

# 2002 ROMAC NEWSLETTER

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Special points of interest:

- MAXBRG has been released in a Beta version
- ROTLOSS released as version 1.0
- Bearing rig is up to 7840 RPM
- Flywheel test rig demos mu control, 17000 RPM

# Message from the Director

*Eric Maslen*

A lot has happened in ROMAC in the past year and this annual newsletter tries to highlight this activity. Some feature developments include:

- ◆ Guoxin Li's flywheel test rig successfully implements speed scheduled  $\mu$  control, passing through numerous structural modes and the first bending mode of the rotor to reach 17,000 RPM,
- ◆ Bob Brechting has successfully increased the testing speed of the bearing test rig from 2250 rpm to 7840 rpm with a concomitant increase in static load capability,
- ◆ Minhui He's program MAXBRG has been released in a beta version.
- ◆ Alexei Filatov's program ROTLOSS has been released as version 1.0

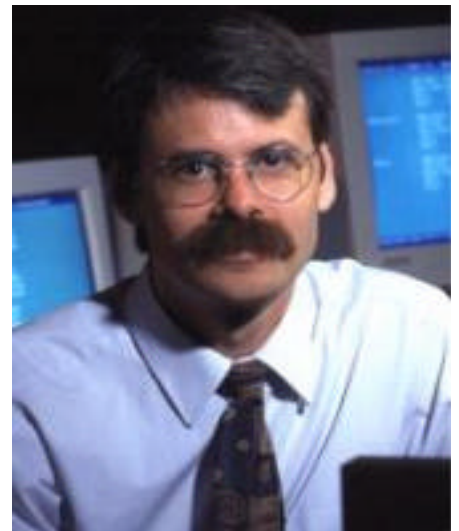
As we discussed at the annual meeting in San Diego, we have another dues increase this year to complete the phased increase to \$16,000. With this, we reach a sustainable funding level which should hold us for the next couple of years.

The 2002 annual meeting in San Diego at Humphrey's Half Moon Inn was well attended and a resounding success, both in terms of venue and content. We thank all of the industrial members who helped by providing excellent and provocative papers. If you were not able to attend, please see our web site (<http://www.virginia.edu/romac/>). If you go to the "Annual Meetings" link, you can view the schedule which provides links to the visual materials of most of the talks. We also especially thank Solar for their very gracious hospitality including a fascinating plant tour and a spectacular bay cruise aboard the company yacht.

A number of organizational issues arose at the San Diego meeting and I'd like to report on our progress. As you may know, there has been some difficulty in organizing completion of the improvements to RotorLab. These problems are nearly resolved as of press date and we hope to roll out the new version by next summer. This will include restructuring to permit more flexibility in evolving the solvers for the code as well as a number of valuable usability improvements pushed by ExxonMobil.

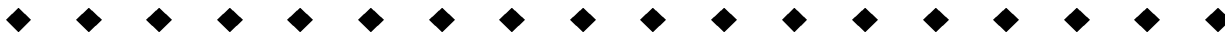
Another issue which came up was

the possibility of ROMAC operating an electronic bulletin board forum for exchange of ideas and tips on use and development of the ROMAC software. We auditioned a number of software packages and have identified a product with the right combination of cost and performance. This bulletin board is now functional and can



Dr. Eric Maslen  
Associate Professor of Mechanical and Aerospace Engineering and Director of ROMAC

be accessed through the ROMAC web site. Note that it's on the secure site so you have to log in using your company's ID and password. Please give us feedback on this new service!



# Message from the Director Cont.

Next year's annual meeting will be in Charlottesville at the Omni Hotel (as in 2001). Details of the site and the emerging schedule are provided in a short article on page fourteen of this newsletter. Plan now to attend and consider making a technical presentation, especially if you haven't done so in a while.

As always, we (the ROMAC faculty) solicit your comments on our program and hope that you'll share them either directly with the directing faculty member or with me. We look forward to seeing you next June in Charlottesville.

## Rotordynamics

### Rotating Machinery Stability Test Rig

Student: C. Hunter Cloud

Advisors: Lloyd Barrett, Eric Maslen

Project Start Date: January 1990

Sponsor: ExxonMobil

#### *Project Objectives:*

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 phe-

nomena such as unbalance influence the actual stability levels and thresholds versus modeling predictions

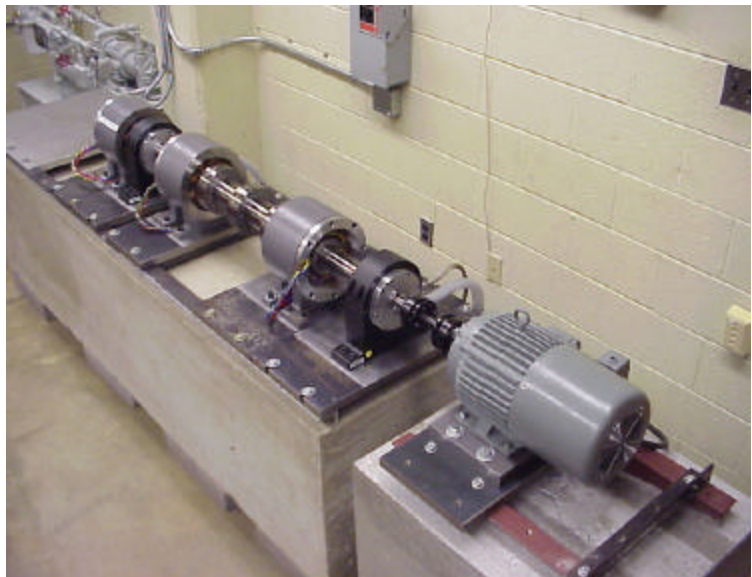
To investigate these issues, a test rig is being constructed which will simulate the dynamic behavior of many types of turbomachinery such as pumps, compressors and steam turbines. Magnetic actuators will supply excitations in the form of destabilizing cross-coupled stiffness and non-synchronous forcing (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.

#### *Progress in the Past Year:*



Test rig is 99% mechanically complete. Current efforts are focused on instrumentation as well as actuator cross-coupling and excitation control system development. Rotor and pedestal modal testing has been completed. Initial testing to begin by year-end.

Test rig is 99% mechanically complete!



# Rotordynamics Cont.

## API 617 Performance Standard Emulation through Mu analysis

Students: Jee-uk Chang, Chanjung Kim

Advisors: Eric Maslen, Tetsuya Iwasaki, Hyeong-Joon Ahn

Project Start Date: December 2000

### Project Objectives:

The rotordynamic performance of API 617 standards provide two primary requirements. First, the standard stipulates system damping near the expected operating speed range. This takes the form of a combination of damping requirements and separation margins, depending on where the system critical speeds lie relative to the operating range. (Separation margin requirement) Second, the standard requires a specific bound on worst case unbalance response at critical clearances. (Unbalance response requirement)

The problems this poses for machine designers are 1) feasibility: can bearings be designed for a given rotor to meet API 617 and 2) if so, how can these bearings be designed? This paper examines the feasibility problem. One possible approach to assessing feasibility would be to pick bearings, model the final machine (including bearing) and to assess the resulting API 617 compliance. The problem with this approach is that the choice of bearing dictates the outcome and it may be difficult to select an optimal bearing for API 617. Consequently,

failure of this test does not imply non-feasibility.

An alternative approach is to convert the API requirements to an optimization cost function. With this approach, it is not necessary to pre-design or pre-select the bearings: we can determine directly whether a bearing set exists that satisfies the cost function. In this case, feasibility won't imply that a given type of bearing (fluid film, rolling element, ...) can meet the API standard, but it does imply that the requirement can be met through some mechanism (perhaps a magnetic bearing). Therefore, our primary effort in this research is to convert the API requirements to an optimization cost function for a bearing design. This permits direct assessment of

"An alternative approach is to convert the API requirements to an optimization cost function."

the feasible design problem as well as providing a means to synthesize optimal bearing dynamics. In addition to providing synthesis of magnetic bearings, the resulting bearing transfer functions give direct guidance to selection of more conventional fluid film or rolling element bearings.

### Progress in the past year:

Although the unbalance response requirement can easily be converted into a formal H-infinity performance measure, the separation margin requirement is not analytic so it is not easy to directly formulate this requirement as a linear system analysis problem. We found from the last year's research that the separation margin requirement is essentially a pole placement problem: relatively large damping within the operating range. This pole placement problem can be approximated as a robust stability problem with frequency shaped uncertain modal damping. Since the unbalance response requirement can already be expressed as an H-infinity problem, the two API 617 requirements can be cast as a single mu-analysis problem. However, this approach can be applied only to the controller synthesis of AMB with a heuristic way due to the restriction of the modal transformation. Now, we are seeking a more general cost function for the separation margin and trying to synthesize AMB controllers with frequency shaped uncertain modal damping to try to automatically (and optimally) satisfy API 617.



# Rotordynamics Cont.

## Advanced Balancing Methods for Rotors

Student: Costin D. Untaroiu and Guoxin Li  
Advisor: Paul Allaire  
Project Start Date: January 2001  
Industrial Contact: William Foiles

### *Project Objectives:*

The conventional influence coefficient balancing method has some difficulties in application because in many cases the calculated correction weights may have excessive magnitude or can't be applied in the location of the balance planes (this may

be due to a large amount of correction weights from previous balancing or thread fault of balancing plane holes). Also in many cases for residual vibrations, we need to limit the level at some locations and to minimize their level at the critical locations (for instance the seal locations). The objective of this research is to develop a new generalized approach to rotor balancing using the influence coefficient method with an LMI optimization technique.

### *Progress in the Past Year:*

An optimization algorithm that theoretically minimizes the level of vibra-

tion at some critical locations was developed. Residual vibration in 2-norm or infinity norm as well as the correction weights bound were formulated as the constraints of semi-definite programming. An initial development in Matlab provided a code that solves the LMI optimization problem. The code was tested in several numerical examples. A generalized C code is being developed to provide a user friendly interface and computational efficiency. The code will be verified both numerically and experimentally. Many industrial members are interested in the results.



## Model Reconciliation

Student: Qingyu (Flofish) Wang  
Advisor: Eric Maslen  
Project Start Date: January 2000 (1995)  
Report Numbers: 432, 444

### *Project Objectives:*

Model reconciliation is a technique which improves analytical models by modifying existing engineering models to make them match experimental data. It is proposed that models of real systems can be composed of a high confidence nominal model combined with certain unknown dynamic mechanisms acting at specific locations. The objective of the reconciliation process is to identify the transfer functions of the unknown dynamic mechanisms. Because there always exist some uncertainties in

the model and the data, this effect should be considered in the reconciliation process. The product of this research should be software tools that allow engineers to meld existing models with available experimental data to produce an enhanced model that more accurately describes real hardware. Interestingly, this also serves as a valuable paradigm for analysis of test results in test apparatus, particularly for identification of bearing and seal properties.

### *Progress in the Past Year:*

In the past year, we have derived some theories for the reconciliation and performed a series of simulations. In contrast to common updating methods, which improve the quality of models through direct modification of existing M, C, and K matrices, our method requires far fewer sensors and provides signifi-

cant numerical advantages. It also permits detection of effects that materially increase the system order, such as substructure effects, which are not well handled by other updating methods. One of the limitations of our method is that we need very good engineering models. While most of the models have some uncertainties, we have to consider uncertainty models in the reconciliation process. This year, we introduced robust control synthesis methods into the reconciliation process. A MATLAB code for accomplishing the reconciliation is completed and will be used as a prototype for later development of hard coded solutions that will be accessible to ROMAC members. Numerical experiments with simulated data show good results. We will soon have data from Hunter Cloud's stability test rig with which to test and develop this method.

# Flywheels

## Passive Electrodynamic Magnetic Bearings for Flywheels

Project start date: September 2000

Students: Alexei Filatov

Report: #481

Advisor: Eric Maslen

### *Project Objectives:*

Using electromagnetic forces to suspend rotating objects (rotors) without mechanical contact is often an appealing technical solution. However, in real life, magnetic suspensions have to satisfy many engineering performance requirements beyond the simple compensation for the rotor weight. These typically include adequate load capacity and stiffness, low rotational loss, low price, high reliability, and manufacturability. With recent advances in permanent-magnet materials, the magnitudes of the required forces can often be obtained by simply using the interaction between permanent magnets. While a magnetic bearing based entirely on permanent magnets could be expected to be inexpensive, reliable and easy to manufacture, a fundamental physical principle known as Earnshaw's theorem maintains that this type of suspension cannot be statically stable. Therefore, some other physical mechanisms must be included.

One such mechanism employs the interaction between a conductor and a non-uniform magnetic field in relative motion. Its advantages include simplicity, reliability, wide range of operating temperature and system autonomy (no external wiring and power supplies are required). The disadvantages of the earlier embodi-

ments were high rotational loss, and low stiffness and load capacity. It was realized, however, that rotational loss, load capacity and stiffness depend strongly on the topology of the conductors and the magnetic fields.

In theory, the rotational loss in the equilibrium position in the absence of external loading can be made zero by designing a system such that no electric field develops in the conductor during the rotor rotation. In our work, we introduced the term "Null-E" to describe this condition. In the earlier embodiments, the Null-E condition could not be satisfied exactly.

Load capacity and stiffness can be maximized also through choosing shapes of the conductors and the fields. From this point of view the field and the conductor shapes used in the so called Null-Flux Bearings were found to be advantageous: the conductors were shaped as planar loops with central openings and the fields were orthogonal to the loop planes and periodic in the direction of the conductor motion.

To reduce rotational losses an additional restriction was imposed on the field shape (i.e., the "Null-Flux" condition): the flux variation within each loop had to be zero at equilibrium. This condition lowered the average value of the electric field in the conductor, but the topology did not allow making it zero everywhere. The satisfaction of the "Null-Flux" condition was extremely sensitive to manufacturing inaccuracies.

We proposed a novel type of magnetic bearing stabilized by the field-

conductor interaction. In contrast to the other bearings based on this principle, the proposed design allows exact satisfaction of the Null-E condition in the equilibrium regardless of the conductor shapes and even in the presence of an axial loading. Because of this, we refer to it as the Null-E Bearing. Null-E Bearings also have potential for higher load capacity and stiffness than Null-Flux Bearings. Finally, their performance is highly insensitive to the manufacturing inaccuracies.

The Null-E Bearing in its basic form can be augmented with supplementary electronics to improve its performance. The power rating of the electronics in this case can be much lower than in conventional active magnetic bearings. Depending on the degree of the electronics involvement, a variety of magnetic bearings can be developed ranging from a completely passive to an active magnetic bearing of a novel type.

Our report contains theoretical analysis of the Null-E Bearing operation, including derivation of the stability conditions and estimation of some of the rotational losses. The validity of the theoretical conclusions has been demonstrated by building and testing a prototype in which non-contact suspension of a 3.2-kg rotor is achieved at spin speeds above ~18 Hz.

### *Progress in the past year:*

The work has been completed, resulting in Alexei Filatov's successfully defended PhD dissertation. The dissertation was made into ROMAC Report Number 481.

# Magnetic Bearings

## Magnetic Bearing Finite Element Loss Computer Program

Student: Robert Rockwell

Advisor: Paul Allaire

### Project Objective:

A 3-D finite element computer code is under development for magnetic bearing configurations. It includes

the effect of the moving magnetic material in the rotor to evaluate the eddy currents generated in the rotor and the power losses. It will be capable of modeling both heteropolar and homopolar bearings. Eddy current losses in laminated rotors are modeled using an analytical solution for the magnetic vector potential in the

rotor. This analytical solution will be coupled to the finite element solution in the rotor to allow for a full solution of the eddy currents in each lamination.



## Real Time Control of High Speed Magnetic Bearing Systems

Students: Bin Huang, Guoxin Li

Advisors: Paul Allaire, Zongli Lin

### Project Objective:

Computer control of magnetic

bearing systems requires high speed real time control. The computer system must have high throughput rates that should be modular in nature. Newer and faster computers are continually coming online and other components such as A/D and D/A devices are improving as well. A methodology is being developed for implementation of high speed

magnetic bearing real time controls using Unix based systems which can include new, more advanced hardware as it comes along while only a minimum of software changes need to be made in the system.



## Rotating Losses in Magnetic Bearing Journals, Including Hysteresis Effects

Project start date: August 2001

Students: Alexei Filatov

Report: #480

Advisor: Eric Maslen

### Project Objectives:

Program ROTLOSS is aimed at predicting the iron losses in a rotating magnetic bearing journal. It includes the effects of eddy current production and hysteresis. It does not include windage losses as would occur if the bearing is not run in a vacuum: shear

losses will occur in the boundary layer between the rotating journal and the surrounding gas or fluid. The analysis assumes that the magnetic field distribution is identical in each lamination of the journal stack, but allows the field to vary across the thickness of each lamination. Further, it models the stator as a fixed distribution of potential: no analysis of the field distribution in the stator or of field distortion at the poles is carried out. These assumptions permit a very quick analysis whose accuracy is consistent with the likely accuracy of the parameters of the constitutive model. Experimental results are presented which tend to

corroborate the analysis.

### Progress in the past year:

The work has been completed, adapting an earlier analysis code written by David Meeker to now include approximate hysteresis effects. Released as program ROTLOSS, the manual is ROMAC Report #480. The code is compatible with the ROMAC GUI (shell) and has supporting editing scripts for both English and SI units.

# Magnetic Bearings Cont.

## Performance Limitations and Self-Sensing Magnetic Bearings

Student: Dominick Montie  
Advisors: Eric Maslen and Tetsuya Iwasaki  
Project Start Date: Fall, 1993  
Report Numbers: 387, 397, 414 (We will produce a ROMAC report of the dissertation on this research in January, 2003.)  
Project web site: <http://www.people.virginia.edu/~dtm7e/research.html>

*Project Objectives:*  
The experimental objective of this research has been to develop a high-performance method of rotor position estimation using the magnetic actuator itself, without the use of discrete position sensors. The primary benefits of this technology are increased reliability and decreased space requirements. Increased reliability is achieved by reduced wire and part count in the bearing environment, as well as incorporation with actuator fault tolerance. Decreased space requirements (primarily axial rotor length) result from eliminating the necessary rotor sections used as posi-

tion sensor targets. This has the added benefit of reducing rotor flexibility and the control effort and complexity needed to compensate for these dynamics.

The theoretical objective of this research has been to address perceived performance limitations of strongly periodic systems when analyzed with linear, time-invariant (LTI) models. Specifically, the structurally important periodicities of a certain class of systems may be used to provide an alternative input-output signal path to the one derived from an LTI model. This new relationship can be shown to have drastically better robustness properties than its time-invariant counterpart. Traditionally, self-sensing magnetic bearings suffer from poor robustness due to inherent structural properties. Such performance limits, however, are a result of implementing an estimation scheme that closely matches LTI system theory techniques. Using the inherent periodicities of the system, such theoretical and actual limitations have been shown to be substantially reduced.

### *Progress in the Past Year:*

Using recent developments in the literature for the analysis of linear periodic systems, we have demonstrated the improvement in a specific measure of performance that is commonly used in LTI system analysis. This is relevant to a self-sensing magnetic bearing when it is described by a linear periodic (LP) model; when modeled as an LTI system, it apparently suffers from fundamental performance limitations. In our research, we propose that a typical magnetic bearing should be modeled as an LP system, and as such can achieve better performance than commonly believed. Furthermore, we identify a system parameter that has a direct influence on the level of performance enhancement desired and the trade-offs associated with it.



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research.html](http://www.people.virginia.edu/~dtm7e/research.html)

## Chatter Control with Active Magnetic Bearing

Student: Min Chen  
Advisor: Carl R. Knopse  
Project Start Date: September 1999

*Project Objectives:*  
Increasing the metal removal rate in machining has been continuously gaining interest in manufacturing industries. A high metal removal rate

requires high machining speed and a large depth of cut. Active magnetic bearings provide a solution for this kind of high-speed machining. However, due to the onset of chatter, large depth-of-cut may be difficult to achieve. The aim of this research is to develop controller techniques for active magnetic bearings to achieve a large depth of cut and be free of chatter at high speed.

*Progress in the Past Year:*  
Work in the past year has focused mainly on the identification of cutting dynamics and on controller design. We conducted a series of cutting experiments on the lathe with our test rig and investigated the relationship between the cutting force and different cutting conditions (depth of cut, spindle speed, dimension of the workpiece, etc.). The results verify that the cutting process is

# Magnetic Bearings Cont.

a delay system where the delay constant is the spindle rotating period. We also deduced a formula for the stiffness and damping in the cutting process from the experimental results. In order to overcome the speed limit of the lathe, we designed a multi-tooth cutting tool that can be used to simulate the dynamics in higher speed cutting. Cutting experiments with the multi-tooth tool will be conducted soon.

For the controller design, we upgraded our calibration method so that we can calibrate the magnetic bearing in a wider operating region. A

look-up table and a carefully-tuned feedback linearization scheme have been used to compensate the nonlinearity of the magnetic bearing. As a result, we can use a linear model for the nonlinear actuator with only 5% over the entire operating region. Experimental results show that  $\mu$ -synthesis can provide controllers with significantly better performance under this improved feedback linearization scheme.

Other improvements on the test rig were also made in the past year. We modified and extended the bandwidth of the power amplifiers and the

anti-aliasing filter; built an optical isolator circuit and shielded the digital controller to reduce noise and applied new start and switch schemes to inhibit large, undesirable transients during power-on/off and controller algorithm swapping.

The aim of this research is to develop controller techniques for active magnetic bearings to achieve a large dept of cut and be free of chatter at high speed.

## Control of Non-laminated Magnetic Levitation Systems

Student: Lei Zhu  
Advisor: Carl Knospe

### Project Objectives:

The objectives of this project are to develop control algorithms that provide stiff, high servo bandwidth, magnetic suspension for systems with non-laminated actuators, and to quantify the performance limitations for these systems.

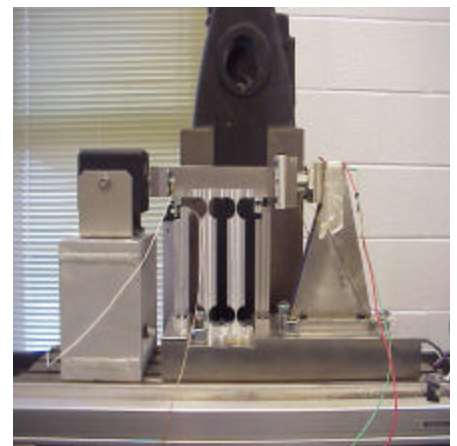
### Progress in the Past Year:

A carefully designed test rig has been built. It is a single-degree-of-freedom (SDF) system, which includes an iron beam; a compliant aluminum flexure supporting the beam; an electrodynamic shaker connected to the beam on one end; a magnetic actuator, whose flotor is attached to the other end, and whose cylindrical stator facing the flotor is fixed on a

supporting base. The stiffness of the SDF system has been measured. Tests done on the shaker show that it is a linear actuator with a bandwidth higher than 600Hz. Necessary sensors such as an accelerometer, displacement sensor, hall probe, and current sensors, have been calibrated and are ready to use as needed. A few circuits have also been built to improve the data acquisition process. Our main effort now is focussed on the testing of the non-laminated magnetic actuator that is machined from a solid piece of Carpenter's Hiperm 49, a magnetic alloy with very low hysteresis and high permeability. Static properties of the magnetic actuator have been tested in experiments. Static finite element analysis has also been carried out and produces results matching the experimental results very well. Dynamic properties of the magnetic actuator have also been carefully tested. Here, the experimental results show very clearly the effects of eddy currents.

Finite element analysis, however, differs strongly from experimental data. Further investigation on this point has now begun.

A few theoretical results have been derived for the performance limits of non-laminated magnetic levitation systems, which can be well presented as linear fractional order systems. The results show a general bound for fractional order systems with unstable poles, and have some useful controller design implications.



ROMAC

# Magnetic Bearings Cont.

## Control of High Speed Gyroscopic Rotors with AMBs

Student: Guoxin Li  
Advisor: Paul Allaire, Zongli Lin  
Project Start Data: January 2000

### *Project Objectives:*

For some rotors, such as flywheel rotors, gyroscopic effects are significant due to the high polar-inertia to bending-inertia ratio 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, the dynamics of the rotor vary with the operating speed, and a single linear time invariant controller often cannot stabilize the system over the entire operating range. Second, high robustness is required to handle the uncertainty of the rotating system. Additionally, gyroscopic effects couple the two radial directions and the natural frequencies are split into forward and backward modes. Advanced multi-variable robust optimal controls, H and  $\mu$ -synthesis, provide systematic

tools to achieve system robustness. To address the speed dependent dynamics, two approaches are being investigated: the piecewise  $\mu$ -synthesis and the gain scheduled control, in particular, the linear parameter varying (LPV) approach. In piecewise  $\mu$ -synthesis design the operating speed range is divided into several regions. Each controller is designed to cover a certain speed range where the gyroscopic effects are treated as uncertainties. 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. In the LPV design the gain scheduling problem is formulated in the context of convex semidefinite programming by linear matrix inequalities (LMIs). The LPV controller is obtained by solving the LMIs using interior point methods.

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 the AMB system under a MIMO controller was analyzed.

### *Progress in the Past Year:*

The piecewise  $\mu$ -synthesis controller was successfully implemented. The test rig spun to 17,000 rpm passing several substructure modes and the first bending critical speed of the rotor. The switching between controllers over a wide speed range (up to 12,000 rpm) is very smooth. Several LPV controllers were developed. The LPV controllers are being tested at a constant speed. Several different gain schedule approaches are being investigated to further reduce the conservatism of the current design. An LPV model reduction and controller reduction method was developed. Efficient real time control algorithms are being developed to implement the gain scheduled controller over a wide speed range. The performance of the piecewise  $\mu$ -synthesis and the gain scheduled design is being compared.

# Bearings and Seals

## Labyrinth Gas Seal Code/Program Development

Student: Jie Zhou  
Advisors: Paul Allaire, Ron Flack  
Project Start Date: Sep. 2000

### *Project Objectives:*

Develop a new gas labyrinth seal analysis program named LABY4, which will replace the current code LABY3, which gives out a decent

result for cross damping, but is not so good at other dynamic coefficients. The key approach is to use more control volumes to a better representation of the stress force and velocity of the flow field in the seals. The 3-D CFD code Tascflow, by AEA, will be used to get a better boundary condition description for each of the laby configurations.

### *Progress in the Past Year:*

Some experimental results available in the literature have been simulated with full 3-D computational modeling to achieve a better understanding of the flow details. Some results of the inlet pressure loss and exit pressure recovery coefficients were obtained. A new fluid flow equation set is under development using the best features of several existing modeling methods for laby seals.

# Bearings and Seals Cont.

## Fluid Film Bearing Test Rig

Student- Bob Brechting  
Advisors- Ron Flack and Lloyd Barrett

Over the past year significant advances have been made on the ROMAC fluid film bearing test rig. First, previous static and dynamic tilting pad bearing testing as a function of load angle has concluded and the results are presented in ROMAC Report #472, "Load Direction Effects on Measured Static and Dynamic Operating Characteristics of Tilting Pad Journal Bearings". Secondly, the ongoing redesign work and updating of hardware and sensors has led to an increase in maximum testing speed, from 2250 rpm to 7840 rpm. Along with the increase in speed came an increase in the maximum static load that can be applied to the test bearing.

### Load Angle Testing

Load angle testing of a five-pad tilting pad journal bearing with rocker back pivots and a preload of 0.314 has concluded. Testing consisted of measuring static position as well as dynamic coefficients at the two common design load angles, load on and load between pads, as well as at various points in between. Updates to

various testing procedures such as revision of the axial alignment method, the elimination of the horizontal load system, sensor upgrades and the rotation of the bearing as opposed to the load vector led to significant reductions in measurement uncertainty as well as increasing the accuracy and repeatability of the measurements. It was noted that maximum cross coupling occurred at load angles other than load on or load between pads. Also, the dynamic coefficients showed more dependence on the load angle at lower Sommerfeld numbers. A rigid rotor stability analysis was done to see the effects of load angle on overall bearing stability. The calculated rigid rotor threshold speeds were found to be infinite for all load angles and load cases that were tested, showing that the rigid rotor stability was not compromised by varying the load angle for the bearing tested.

### High Speed Testing Effort

After the load angle testing was concluded the test rig was updated to run at higher journal speeds. Updates included: overhaul of the lubrication system to handle up to ten gallons per minute, sensor and load cell updates, replacement of journal support

bearings with high precision higher speed ball bearings and the revision of various data acquisition codes.

An investigation into the effects of pivot mechanism on the measured cross coupling in tilting pad journal bearings is currently under way. Initial static and dynamic testing of a five-pad tilting pad journal bearing with ball and socket pivots and a preload of 0.337 has concluded. Journal speeds of up to 7840 rpm and static loads of up to 1000 lbs have been obtained for static testing. Dynamic testing has currently gone as high as 4900 rpm with maximum loads of 300 lbs. Results will be available this winter in Bob's Masters thesis.

Current work consists of dynamic testing at journal speeds up to 7840 rpm and defining the new rig limitations. Future testing efforts will focus on the static and dynamic testing of the tilting pad bearings for the new rotor dynamic stability test rig. Different pivots types and preloads will be tested under a range of load and speeds.

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

Student: Minhui He  
Advisors: Paul Allaire, Lloyd Barrett, John Nicholas  
Project Start Date: September 1996  
Report Number: 458

### Project Objective:

Develop a new finite element bearing code to accurately model fluid film journal bearings. The computer code MAXBRG utilizes the state-of-art TEHD theories and numerical methods. It can be used to analyze conventional fixed geometry and tilting pad bearings, Leading Edge Groove

(LEG) and spray bar tilting pad bearings, and pressure dam bearings. The bearings can be analyzed under flooded or starved oil feed condition. Or it may have axial flow and high ambient pressure.

### Progress in the Past Year:

Major progress was made in the past

# Bearings and Seals Cont.

year. A beta version was presented at the Annual Meeting in San Diego and released shortly after. The code successfully calculates the conventional fixed geometry and tilting pad bearings with thermal and elastic effects. Turbulence is automatically handled during computation. A new two-dimensional generalized energy equation was derived and applied to model axial flow and high ambient pressure applications. Two oil feed models were developed to simulate

the inlet oil starvation. A coupled film-pad approach is used in temperature calculation to improve numerical robustness. Leading Edge Groove (LEG) bearings are modeled by triggered turbulence while a special mixing model is employed for the spray bar bearing. For conventional bearings, the numerical results have been extensively verified by published experimental data with good agreement. For the LEG bearing, preliminary comparison showed

very good agreement. The pressure dam bearing is currently under investigation.

### Future work:

Finish the work on pressure dam bearing modeling. Verify the code for all bearings and operating conditions. Include the suggestions from ROMAC members. Write a user's manual. The final version will be released in January 2003.

## Fluid Flows

### High-Speed Compressor Facility

Students: Nathan Brown, Eric Buskirk  
Faculty Advisors: Eric Maslen, Ron Flack

#### Project Overview:

The initial objective of this work is to construct a test bed with which we can experimentally determine aerodynamic impeller loading for on and off design flow conditions to validate or improve existing computational predictions. A later objective is to develop an active surge control algorithm that is applicable to industrial-scale centrifugal compressors.

Both of these objectives will be real-

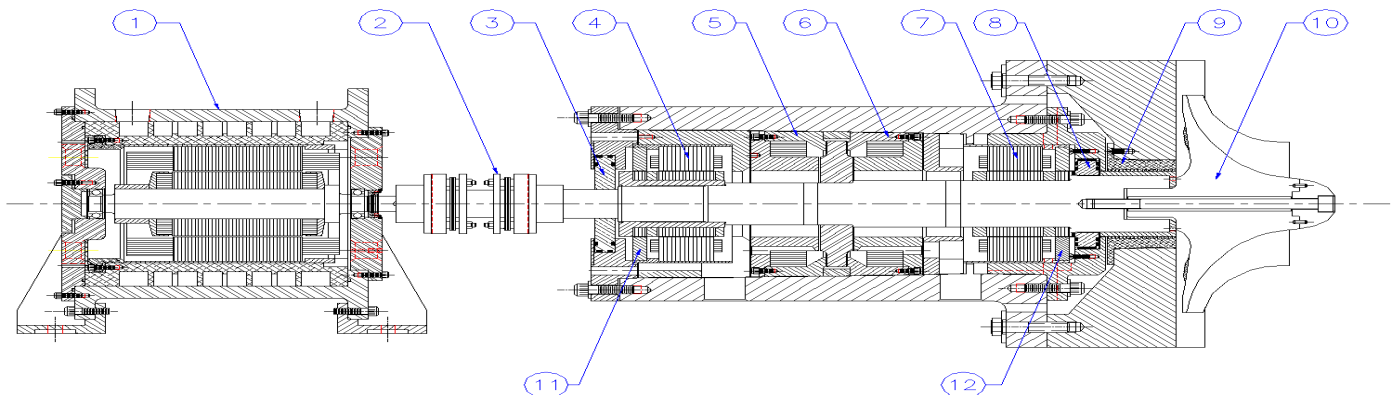
ized by the high-speed centrifugal compressor rig currently under development, which employs an active magnetic bearing (AMB) system to support the rotor in five degrees of freedom. The active nature of the AMB system makes possible the real-time static and dynamic positioning of the rotor shaft, which allows for straightforward modulation of the impeller tip clearance (please see "Surge Stabilization in Centrifugal Compressors"). The AMBs also allow for the direct calculation of the rotor reaction forces from which the static and dynamic impeller force may be determined. The force measurement uncertainty will be further decreased by using an array of Hall Effect sensors to measure the air gap

flux density distributions within the radial and axial AMBs.

#### Progress in the last year:

Kobe Steel has kindly agreed to provide us with a custom designed aero section, which is rated for 52kW gas power at 23,000 RPM. The magnetic bearings, test spindle, and bearing housing to be used with this compressor have been designed and submitted for manufacture. The motor drive has been designed, manufactured, and tested to 25,000 RPM.

FIGURE 1: Test facility layout: 1-Motor Drive, 2-Coupling, 3,8-Auxiliary Bushings, 4,7-Radial AMBs, 5,6-Axial AMB, 9-Scroll Seal, 10-Impeller, 11,12-Radial Sensors (Not shown are compressor housing, pedestal base, and axial sensors)



# Fluid Flows Cont.

## Surge Stabilization in Centrifugal Compressors

Student: Dorsa Sanadgol  
Advisors: Eric Maslen and Hyeong-Joon Ahn  
Project Start Date: Fall, 2001  
Report Numbers: none so far  
Project web site: none so far

### Project Objectives:

The useful range of operation in turbo compressors is usually limited at low mass flow rates by the onset of surge. Magnetic bearings offer the potential for active control of flow instabilities. This capability is highly dependent on the sensitivity of the compressor characteristics to blade tip clearance. If the position of the shaft can be actuated with sufficient authority and speed, the induced pressure modulation makes control of surge possible. Use of axial motion in centrifugal compressors distinguishes this work from related studies which examined radial motion of axial compressors. The ability to modulate the mean tip clearance, rather than to induce a circumferentially periodic perturbation is a significant ad-

vantage of our work. Ultimately, the methods developed in this project will be tested on the centrifugal compressor test stand presently under development at ROMAC.

### Progress in the past year:

A theoretical model describing the sensitivity of centrifugal compressor parameters to tip clearance variations induced by axial motion of the rotor has been established, and a one dimensional incompressible flow model including the effects of tip clearance variation on the compressor characteristic has been derived based on available measured effects of tip clearance on compressor efficiency. Having an unshrouded impeller, generally enhances this sensitivity. With this model in hand, a new feasible control algorithm has been developed which is capable of substantially mitigating flow instabilities using a magnetic thrust bearing as the servo actuator. To do this, a proper Lyapunov function for feedback control was defined and a stability condition for mass flow feedback gain was derived. In addition, tip clearance offset has been integrated in the control in order

to ensure zero steady state offset so as to maintain the efficiency of the compressor. The axial position servo loop is modeled a priori as a third order Butterworth filter to reflect reasonably achievable performance of this subsystem.

Results from simulation of the nonlinear model on a single stage high speed centrifugal compressor show that mass flow and pressure oscillations associated with compressor surge can be quickly suppressed and the stable operating range of the compressor can be increased significantly. Actuator slew rate and load capacity requirements appear to be well within the typical capacities of such systems. This highlights the principal advantage of the proposed approach over conventional surge control methods: in machines already equipped with magnetic bearings, the stable operating range can be extended by simply modifying the thrust bearing control algorithm, dispensing with the need to introduce additional hardware.

# Artificial Heart Pump.

## Artificial Heart Pump Project

Students: Costin Untaroiu, Yi Wu, Yinjie Liu  
Advisors: Paul Allaire, Houston Wood, Zongli Lin  
Post Doctoral Fellows: Xinwei Song, Wei Jiang, Tingshu Hu

### Progress in the past year:

The magnetic bearing supported artificial heart project has started on a new axial flow pump which is approximately 1.5 inches in diameter and 4 inches long. It is intended to be implanted in humans as

a cardiac assist device. This project is sponsored by the National Institute of Health with a \$4,200,000 grant and is carried out jointly with the Artificial Heart Lab of the University of Utah and RK Engineering



## Physiologic Control of the Artificial Heart Pump

Students: Yi Wu,  
Advisors: Paul Allaire, Milton Adams, Gang Tao

### Progress in the Past year:

It is necessary to adjust the speed of the artificial heart motor to match the physi-

ologic needs of the human body. Typical activities are 1) sleeping or resting, 2) sitting or other moderate activity, and 3) stair climbing or other highly active needs. The adjustment of the motor speed to these activity levels should be carried out automatically, without patient intervention. A model of the human cir-

culatory system, the artificial heart and a physiologic controller has been developed and is being improved. It has been found that the controller developed so far can effectively control motor speed under certain conditions.



# Recent Laboratory Equipment Acquisitions

ROMAC participates in the commonwealth of Virginia's Equipment Trust Fund (ETF) Program, wherein the University is granted matching funds by the State, towards the purchase of new laboratory equipment for use in its teaching and research missions. This is one particular method in which ROMAC funding gets leveraged relative to our laboratory needs. The fund matching from the state is typically one-for-one, thus making it possible, in essence, to purchase new equipment at the equivalent of "half-price" to ROMAC. This past year, we have purchased through the ETF a vibratory shaker for calibrating our various accelerometers. This device is a PCB Piezotronics model 394CO6 unit that can be used with the accelerometer heads of up to 210 grams, which covers virtually all of our instrumentation.

Requests for ETF recommendations are solicited early each Summer, and the School of Engineering's total request is considered by the state in the following Fall. A list of approved equipment is subsequently provided to each of the Department Chairs, and purchase requisitions

are then placed near the end of the calendar year. Although this is a long lead-time process, the significant financial benefit to ROMAC and its member companies makes it all very worthwhile. Individual items of capital equipment are also purchased directly on an individual basis by ROMAC during the academic year, on an "as needed" basis. On a related note, we have just completed a renovation of several pieces of test and measurement equipment, including general purpose amplifiers and power supplies, to be sure that any apparatus used by the students is in good repair and has reliable calibration. An on-site service center in the UVA Physics Department has expert electronic technicians who assist us with these tasks. A depot/storeroom for our equipment is run by ROMAC Research Professor George Gillies.

Another mechanism for equipment acquisition is the donation of research hardware to our laboratories. Several of our member companies have provided us with test and measurement equipment, transducers and several other types of

instrumentation in the past. Long-term loans and gifts of equipment are very important to ROMAC Laboratories, and we encourage our members to consider this possibility when evaluating their own inventories of test and measurement hardware and software, which might contain surplus items that could be of use to us. Of particular use to us over the coming year would be Bently-Nevada Digital Vector Filters for use with our bearing test rig. Please contact George T. Gillies at (434) 924-6235 for further information.



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