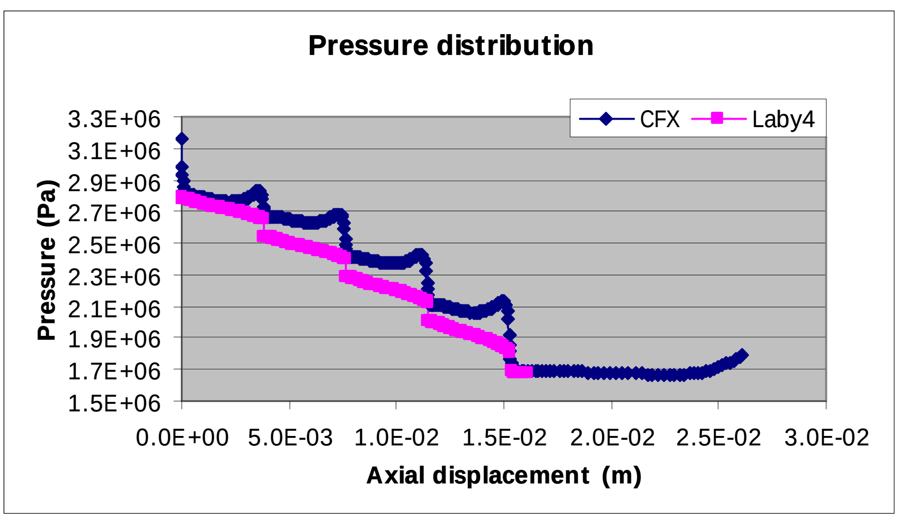
LABY4 is a new gas labyrinth seal analysis program under development. It will replace the current code LABY3. You may recall that LABY3 gives out reasonably good results for cross coupled damping dynamic coefficients but not so good principal dynamic coefficients of stiffness and damping. The new key approach is to use three control volumes, following a method by Prof. Nordmann from Germany, to a better model the fluid stresses, forces and velocity a of the fluid filed in the seals. Tascflow, a 3-D computational fluid flow code from AEA, is being used to determine the flow properties, such as the control volume velocity and pressures as well as suitable boundary conditions to obtain a better flow description for the three control volumes in each industrial labyrinth seal configuration.

Progress in the past year:
The set of equations to be describe the flow in labyrinth seals has been obtained. Also, another equation set based on Scharrer's equation set is finished. Results by both equation sets will be compared and key terms for improvement may be found.

The initial version of LABY4 works now. Improved boundary conditions are now employed. Some convergence problems have been found and are under investigation.

At this time, we are trying to understand the flow in labyrinth seals more accurately.

Our current series of CFD simulations will focus on a 3D eccentric seal model. Some key parameters used in three control volume method, such as the ratio between the second and third control volume axial velocity, and boundary conditions such as inlet loss coefficients, exit recovery coefficient and land loss coefficient are expected to improve with detailed modelling capability from Tascflow. This will allow us to improve LABY4.



TEHD Analysis of Fluid Film Journal Bearings (Computer Code MAXBRG 2.0)

Consultant: Minhui He
Faculty: Paul Allaire
Project Start Date: September 1996
Report Number: 458
Funding: ROMAC

Project Overview:

Fluid film journal bearings are widely used in turbomachinery. An accurate prediction of the bearing properties is critical to a machine's design and analysis. The objective of this project is to develop a state of the art thermoelastohydrodynamic (TEHD) algorithm for industrial journal bearing analysis.

Many advanced models are utilized in this finite element based algorithm. The pressure is calculated from the generalized Reynolds equation. The pad and film temperatures are obtained from a unique energy equation that has computational efficiency and broad capability. Turbulence is automatically handled in these equations. Deformations of the pad, journal, shell, and pivots are all taken into account. A coupled film-pad approach is employed to achieve good numerical robustness.

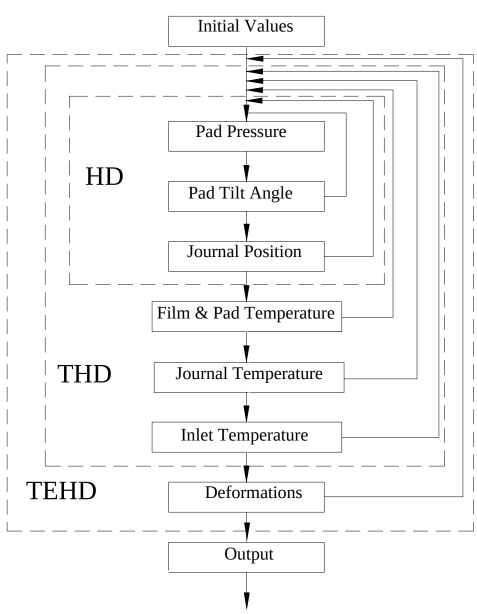
This algorithm can be used to analyze directly lubricated bearings as well as conventional fixed geometry and tilting pad bearings. Modeling of pressure dam bearings is extended to include adiabatic thermal effects. In addition to the normal flooded condition, this algorithm handles several special operating conditions, including starvation, high ambient pressure, and axial flow. Moreover, the computer code is flexible in that the users can select and combine a variety of modeling options according to their needs and engineering judgment.

Progress in the past year

Since the release of Version 1.0 in July 2003, several upgrades have been implemented in the current Version 2.0. To enhance the convergence rate, relaxation factors can now be independently applied to different iteration loops. Each pad can be assigned a different heat convection coefficient on its back. The angular stiffness coefficients are now calculated for fixed geometry bearings. Sump oil has been added as an option in the groove mixing model. The starvation model has been improved for more accurate predictions. The output format has also received some refinement. Per request by ROMAC members, the algorithm has been extended to analyze hydrostatic bearings. However, due to fundamentally different modeling methods, the hydrostatic models have been separated from MAXBRG and integrated into a new computer program (see HYDROBRG)as discussed next.

Future work

MAXBRG will continue to be maintained and upgraded in the future. As in the past, future upgrades will largely be based on feedback from ROMAC members. Please tell us your questions, suggestions and comments. Your input is very important and highly appreciated.



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New Program: Hydrostatic Bearing Analysis (Computer Code HYDROBRG 1.0)

Consultants: Minhui He,

Faculty: Paul Allaire, Xin-wei Song, Houston Wood

Funding: ROMAC

Project Start Date: Aug 2003

Report Number: 511

Project Overview:

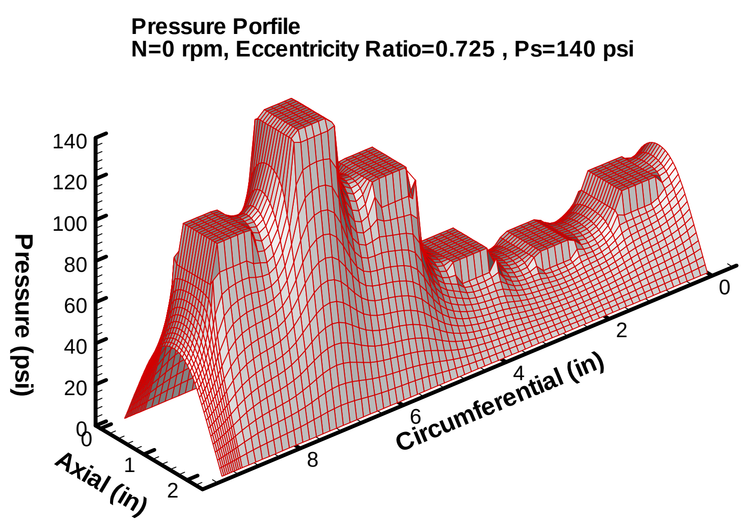
This project originally started as a MAXBRG expansion to include hydrostatic capability. Instead, a totally separate code HYDROBRG has been developed because hydrostatic models are fundamentally different from the hydrodynamic models used in MAXBRG.

HYDROBRG employs the classic approach for hydrostatic bearing analysis. The pressure drop across the orifice restrictor is governed by an orifice equation. The pressure drop at the pocket edge is calculated using an empirical head loss equation. The pressure distribution in the land region is obtained by solving the generalized Reynolds equation. These three equations are then coupled together by virtue of flow continuity. In this version of HYDROBRG, the pocket must be sufficiently deep so that the pressure inside can be assumed constant.

Previous studies indicate that the orifice discharge coefficient is a very important parameter in analysis. Thus, extensive CFD simulations were conducted to investigate the general relationship between the discharge coefficient and the governing parameters, including the orifice *L/D* ratio, inlet geometry, and the Reynolds number. A dimensionless parametric correlation equation for square-edged orifices was obtained based on the CFD results. Using this equation, HYDROBRG internally calculates the orifice discharge coefficient as part of the solution procedure, which improves both accuracy and convenience.

Future work

The work described was completed and delivered in May 2004. Future work could include variable pocket pressure, thermal effects, and CFD investigation on the pressure loss at pocket edge. However, future work will be carried out only if the demand is high.



Rolling Element Stiffness and Damping Evaluations

Student: Amir Younan
Faculty: Paul Allaire
Funding: ROMAC

The evaluation of rolling element stiffness and damping properties remains a topic that many ROMAC companies want to see developed. We will develop a ball and roller bearing code to evaluate the equivalent stiffness and damping properties of these bearings. This code will evaluate the stiffness and damping properties of various rolling element bearing types for use in rotor dynamics computer codes. A fairly extensive literature review has been carried out on this topic.

A new Ph. D. student, Mr. Amir Younan, has been admitted to carry out this project and he starts at UVA in January, 2005. He has an M. S. degree from the University of Cairo, which has a very good reputation in the rotor dynamics community under Prof. El Sharif. This project will be supervised by Paul Allaire, with assistance from other ROMAC staff.

A short review of rolling element bearings follows. Wensing and van Nijen [2001] developed a computer analysis of stiffness and damping properties of rolling element bearings. Akturk [2003] determined the effects of preload and number of rolling elements on angular contact bearing stiffness and how it affects rotor natural frequency. The work by Dietl, Wensing, and Nijen [2000] conducted an experimental and theoretical study of damping in rolling element bearings at SKF.

Very significant recent work on rolling element bearings has been funded by NASA, under the supervision of Dr. David Fleming, and carried out by J. V. Poplowski & Associates under SBIR funding so it is in the public domain. This work developed a computer model, COBRA-AHS, (Advanced High Speed – Computer Optimized Ball and Roller Bearing Analysis). It considers up to five bearing rows on a flexible or rigid shaft loaded in 5 degrees of freedom. The list of program capabilities is extrensive and my be seen in the COBRA-AHS website. This analysis and computer program will be used to guide us in the development of our new ROMAC code. There are three versions of this code: baseline, intermediate, and full. The baseline analysis is equivalent to the Jones code with some Windows enhancements. The intermediate version has the same functions as the baseline version plus and interactive roller crown design cell with edge stress estimation. The full has all of the intermediate features plus ANSYS integration for temperature distributions and more rigorous fit-up analysis. A published paper by Fleming and Poplawski [2003] illustrates the use of this code for unbalance response of rotors on ball bearings using speed and load dependent nonlinear bearing stiffness.

We expect that significant interactions will take place in the next year or so to determine the code features most desired by the ROMAC members.

"A new Ph.D. student, Mr. Amir Younan, has been admitted to carry out this project"

Control of High Speed Gyroscopic Rotors with AMBs

Student: Guoxin Li

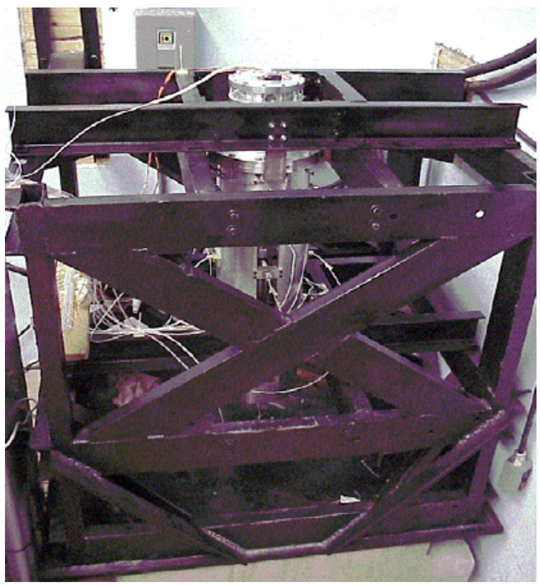
Advisor: Paul Allaire, Zongli Lin

Funding: Not ROMAC

Project Start Date: January 2000

Project Objectives:

For some rotors, such as flywheel rotors, gyroscopic effects are significant due to the high polar inertia as compared to bending inertia as well as the high operating speeds. Control of a strongly gyroscopic rotor over a wide speed range with magnetic bearings is a very challenging problem. Two dominant issues must be addressed in the control design. First, high bandwidth controllers are often required to stabilize the rigid bode modes. This may compromise high robustness requirements. Second, the dynamics of the rotor vary with the operating speed; a single linear time invariant controller often cannot stabilize the system over the entire operating range. Advanced multi-variable robust optimal controls, $H\infty$ and μ-synthesis, provide systematic tools to achieve system robustness. To address the speed dependent dynamic problems, gain scheduled robust control including the switching control techniques are being investigated. The linear parameter varying (LPV) approach is employed to design gain scheduled H_∞ controllers. The gain scheduling problem is formulated in the context of convex semi-definite programming by linear matrix inequalities (LMIs). The LPV controller is obtained by



solving the LMIs using interior point methods. A piecewise μ-synthesis design is also adopted. Overall control is implemented by switching between controllers as speed varies from one region to another. A bumpless transfer scheme is implemented to guarantee smooth transition between controllers.

A test rig was constructed as a platform for investigating different controllers. First, an accurate nominal model including the substructure modes was developed from physical laws and refined by experimental data. An uncertainty representation and a performance criterion were developed for the model AMB system. The influence of gyroscopic effects on the stability and performance of AMB system under a MIMO controller was analyzed.

Progress in the Past Year:

To complete this project, we worked on several tasks. First, we evaluated several controller design approaches including the PID, H_∞ and μ-synthesis. The performance and robustness from different controllers were classified and evaluated based on the testing data collected before. Second, we tested two different identification techniques for the substructure and rotor models in order preserve the structural property. Third, different classifications of uncertainties and uncertainty modeling techniques were investigated. Fourth, we also evaluated model updating and model validation techniques. In addition, we also worked on developing a unique gain scheduling control technique. The results will be released in a ROMAC report.

Performance Limitations and Self-Sensing Magnetic Bearings

Student: Roza Mahmoodian
Advisor: Eric Maslen
Funding: NSF
Project start date: October 2004

Project Objectives:

Having developed a theoretical base to understand the mechanisms that control attainable performance in self-sensing magnetic bearings over the past three years, we are now in the position to return to development of hardware realizations and exploring practical implementation issues.

The immediate goals of the new project include estimator realization through an FPGA or similar very high speed digital mechanism; exploration of a number of competing estimation approaches both through simulation and using this FPGA platform in conjunction with an existing rigid rotor test bed; and development of measurement and signal processing methods for accurate determination of sensitivity margins in linear periodic systems (which self-sensing AMBs exemplify). An additional and important longer term goal is to revisit some methods proposed by Noh in the late 90's for self-sensing gap estimation in the presence of strong actuator saturation, a problem which has proved to be more difficult than might be expected.

Progress this year:

This work has been restarted under a recently acquired three year grant from the National Science Foundation. In addition, a new graduate student, Roza Mahmoodian, has joined the lab to work on this problem during pursuit of her Master's and Doctoral degrees. Generous funding from NSF means that this project will not impose noticeable burdens on ROMAC resources, but we hope that the very direct contact with this work available to ROMAC members will prove to offer some value to those involved with magnetic bearing technologies.

Magnetic Bearing Systems Sensitivity

Students: Guoxin Li, Qingyu Wang

Advisor: Eric Maslen

Funding: NEDO/Japan

Project start date: May 2000

Project Objectives:

The newly formulated ISO standards for magnetic bearing acceptance propose some standards describing acceptable stability margins for AMB systems. Specifically, these standards prescribe a method of measuring stability margins (the output sensitivity function) and set limits to the peak gain of this function for various performance "zones". The goal of this project was to explore a number of issues surrounding this measurement, including how readily the actual sensitivity peaks can be measured in a practical environment and how well the essentially single-input-single-output structure adopted by the standard reflects the sensitivities of more complex and dynamically coupled machinery. In addition, we wanted to get a sense of how well sensitivity functions can be predicted based on machinery models prior to actual construction of the equipment: it's clear that this question bears on the reliability of vendor predictions during a bidding process. This work is funded by a grant from the Japanese New Energy Development Organization.

Magnetic Bearing Systems Sensitivity (cont)

Progress this year:

The intent of the project was to use experimental work on Hunter Cloud's test rig to explore the issues raised above. However, continuing delays because of problems with the NI real-time controller prompted us to look elsewhere for a suitable data source. Fortunately, earlier work performed by Guoxin Li on the AFS flywheel test rig turned out to be ideally suited to the purposes of this study. With relatively little effort on Guoxin's part, we were able to transform that data into the form required for this study and to extract at least partial answers to most of the central questions. What remains is a short study of the predictive accuracy of the original engineering models of the entire system in assessing system sensitivity expectations.

Modeling and Control of Non-Laminated Magnetic Actuators for Magnetic Levitation

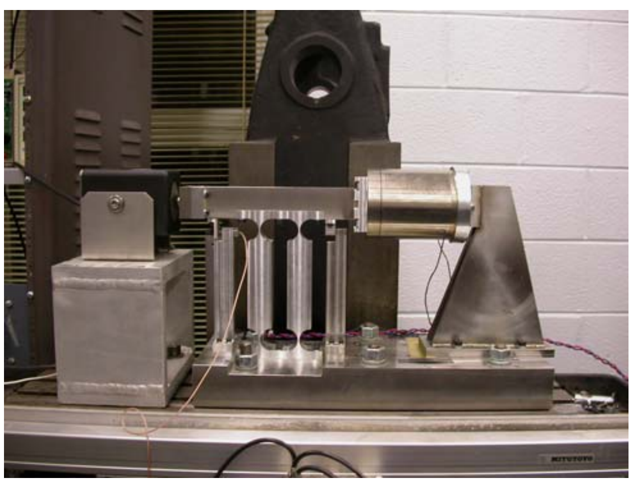
Student: Lei Zhu
Faculty: Carl Knospe and Eric Maslen
Funding: NSF
Project start date: Sept 2001

Project Objectives:

The main objective of this research is to develop control algorithms that provide high servo bandwidth magnetic suspension for systems with non-laminated actuators. A secondary objective is the quantification of performance limits for these systems

Progress in the Past Year:

A new non-laminated cylindrical magnetic actuator was constructed from Carpenter's Hyper49. Important dimensions of the actuator are listed as follow: inner pole diameter 50mm, outer pole outer diameter



86mm, outer pole inner diameter 70mm, pole length 80mm, and flotor thickness 15mm. The actuator was annealed for optimal magnetic properties. Swept sine tests conducted on this actuator show that the analytic model derived for cylindrical actuator is very accurate. The difference between analytic model and experimental model is around 10%. Controller design is now being carried on. Initial results show the possibility of greatly improving the bandwidth of systems with non-laminated magnetic actuators.

The modeling approach developed initially for cylindrical actuators has been applied to C-shaped actuators, and produced a compact analytical result. 3-D finite element analysis using ANSYS shows that the analytic model derived is much more accurate than those given in literature.

Surge Stabilization in Centrifugal Compressors

Student: Dorsa Sanadgol

Advisor: Eric Maslen, Ron Flack

Project Start Date: Fall 2001

Funding: ROMAC

Project Objective:

The objective of this project is to use the sensitivity of the compressor characteristic to the tip clearance of the impeller to design a controller which is capable of actively suppressing the oscillations induced by compressor surge. This would be achieved, using a magnetic thrust bearing to modulate the tip clearance of the impeller. This way, the stable region of the compressor operation will be significantly increased and the compression system will not enter surge cycles for a wide variety of disturbances that might occur downstream of the compressor pipeline. Since no additional hardware is required for implementing this method on existing machines that are already equipped with magnetic bearings, this method is advantageous over conventional surge control methods.

Theoretical Basis:

A theoretical model describing the sensitivity of the centrifugal compressor parameters to tip clearance variations induced by axial motion of the rotor was previously established; based on available measured effects of tip clearance on compressor efficiency. The well-known Greitzer compressor model was then modified to include the effects of tip clearance variation on the compressor characteristic. This provides a control mechanism: modulation of tip clearance in unshrouded compressor impellers - to affect and hopefully stabilize surge.

Progress in the past year:

In an effort to overcome some algebraic difficulties associated with use of sliding mode methods, we have begun to investigate backstepping techniques, which promise a simpler formulation which does not rely on a cascade canonical form. A backstepping controller has been developed which is capable of substantially mitigating flow instabilities using the magnetic thrust bearing as the servo actuator to modulate the impeller tip clearance. The controller was designed with the objective that system trajectories remain on the steady state compressor characteristic curve in the presence of disturbances downstream of the compressor which is modeled by changes in the throttle opening. This ensures zero steady state offset of the impeller, which maintains the efficiency of the compressor.

Results from the simulation of the nonlinear model for a single stage high speed centrifugal compressor show that, using backstepping control, mass flow and pressure oscillations associated with compressor surge are quickly suppressed. Throttle changes producing a reduction in mass flow rate from 60% to 20% in under 2 seconds are readily accommodated by the controller with readily accepted impeller excursions. Further, the stable operating range of the compressor can be increased significantly. Actuator slew rate, peak force, and maximum tip clearance excursion requirements are well within the typical capacities of such systems.

The ultimate goal of the backstepping control development is to easily accommodate finite actuator dynamics as well as an essential lack of knowledge of throttle position. Present control requires knowledge

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Surge Stabilization in Centrifugal Compressors (cont)

of the throttle position, obviously reducing the utility of the method when throttle position is viewed as a model for downstream pressure disturbances. However, it appears that the method can be adapted to handle a "don't care" state - a state which is excluded from the underlying Lyapunov functions and must rely on system structural properties for stability. If this can be accomplished, then it is a small step to stabilize in the face of bounded but unknown throttle disturbances, thereby accommodating more general models of downstream pressure disturbances.

Compressor Test Facility

Student: Eric Buskirk

Faculty: Eric Maslen

Funding: ROMAC & equipment grants from SKF/ Revolve and Kobe Steel

Project Objective:

The goal of this work was to develop a high-speed air compressor test rig. Research objectives of the test facility include the identification of radial and axial impeller loads at on- and off-design operating conditions, and investigation of potential surge suppression control using the axial magnetic bearings to modulate the impeller tip clearance (See "Surge Stabilization in Centrifugal Compressors").

The test rig incorporates two radial active magnetic bearings (AMB) and one thrust AMB. A unique sectioning of the thrust bearing stator was used to decrease eddy current effects and increase the bandwidth of the actuator. All three AMBs are used for both support and as load cells. A register-level C++ Linux-based controller is used for the AMBs. National Instruments data acquisition equipment is used to control and monitor the test rig.

Progress this year:

All hardware is now completed and at UVA for this test rig. The compressor/impeller/volute provided by Kobe Steel is also at UVA. The AMB controller, using a register level C/ Linux program, has been developed and tested. A National Instruments data acquisition package has been purchased and the LabView programming has started. Initial assembly of the test rig has started. Current work is focused on levitation of the rotor on the AMBs and is expected by December 2004.

Hysteresis Experiment

Student: Eric Buskirk
Faculty: Eric Maslen
Funding: ROMAC
Project start date:June 2003

Project Objective:

The goal of this research is to investigate the stability of minor hysteresis loops of a magnetic field. The current approach to estimating uncertainties due to hysteresis assumes that minor loops stay pinned at the center of the first excursion: the center should not drift with time, thus producing a large uncertainty of the flux measurement. The goal of this research is to determine if, instead, the centers of minor hysteresis loops tend to drift towards the virgin curve of the magnetic material - that is, if repeated constant amplitude cycling of the material shows a tendency to "de-Gauss" it. If this occurs, the uncertainty bound on the magnetic flux can be decreased, improving the uncertainty of active magnetic bearings as load cells.

The experiment uses a split Rowland Ring with a flux sensor in the air gap and a current sensor to create magnetic fields and measure them in the iron specimen. A Labview-based data acquisition program is used to control and monitor the experiment. After an initial saturation of the test coil, small sine sweeps of current with a DC bias create the minor hysteresis loops. All tests are done on the order of 1Hz to prevent eddy currents from affecting the data.

Progress this year:

All experimental equipment has been received and calibrated for this test rig. Several initial experimental runs show promise for this test. Work will continue into early 2005

Rotating Machinery Stability Test Rig

Student: C. Hunter Cloud

Advisors: Lloyd Barrett and Eric Maslen

Project Start Date: January 1999

Funding: ROMAC, Petrobras, ExxonMobil

Project Objective:

With stability of turbomachinery being a major concern, this project is focused on avoiding these problems in the future by conducting research in the following two areas:

A. Determining test techniques which are suitable for accurately measuring the stability of a rotor/bearing system.
B. Examining how tilting pad bearing characteristics and common phenomena such as unbalance influence the actual stability levels and thresholds versus modeling predictions.

To investigate these issues, a test rig is being constructed which will simulate the dynamic behavior of many types of turbomachinery such as pumps, compressors, and steam turbines. Magnetic actuators will supply excitations in the form of destabilizing cross-coupled stiffness and non-synchronous forcing (sine sweep, impulse, etc). Several bearing designs will be tested with the base design being a 5 pad, load between pad bearing with L/D = 0.75, 0.3 preload, center offset rocker back pivots.

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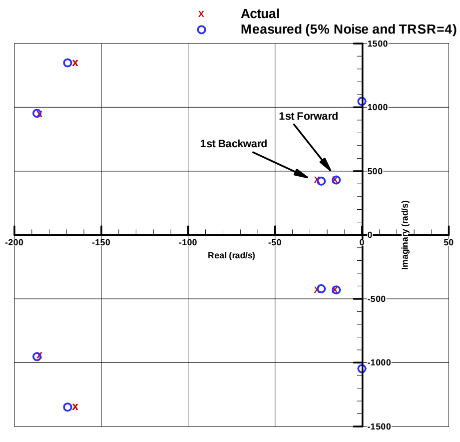
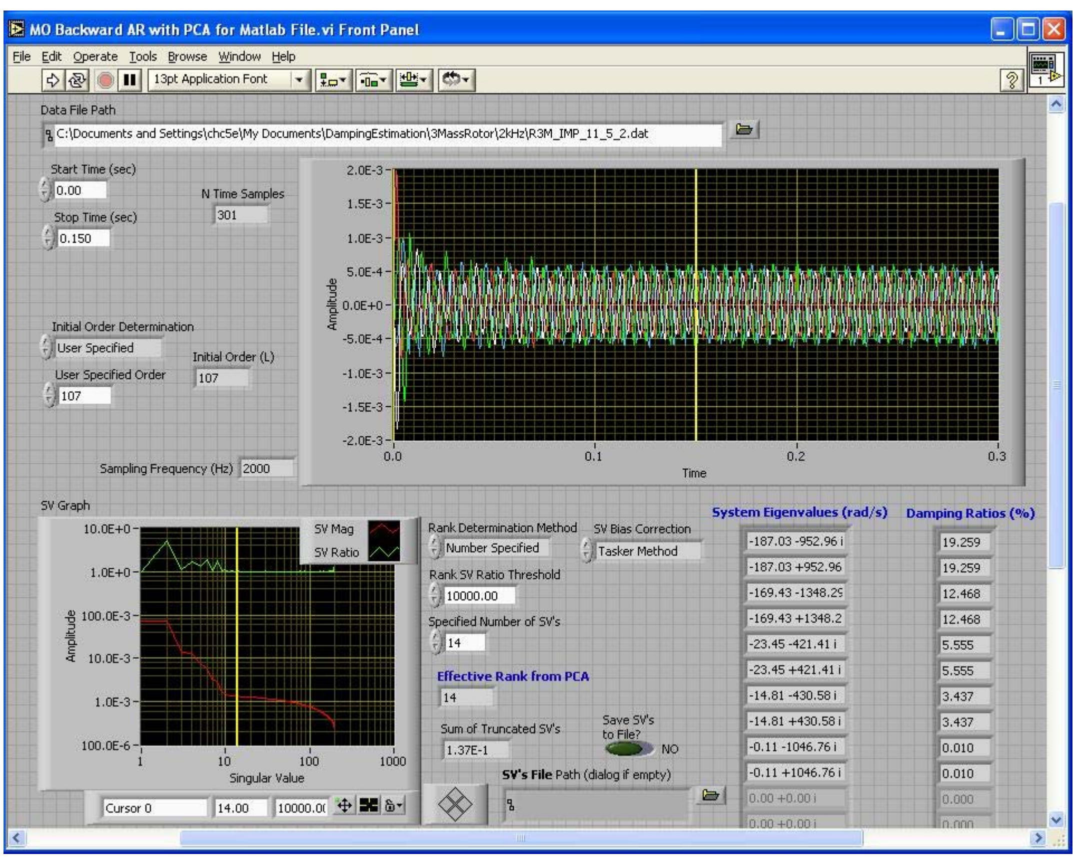
Rotating Machinery Stability Test Rig(Cont)

Progress in the Past Year:

Current efforts are focused on the magnetic actuator cross-coupling and excitation control system development and commissioning to make the rig fully operational for stability testing. Static calibration of the actuators has been completed. Because of problems and limitations with the LabView based control system, it is being converted to a Linux based system using controller algorithms similar to that being implemented on the compressor test rig. Analytical efforts have identified a time domain technique which appears to be very appropriate for accurately measuring a rotor's stability level (ROMAC Report #504). In conjunction, LabView software is being developed to implement this technique on the test rig.



MOBAR pole estimates vs. actual (1st Forward Mode: Actual = -15.51 ± 433.36 rad/s (ζ = 3.575), Measured = -14.81 ± 430.58 rad/s (ζ = 3.437))



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BALOPT—NEW BALANCING CODE

Students: Bin Huang and Guoxin Li

Advisor: Paul Allaire and Zongli Lin

Funding: ROMAC

Project Start Date: January 2002

Project Objectives:

Since the 1950s balancing has been an important technology for engineers concerned with synchronous vibration problems. While the technology has improved over the years, there is still few efficient computer programs to solve some of the basic balancing problems, such as the minmax balancing problem. In many cases, the conventional least squares method of balancing is not optimum for balancing high-speed flexible rotors. It cannot guarantee that the maximum vibration at certain rotor locations is below a certain level. The objective of this research is to develop a new generalized approach to rotor balancing with a convex optimization technique. This formulation not only solves the minmax balancing problem, i.e. the maximum vibration amplitude is minimized, but also allows balancers to deal with various kinds of practical constraints and data uncertainty. Furthermore, this formulation can be extended to a unified approach in which the modal trial weight distribution is obtained by solving inequality constraints.

Progress in the Past Year:

A beta version of the new ROMAC balancing code, BALOPT, is complete. The previous user interface using Script Editor is enhanced to include the feature of weight split. This version of BALOPT contains the following basic functions: influence coefficient estimation, run out compensation, weighted minmax, weighted least squares, correction weight constraints, orbit constraints and weight split. The code has been tested numerically. The version has been verified by some of the ROMAC members who participated in this project. An optimum stochastic balancing method that considers uncertainties within influence coefficients has been developed.

"A beta version of the new Romac balancing code, BALOPT is complete. The previous user interface using Script Editor is enhanced to include the feature

Future Work:

The effectiveness of the stochastic balancing method is being verified by experiments on the test rigs of ROMAC lab. BALOPT is being tested both numerically and experimentally on the laboratory test rigs and the industrial rotors. New functions such as the robust balancing, stochastic influence coefficient estimation will be added. Different solvers will be tested, and the user interface will be enhanced. Members are encouraged to try the beta version and feedback is needed to improve the code.

Model Reconciliation

Student: Qingyu (Flofish) Wang

Advisor: Eric Maslen

Funding: Romac

Project Start Date: January 2000

Report Numbers: 432,444

Project Objectives:

In a rotor-bearing system, there are usually some uncertain dynamic mechanisms which are considered frequency dependent, such as foundation compliance or bearing/ seal effects. This project develops a method to identify these uncertain dynamic mechanisms based on an accurate engineering model of the rest of the system. The theoretical framework permits consideration of a general flexible rotor and allows that the test excitations, sensors, and mechanisms to be identified are not collocated. No matter how accurate the engineering model is, however, there are always some model errors and they will propagate through the calculation, degrading the identification results. Therefore, an estimate of the quality of the results becomes very important and must be included in the identification process. Such an estimate can be defined as a bound on the error in the parameter estimates given a bound on the engineering model error and signal noise. MU-analysis is introduced to find the bound for the uncertainty in these frequency dependent parameters.

Progress in the Past Year:

Last year, we proposed this identification and bounding method as robust model reconciliation (RMR). Subsequent work in the past year is based on the same model structure as RMR, considering the discrepancy between the model and the data as the result of unmodelled dynamics or incorrect parameters, but it employs different calculation method from RMR. Instead of a parameterized model, this method directly yields a transfer function for the frequency dependent parameters or unmodelled dynamics. The new approach also fully considers the model errors and the experimental noises. It derives a bound for the identified model instead of trying to find the best model. So far, evaluation of the new method has been based on simulation data, which are used to illustrate the process and compare it to other bounding methods, thereby demonstrating the effectiveness of the MU-analysis. At present, work on Hunter Cloud's test rig is partly aimed at developing good experimental exemplars for further validation of the method and exploration of its limitations.

Rotordynamics

Student: Bahar Sharafi beginning in January 2005

Advisor: Pradip Sheth, Lloyd Barrett, Paul Allaire
Lab Engineer: Hunter Cloud

Funding: ROMAC

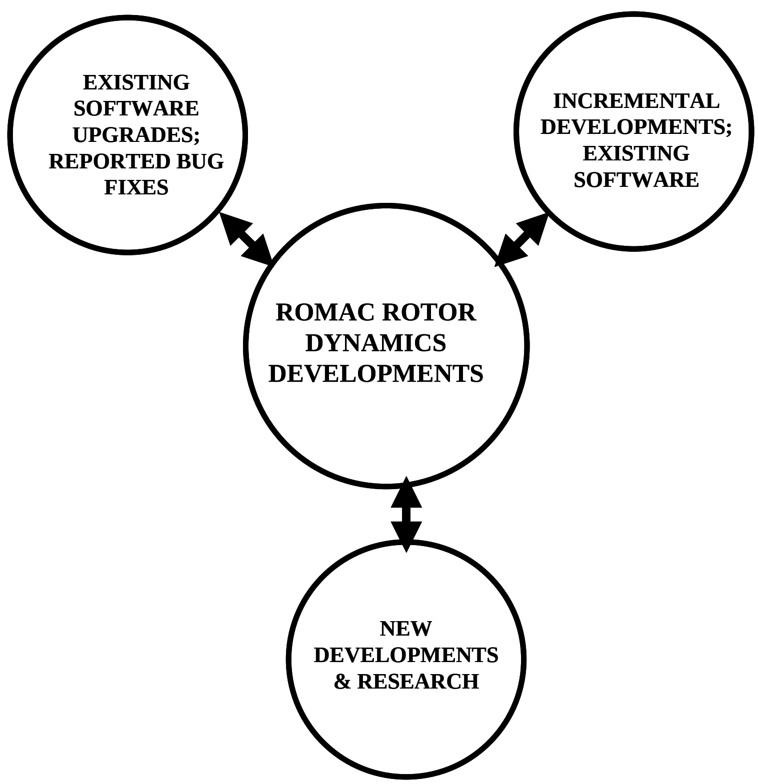
Consultant: Minhui He

ROMAC has built a rich history of developments in rotor dynamics, going back to 1972 and the resulting technology has been embedded in the software available to the ROMAC members. This history includes the development of analytical and computational methods, software implementations, and perhaps most importantly experiences with the correlations between the field tests and the model analyses and the ongoing process of continuous improvements resulting from these experiences. At this stage, an interrelated set of activities is being defined as illustrated in the diagram to the right.

Our ***highest priority*** efforts are directed towards ***upgrades of existing software and fixing any bugs or needs for improvements*** as reported by ROMAC members. Hunter Cloud and Minhui He have reported on this activity under "SOFTWARE HIGHLIGHTS" for FORSTAB, TWIST2, and the TORTRAN3 packages.

We invite comments and feedback from ROMAC members on their experiences in utilizing our Rotor Dynamics software so that a continuous improvement process can be carried out at ROMAC.

Associated with the upgrades of existing software and fixing any bugs, we are working on ***incremental developments of existing software***. For example, in the process of investigating TORTRAN3, Hunter and Minhui discovered that it is important to rationalize the full model versus the reduced model, and the selection of number of modes in the reduced model including the choice of master coordinates can have a signifi-



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Rotordynamics

cant influence on the accuracy of the results. Clearly, all of these issues should remain as transparent to the User as possible to minimize the need for the User's involvement and decisions in these issues while keeping the focus of the User on the actual results of the analysis. We are, therefore, investigating the processes of model reduction and their applications to nonlinear, time-history solutions. This is an example of incremental improvements. Other tasks within this activity include the modeling of short circuit electric faults, reclosure, variable frequency drives, and coupling nonlinearity within TORTRAN3.

The third activity is somewhat longer range, and can be classified ***as new developments and research".*** This activity will be shaped by active feedback from ROMAC members and their preferences for any new directions our Rotor Dynamics efforts should embark on. Bahar Sharafi will join ROMAC beginning in January 2005 who will be pursuing doctoral research in Rotor Dynamics. Some examples of new developments and research include:

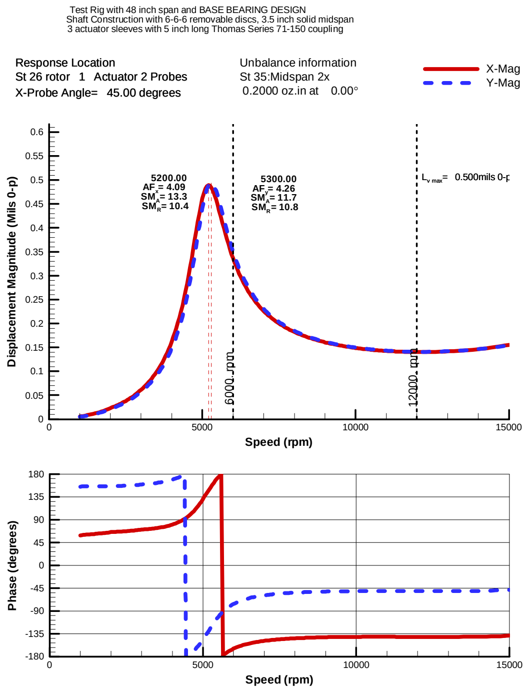
1. A common, robust suite of library routines for eigenvalues, SVD, numerical integration, matrix manipulations, etc. which can be utilized across all software packages of ROMAC.
2. Implementation of a common rotor dynamic model which can then be exported to the specific application such as TORTRAN3 where the application is intelligent enough to "dress up" or "dress down" the common model for its requirements.
3. Coupled lateral/torsional vibrations modeling and analysis capability.
4. Signal processing applications for rotor dynamic fault analysis.

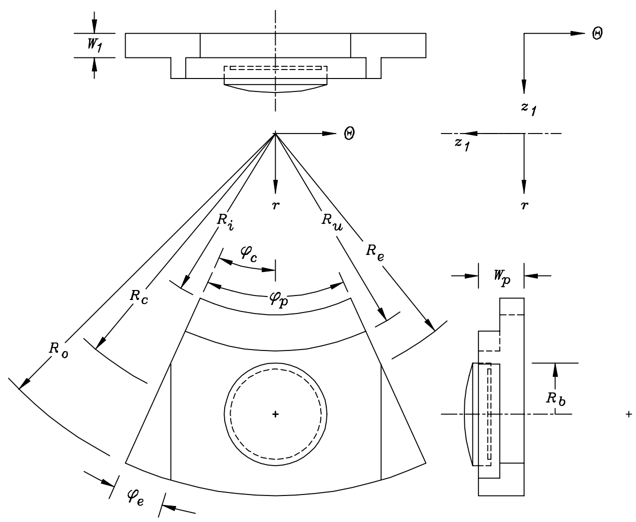
We will present our ideas for longer-range developments at the ROMAC meeting in June 2005 for your agreements. We encourage feedback from members on these and other topics.

"Our highest priority efforts are directed towards upgrades of existing software and fixing any bugs or needs for improvements"

SOFTWARE HIGHLIGHTS

FORSTAB
*Released version 1.72
*Corrected some bugs associated with the reading of seal coefficients
*Corrected relative phase of Y probe outputs (90 degrees)
*Associated corrections were made in PLOTSTB v 1.32

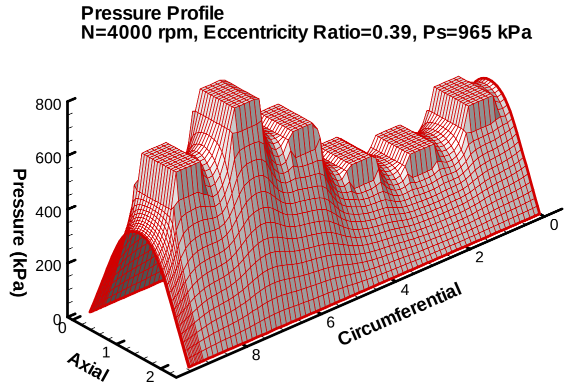




THRUST
*Released version 4.03
*Increased maximum number of pads to 50
*Additional research and capabilities are in progress (see other newsletter section).

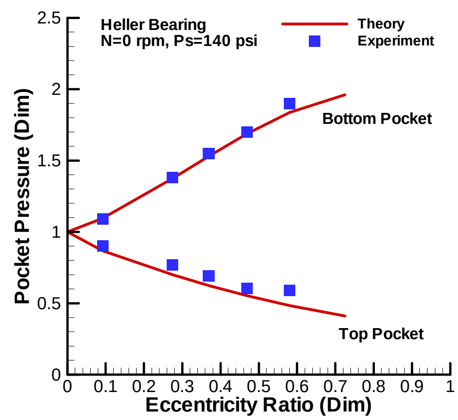
MAXBRG
*Released version 2.0
*Additional groove mixing model using sump temperature
*Moment stiffness coefficients for fixed geometry bearings
*Different convection coefficients for different pads allowed
*Output format improvements
*Supply flow rate input changed from CIPS to GPM
*Separate relaxation factors for pressure, temperature and deformation calculation

ROTORLAB
*New UVA.dll incorporated
*Runs the following analyses:
-Undamped Critical (CRTSP2)
-Unbalance Response (RESP2V3)
-Stability (ROTSTB)

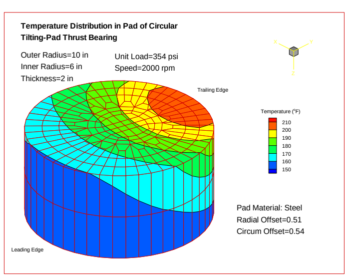


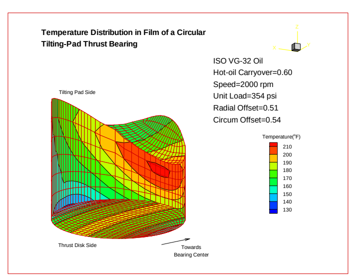
-Bearing (THBRG, THPAD, MAXBRG)
-Seal (SEAL3, LABY3)
*User workgroup being established to guide optimization of interface
*Torsional analysis (TWIST2) capabilities being added

<u>HYDROBRG</u>
NEW HYDROSTATIC BEARING CODE
*Combines and improves upon the capabilities of HYDRB and HYDROB
*Deep pockets required
*Axial grooves allowed
*Multiple pockets per pad
*Different number of pockets per pad
*Internal calculation of orifice discharge coefficients



<u>WORK IN PROGRESS</u>
*TWIST2
-Automatic calculation of penetration factors with effective length adjustment
-Additional element cyclic torque output
*TORTRAN3
-Resolve problems when using multiple rotors with gearbox
-Add capabilities for performing electrical fault analysis or more general time transients
-Conduct numerical stability investigation vs. TORTRAN2
-Generalized torsional stiffness model for elastomeric couplings (more general polynomial equation as well as possible interpolation for user input curve)
-Frequency dependent elastomeric coupling damping model
-Additional coupling element cyclic torque output
*SEAL3
-Create speed case output capabilities for use with rotordynamic codes
*THRUST
-Resolve convergence problems for turbulent flow AND conduction situation
-Major effort requiring reformulation of runner, film and pad equations
-Additional mesh routines needed to fully couple components





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HEART PUMP

Students: Matthias Glauser, Alex Untariou, Amy Throckmorton, Sonna Patel

Faculty and Collaborators: Don Olsen (Utah Artificial Heart Institute), Paul Allaire, Houston Wood, Zongli Lin, Curt Tribble (Heart Surgeon), Ben Peeler (Heart Surgeon), Paul Matherne (Cardiologist), Scott Lim (Cardiologist), Wei Jiang (Research Engineer), Ron Kipp (Kipp Engineering), Xinwei Song (Research Scientist)

Funding: NSF, Medforte Foundation, National Institute of Health (pending)

We have constructed a new axial flow left ventricular assist device for use with human patients undergoing congestive heart failure. It will be implanted in the chest cavity to work in parallel with the underperforming diseased heart. It pumps blood in a design flow range of 2 to 10 liters per minute with a design flow of 6 liters per minute. The pressure rise is 100 mm of Hg. The dimensions are 65 mm long and 35 mm in diameter. It is fully magnetically suspended, with a combination of permanent magnet and active magnetic bearings. The rotor position sensors are Hall effect sensors which are used to both active feedback control to the radial magnetic bearing and flow control by estimating the pressure drop over the pump impeller.

A magnetic bearing and motor test rig has been constructed and used for successful testing of the magnetic suspension and the specially designed motor. A simulated cardiac test loop is available for pulsatile pump testing in water or simulated blood conditions. Animal testing for 30 days is planned soon.

We have had very large funding from NIH and other sources totaling approximately $6,,000,000 with our original centrifugal artificial heart pump over the past 8 years. Our first large grant application on this new axial flow pump to NIH for $6,800,000 over 5 years was turned down for funding by a narrow margin but we received encouraging reviews from NIH to resubmit with relatively minor revisions. The head of the NIH Heart, Lung, and Blood Institute personally visited our lab in August to see the pump. That revised grant is currently under review and we will know if it is funded by March 2005.

ANNUAL MEETING

Charleston, SC

June 12-15, 2005

The 2005 Annual Meeting will be held in Charleston, South Carolina at the Charleston Harbor Resort & Marina. You can visit their website at: CharlestonHarborResort.com. They are giving us a nightly rate of $129.00 per single/double room. The meeting will begin with a welcome reception on Sunday afternoon at the hotel. Lunch and breaks will be provided each day and there will be a dinner on Monday night. Registration materials will be mailed out in March. If you should have any questions, contact Karen Marshall at (434)924-3292. Details are also on our web at http://Virginia.edu/romac/. Make plans now to meet us in Charleston!

LABORATORY EQUIPMENT ACQUISITIONS

There are a number of mechanisms through which ROMAC obtains research instrumentation and other equipment for its laboratories. These include:

- Budgeted purchase using ROMAC funds
- Budgeted purchase via a sponsored research grant or contract
- Long-term loan from a member company or a national laboratory
- Donations of equipment from industry
- Purchase with 50% fund match via the Virginia Equipment Trust Fund

Equipment purchased via sponsored research contracts is typically titled to the University unless negotiated otherwise by the sponsor, and it often becomes generally available to the whole ROMAC laboratory following completion of the project for which it was obtained. We presently maintain a large and well-used collection of standard electronic test and measurement instruments, Bentley probes, vibration and acceleration sensors, and calibration devices. Our laboratory facilities include two benchtop areas that are given over to bread-boarding and circuit assembly, and we have a small in-house machine shop area as well. In addition, there are excellent shop facilities in both the Department of Mechanical and Aerospace Engineering and the Department of Physics, and all but very large scale fabrication and assembly tasks can routinely be carried out in those shops. The University also maintains a well-staffed electronics shop in the Department of Physics, the personnel of which are called upon as needed to assist with maintenance, repairs and calibration of our instrumentation.

Several of our most recent acquisitions have been in support the work on our instability and compressor test rigs. We are very grateful for the support of the industrial members who have assisted with the equipment needs of those projects. In addition to that work, we're also going through an assessment process aimed at defining the equipment that might be needed for the development of a high speed bearing test rig, and similar support from the industrial members would also be critical to seeing that project go forward.

With the changeover from 35 mm slide presentations to all electronic ones, we chose this past Summer to apply to the Commonwealth of Virginia's Equipment Trust Fund for matching funds to purchase a computer projector, for use at the ROMAC Annual Meeting and at our student seminars. As mentioned above, the Equipment Trust Fund provides a 50% match against available funds from sponsored research and other sources, thus allowing significant leverage of our ROMAC equipment budget. We look for every opportunity to take advantage of this program for the benefit of our sponsors. Purchase requests made to it are ranked competitively by the University administration, based on the need for each item, its cost, expected service life, etc. Several of our most generally useful instruments have been procured in this way, including spectrum analyzers, heavy duty power supplies, and so on.

It is our aim to ensure that all of the ROMAC research students always have the instruments and equipment they need for their work. As in any busy enterprise, though, it sometimes happens that the most widely used items of test and measurement equipment are tied up on one project but nevertheless needed on another. Therefore, we do ask the member companies to keep us in mind when it comes to disposition of surplus equipment that might still have a useful service life. If you are going through any project close-downs or laboratory consolidations that might make such items available (eg., DVMs, waveform generators, vibration sensors, oscilloscopes, etc.), please let us know. The ROMAC contact point for this is George T. Gillies, who can be reached at gtg@virginia.edu or by calling (434)924-6235.

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We are on the Web!

www.virginia.edu/romac