Rotating Machinery and Controls Laboratory

ROMAC

Mechanical & Aerospace Engineering
University of Virginia

Special points of interest:

- MAXBRG Addresses LEG Bearings pg 4
- Compressor Facility Set to Spin in early Spring pg 5
- Chatter Control Proceeds to Cutting Experiments pg 8
- Rotor Stability Rig Nearly Complete pg 10

Inside this issue:

Message from the Director

Message from the Director
Eric Maslen

This edition of the ROMAC annual newsletter features a couple of especially exciting developments including the work done over the last few months by Minhui He and Paul Allaire on the new MAXBRG fluid film bearing code. They've developed new theory to explain the thermal performance of LEG tilting pad bearings which appears to reconcile predictions to measurements. After several years of disappointing progress, the compressor test facility work has gained substantial momentum. With many parts in fabrication, we expect a mid-spring rollout.

Probably the most important news to you as ROMAC members is that we have decided, after lengthy deliberation, that we must increase the annual ROMAC membership dues. The dues have been $14,000 per year since 1997. Since then, we've managed to maintain a constant fee level without a significant reduction in research activity by implementing a number of austerity measures. Now we've pretty much run out of viable austerity measures and are obliged to raise our fees or face substantial cash shortfalls.

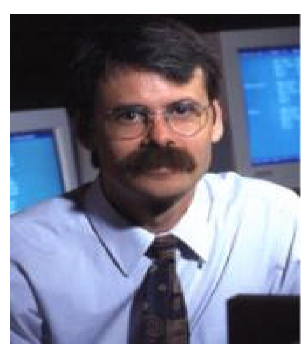
The actual fee increase requirement, based on projected membership and planned expenditures, is to $16,000 per year. However, we realize that this was not discussed at the annual meeting and therefore has not been part of your budgeting. Consequently, you'll see that we've elected to increase only to $15,000 for fiscal year 2002. We plan to introduce a second increase for fiscal year 2003, to bring us to the $16,000 that satisfies our budgetary projections. I trust that you'll agree that an average annual increase of only 2.2% is pretty modest!

Last year's annual meeting in Charlottesville at the Omni Hotel was well attended and seemed to be well received. 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'll continue this practice in future years and hope that it proves useful to our members.

Next year's annual meeting will be in San Diego, graciously hosted by Solar Turbines. Details of the site and schedule are provided in a short article on page eleven of this newsletter. Plan now to attend and consider making a technical presentation, especially if you haven't done it 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 San Diego.

As always, we (the ROMAC faculty) solicit



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

Energy Storage Flywheel Project-Mu Synthesis Control of Magnetic Bearing Supported Rotors-Low Loss Magnetic Bearings

Students: Guoxin Li, Edgar Hilton, Hai Zhang, Bin Huang, Bob Rockwell, Brian Overby, Yingjie Liu

Advisors: Paul Allaire, Zongli Lin, Kevin Skadron, Marty Humphrey

Progress in the Past Year:

Work continues on UVA's joint research project with AFS Trinity on a high speed energy storage flywheel supported in magnetic bearings. Recently we have developed a very detailed rotor and substructure model which allows us to design very high performance controllers for the magnetic bearings. The controller design uses mu-synthesis methods to account for the rotor stiffness and gyroscopic effects, active magnetic bearing properties, substructure modes, and uncertainties in the model. Control has been achieved up to an operating speed of 20,000 rpm in the test rig. The rotor gyroscopic terms vary with operating speed so they are taken into account using a bumpless transfer in the mid-speed range to switch controllers from a low speed one with gyroscopics in that low speed range to one where the gyroscopic effects are taken into account in the high speed ranges. The switching dynamics are held to less than a few mils by the bumpless transfer method. Work also continues on the development of low loss high speed magnetic bearings due to eddy current losses, hysteresis losses and others. Additional work continues on the development of real time controls using Linux for the magnetic bearing controls.

A Passive Magnetic Bearing for Flywheels

Student: Alexei Filatov

Advisor Eric Maslen

Project Start Date: March 2000

Project Objectives:

Develop a new type of magnetic bearings capable of non-contact supporting high-speed rotors without using external energy sources and external control systems. The expected advantages of the new bearing are high efficiency, reliability and low cost. One of the possible applications is in flywheel energy storage systems, which are considered to be an attractive alternative to electrochemical batteries due to higher stored energy density, higher life term, deterministic state of charge and ecological nature. While demand for reliable and inexpensive energy storage systems grew dramatically in the last few years because of rapid progress of computer systems, which require higher quality of energy supplies than can be provided by public electrical networks, the progress in development of flywheel energy storage systems was in large degree held by the lack of reliable, efficient and inexpensive high-speed bearings.

Progress in the Past Year:

We have measured rotational energy loss in the bearing prototype. As reported in the previous issue of the ROMAC newsletter, this prototype allows non-contact suspension of a 3-kg rotor when the rotor rotates above a critical speed of approximately 1200 RPM. The major part of the loss was found to be due to air resistance. When run in a rough vacuum (0.75 mm of Mercury), the loss was reasonably low: 2.5 W at 3000-RPM rotational speed. Some data indicated that the remaining loss was caused by the eddy currents induced in the conducting bearing parts, primarily in the bulk aluminum housing. Further refinement of the design may result in further loss decrease.

On the theoretical front, the theory of the bearing operation was generalized to cover a broader spectrum of the rotor geometries. The major results of this work can be found in the following journal articles:

A.V. Filatov and E. H. Maslen "A Passive Magnetic Bearing for Fly-Wheel Energy Storage Systems", *IEEE Transactions on Magnetics*, Vol. 37, No. 6, November 2001

A.V. Filatov, E. H. Maslen and G.T. Gillies, "A Method of Non-Contact Suspension of Rotating Bodies using Electromagnetic Forces, *Journal of Applied Physics*, tentatively scheduled to appear in February 2002. The articles will be included in 2001-2002 Publications of ROMAC Members. This research will also be covered in the dissertation of A. V. Filatov, which is expected to be completed next summer and will be released as a ROMAC report.

Labyrinth Gas Seal Code/Program Development
Student: Jie Zhou
Advisor: Paul Allaire
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.

Fluid Film Bearing Test Rig
Student: Bob Brechting
Advisors: Ron Flack and
Lloyd Barrett
Progress in the Past Year:

Currently the research on the fluid film bearing test rig includes experimentally verifying the dynamic coefficient versus load angle measurements that were previously made for the 0.75 L/D, 0.3 preload, rocker back tilting-pad test bearing. The goal of this research is to explain the non-symmetric differences in dynamic coefficients that were measured between the on-pad loading of two adjacent pads. Modifications that have been done include the revising of the bearing axial alignment procedure, the recalibration and replacement of various sensors and the elimination of the horizontal load system. The gravitational sag of the horizontal load system has been found to induce a moment, which caused uncertainty in the angular orientation of the load vector. The various load angles are now being achieved by a rotation of the bearing as opposed to a rotation of the load vector. This testing will conclude shortly and then work will continue onto the next phase, which is to increase the testing speed.

Work is also currently being done to increase the maximum testing speed of the rig from 2250 rpm to a goal of 7000-10000 rpm. Preliminary tests on the rotor-drive system have yielded speeds of up to 8000 rpm. Also the data acquisition hardware and software are being revised and updated to increase the robustness of the rig's measurement capabilities at higher testing speeds. Initial tests will consist of static operating position and oil film heat generation, with the measurement of dynamic coefficients to follow. The first bearing to be tested will be the current rocker back test bearing, with the possibility of different bearing designs to follow.

Tilting Pad Journal Bearing Pivot Stiffness Study
Student: Gisela Vázquez
Advisor: Lloyd Barrett

This project centers on an evaluation of the effects of pivot stiffness in tilting pad journal bearings. The intent was to partially to examine the present status of THPAD that includes pivot stiffness effects, but requires the input of the individual pivot stiffness rather than an internal calculation of the stiffness for each pivot based on pivot material and geometry and the load carried by each pad. Implementation of an internal pivot stiffness calculation in THPAD introduces an additional level of iteration in the overall bearing solution calculations and an assessment of the pivot stiffness effects on overall tilting pad bearing stiffness and damping coefficients is prudent prior to making any additional modifications to THPAD. The study is an extension of work by J. C. Nicholas and by R. G. Kirk and S. W. Reedy.

The study also examines effects of various modeling strategies for tilting pads in series with the pivot for synchronous and nonsynchronous rotor dynamic analyses. A detailed report on the study will be released at the next ROMAC Annual Meeting. General conclusions are that the present implementation of pad pivot stiffness in THPAD is adequate for most analyses, provided a reasonable estimate of the pivot stiffness is made prior to running THPAD. This estimate can be made from the overall bearing load using pivot stiffness models given by the above cited researchers.

Finite Element Modeling of Fluid Film Journal Bearings Including Direct Lubrication and Special Flow Conditions (Computer Code MAXBRG)
Student: Minhui He
Advisor: Paul Allaire
Project Start Date: September 1996
Report Number: 458
Project Objectives:

Develop a new finite element bearing code to accurately model fluid film journal bearings, including the bearings with leading edge grooves and spray bars. The code will also model the bearings with axial flow and bearings with high ambient pressure.

Progress in the Past Year:

Major progress was made in the past year. Two beta versions of MAXBRG were released in July and September 2001. It successfully calculates the conventional fixed geometry and tilting pad bearings with thermal and elastic effects. Turbulence is automatically handled. A new 2-D generalized energy equation was derived and applied to model axial flow and high ambient pressure applications. A coupled approach is used in temperature calculation to improve the numerical robustness. For conventional bearings, the numerical results have been extensively verified by experimental data with good agreement. Leading edge groove (LEG) bearings are modeled as triggered turbulence. The preliminary verification showed good agreement with published test data. Spray bar bearings are currently under investigation.

Modifications to THRUST
T. Brockett and L. Barrett

ROMAC has undertaken a project to modify the fixed and tilting pad bearing program THRUST to include tilting circular pad geometries. An interim Beta version of the modified program was completed early this past summer and included the circular pad geometry. Several numerical issues arose that have led to additional modifications. These issues primarily focus on instabilities in the thermal calculations, so called convection diffusion oscillations common in these types of problems. Their appearance in circular pad modifications is mainly due to that geometry which makes it more difficult to determine the exact boundaries of the leading and trailing edges of the pad and to precisely determine the elemental flows. In the Beta version, the oscillations could be reduced substantially by using extremely fine mesh grids for the problem. However to run the program with these fine meshes requires very fast computers (1 gHz or faster) with large amounts of memory (>256 mb).

Although computers that meet these requirements are now routinely available, it was felt that additional modifications should be made. The modifications focus on an improved mesh algorithm for circular pad geometries and including an upwind differencing scheme for the energy equation. The improved mesh algorithm was first implemented and generates a mesh where the elements are more nearly "aligned" with the elemental flows that would be expected. This modification alone has substantially reduced the thermal oscillations. Following that an implementation of an upwind difference scheme based on earlier ROMAC work by Rita Schnipke for general CFD flow analysis was undertaken. At present some difficulties have arisen in the adaptation and implementation of this scheme.

The program is being currently released with the new mesh routine with an update to be released as soon as the upwind scheme difficulties are overcome. As noted above, the mesh modifications alone have reduced the thermal oscillations and the mesh sizes required, while still larger than we would like, are larger than required in the Beta version.

COMBUSTION

Active Control of Combustion Instability
Student: Les Snodgrass, Jr.
Advisor: Carl Knospe
Project Start: June 2000
Project Objective:

Combustion systems can exhibit strong, self -induced, pressure oscillations. These oscillations can lead to excessive noise levels, component fatigue, and premature system failure. The objective of this project is to understand the basic phenomena driving such oscillations in pre-mixed combustion systems, then to use this understanding to model the phenomenon. Finally, an active control scheme will be implemented to eliminate this instability on a laboratory combustor.

Progress in the Past Year:

The laboratory scale combustor constructed last year was fitted with a microphone and thermocouples to measure pressure and temperature. A digital data acquisition system was set up to analyze the instability in the combustor in real time. This data was used to construct a model of the combustor. Finally, mu -synthesis techniques were used in controller design. The ability to reduce the pressure oscillations in the system has been shown, but the instability has yet to be eliminated.

FLUID FLOWS

High –Speed Compressor Facility
Student: Nathan Brown
Advisors: Eric Maslen, Ron Flack
Project Objectives:

This program will develop a test compressor of commercially realistic size which is equipped with magnetic bearings capable of measuring bearing forces under a wide range of operating conditions. The test facility will be used to carry out two classes of experimental work. The first is focused on correlation of bearing loads in off-design operating conditions to computational predictions. The objective is to provide a well documented base of data at off-design point to use in validating and improving the computational prediction. A second class of work will focus on flow instabilities such as rotating stall and surge. The objective will be to determine sensitivity of such phenomena to controllable parameters of the compressor: primarily axial oscillation of the impeller. If successful, this study will lead to new control algorithms for active thrust bearings in centrifugal compressors capable of substantially mitigating these flow instabilities.

Progress made in the last year:

The high-speed drive motor has been completely redesigned and is currently being manufactured by Turbo Components Engineering. Significant design work has been done on the bearing housings and test spindle, which will be put out to bid shortly. Kobe Steel has graciously agreed to supply the first test impeller/volute pair, which are designed for open cycle air operation at power/speed levels compatible with our drive. Part of the design work over the past year has focused on compatibility of the test spindle, housing, and pedestal with the existing Kobe aero section components.

Plexiglas Pump
Student: Daniel Baun
Advisor: Ron Flack
Project Objective:

The Plexiglas pump apparatus was previously modified and magnetic bearings/load cells were installed which can directly measure the reaction loads at the bearing locations. Both average (static) and instantaneous (dynamic) force measurements can be made. All the bearings have been calibrated to establish their force versus air gap and coil current characteristics. In addition the uncertainties due to hysteresis and the frequency limitation of the bearings were determined. The complete control and instrumentation system (calibrated differential proximity probes, high output power amplifiers, analogue PID controllers, and data acquisition system) were installed and their functions verified.

The measured lateral impeller force characteristics and hydraulic performance characteristics were compared between a 4 and a 5 vane impeller each operating in a spiral volute, concentric volute and a double volute. The test rotor was supported in the magnetic bearings. In addition to supporting and controlling the rotor motion, the magnetic bearings also served as active load cells and were used to measure the forces acting on the pump rotor. The lateral impeller force characteristics as a function of normalized flow coefficient were virtually identical between the 4 and 5 vane impellers in each respective volute type. The measured impeller forces for each volute type were compared with correlations from the literature. The head versus flow characteristics of the 4 vane impeller in each volute type were stable over a greater flow range than the corresponding characteristics of the 5 vane impeller. At higher flow rates in the stable region of the head characteristic curves near the best efficiency point the 5 vane impeller produced higher head than the 4 vane impeller in each volute type.

CFD was used to predict the flow field in the pump. Multiple frame of reference simulations were conducted on a full pump model, a four vane impeller, a spiral volute and an axial inlet pipe, using water as the working fluid. The impeller angular position was systematically indexed relative to the volute to simulate the rotation of an impeller vane passage by the volute tongue. Relative tangential and meridional velocity profiles at the impeller exit and across the volute were reconstructed from the quasi-steady simulations and compared with directly measured profiles obtained from laser velocimetry. In addition, the impeller slip at the design flow was evaluated from the CFD results and compared with the slip obtained using laser velocimetry. Average pressure profiles around the impeller circumference and around the outer wall of the volute were reconstructed from the quasi-static CFD simulations and compared with measured profiles. The pump hydraulic characteristic was evaluated from the CFD and compared with the measured characteristic. The CFD model developed and validated.

Lateral impeller forces for both incompressible and compressible fluids were calculated using the CFD model developed above. The impeller forces are evaluated by integrating the pressure and momentum profiles at both the impeller inlet and exit planes. Direct impeller lateral force measurements were made using a magnetic bearing supported pump rotor. Comparisons between the simulated and measured forces are made for both average and transient impeller forces with water as the working fluid. Air was substituted as the working fluid in the validated CFD model and the affect of impeller Mach number and Reynolds number on the static impeller lateral forces was investigated. The non-dimensional lateral impeller force characteristics as a function of normalized flow coefficient are similar in character between the incompressible and compressible case. At the matching point flow coefficient the non-dimensional impeller force magnitude was the same for all compressible and incompressible simulations. For any normalized flow rate other than the matching point flow rate, the magnitude of the non-dimensional impeller force increased as the Mach number increased. As the choke condition was approached the magnitude of the impeller force increased exponentially. As the Mach number increased the transition of the force orientation vector from the low flow asymptote to the high flow asymptote occurred over a progressively smaller range of flows.

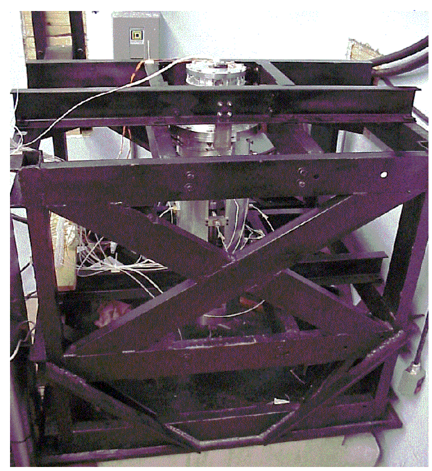
MAGNETIC BEARINGS

Control of Magnetic Bearing Supported Gyroscopic Rotors
Student: Guoxin Li
Advisor: Paul Allaire, Zongli Lin
Project Start Data: January 2000
Project Objectives:

For some rotors, such as flywheel rotors, gyroscopic terms play an important role due to the high polar inertia and bending inertia ratio as well as the high operating speeds. Control of a strong gyroscopic rotor over a wide speed range with magnetic bearings is a very challenging problem. Gyroscopic effects couple the two radial directions and the natural frequencies are split into forward and backward modes. The system becomes linear parameter varying (LPV). This project is focused on the application of μ-synthesis to the control of gyroscopic system. A piecewise μ-synthesis controller design is proposed to deal with the strong gyroscopic effects. A test rig was constructed as a platform for investigating of different controllers. First, an accurate nominal model including the substructure modes is developed from physical laws and fine tuned by experimental data. An uncertainty representation as well as performance criterion are developed for the model AMB system. The influence of gyroscopic effects on the stability and performance of AMB system under a generalized μ-synthesis controller is analyzed. Several controllers were designed, one for each speed region. The gyroscopic term is treated as uncertainties for each controller synthesis. The overall controller is implemented by switching between controllers as rotor speed varies from one region to another. A bumpless transfer scheme was very successfully implemented to obtain a smooth switching.

Progress in the Past Year:

Currently, several μ-synthesis controllers were successfully implemented. The test rig is spun up to 17,000 rpm passing several substructure modes and the first rotor bending critical speed. The switching between controllers over a wide speed range (up to 12,000 rpm) is very smooth.



Performance Limitations and Self-Sensing Magnetic Bearings
Student: Dominick Montie
Advisor: Eric Maslen
Project Start Date: Fall, 1993
Report Numbers: 387, 397, 414
Project Objectives:

The experimental objective of this research is 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 position 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 is to address perceived performance limitations of strongly nonlinear systems when analyzed with linearized models. Specifically, the structurally-important nonlinearities of a certain class of systems may be used to provide an alternative input-output signal path to path to the one derived from a linearized model. This new relationship can be shown to have drastically better robustness properties than its linearized counterpart. Traditionally, self-sensing magnetic bearings suffer from poor robustness due uncertainty in system parameters. Such performance limits, however, are a result of implementing an estimation scheme that closely matches linear system theory techniques. Using the inherent nonlinearities of the system, such theoretical and actual limitations can be substantially reduced. For more details, please refer to our project web site http://www.people.virginia.edu/~dtm7e/research.html.

Progress in the Past Year:

Our main theoretical progress has been on demonstrating, through simulation, the drastic reduction in the performance limitations for a self-sensing magnetic bearing. Further simulation work has been focused on exploring the effect of relative nonlinearity magnitude on overall system performance. Experimental progress has been limited primarily to decreasing the complexity of the position estimation electronics. By Summer, 2002, we plan to produce a ROMAC report of the dissertation on this research.

See our project web page (http://www.people.virginia.edu/~dtm7e/research.html

Control of Non-laminated Magnetic Levitation Systems
Student: Lei Zhu
Advisor: Dr. Carl Knospe
Project Objective:

Non-laminated actuators must be used in many applications of non-contacted magnetic levitation to manufacturing processes, due to the fact that in many cases, the levitated part will not be composed of laminations; and in some others, the geometry of the electromagnet is complex and a laminated construction can be very costly. The dynamics of non-laminated actuators is very complex and has profound consequences for the magnetic levitation's achievable dynamic stiffness and servo bandwidth. The development of a fundamental knowledge base regarding non-laminated actuator dynamics and their control is critically important to progress in the emerging technology of non-contact processing.

The source of these troublesome actuator dynamics is eddy current within the non-laminated actuator. Without laminations, a rapid change in current applied to the electromagnet coil will result in a much slower change in applied force due to the eddy currents induced within the actuator by the changing field. These dynamics have a fundamental impact on the stiffness and servo bandwidth which can be attained by a magnetic levitation and also impose fundamental limitations on performance that cannot be overcome by any control technique. Our ability to predict, identify, and model these actuator dynamics is critical to attaining high stiffness/servo bandwidth levitation and to understanding the limits to what we can accomplish.

Our main objectives are to develop control algorithms that provide stiff, high servo bandwidth, magnetic suspension for systems with non-laminated actuators, and the quantification of performance limits for these systems. The successful outcome of this research will enable non-laminated magnetic levitations that provide highly accurate positioning in spite of disturbance forces and reposition the levitated object quickly. Furthermore, this research will increase our understanding of the control problems involved and will bring into sharp focus the boundaries between what can and cannot be achieved. We hope that this research, funded by the National Science Foundation, will help define new opportunities in high performance magnetic levitation.

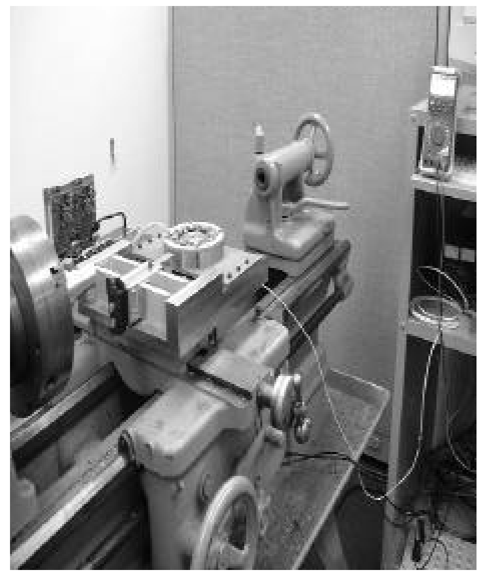
Chatter Control with Active Magnetic Bearing
Student: Min Chen
Advisor: Carl R. Knopse
Project Start Date: September 1999
Report Number: (none so far)
Project Objectives:

Chatter is a self-excited vibration which limits the maximum achievable metal removal rate in machining. The objective of this project is to develop control algorithms for the stabilization of chatter using active magnetic bearings as actuation. Such control should allow high metal removal rates free from chatter. Of particular interest is the development of controllers that are optimized for the cutting dynamics and that can be changed during operation as cutting conditions change. This research is sponsored by a grant from the National Science Foundation.

Progress in the Past Year:

Based on experimental data from the test rig that was constructed last year, a system model and its uncertainties were calculated. A static feedback linearization algorithm was applied to cancel the nonlinearity of the active magnetic bearing, so that the bearing linear operating region was significantly extended; this simplified controller design considerably as well. A series of μ-synthesis controllers have been developed and implemented on the test rig. Experimental results show that comparing to PID controllers, lower dynamical compliance of the cutting tool was achieved with the μ-controllers (greater dynamic tool stiffness). Cutting experiment results have verified that the μ-controller could suppress the onset of chatter.

Several cutting experiments were conducted to help understand the actual cutting dynamics. We found the lathe spindle speed was not invariant with different depth of cut due to the change of the loading. This, in turn, significantly complicates the identification of the cutting dynamics from experimental data. So a speed control loop was developed to regulate the spindle speed. This feedback loop consists of an optical sensor, a variable frequency device as the actuator, and a digital controller. Experiments show this feedback loop effectively regulates the spindle speed during cutting.



ROTORDYNAMICS

Advanced Balancing Methods for Rotors
Student: Costin D. Untaroiu
Advisor: Paul E. Allaire
Project Start Date: January 2001
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:

We have developed an optimization method that theoretically minimizes the level of vibration at some critical locations (or conditions) and verifies the mixed constraints (in 2-norm or infinity-norm) imposed at the level of the residual vibration and the amount of the correction weights in an LMI form. Using the Matlab LMI-Toolbox, we have realized a program which can obtain the optimal solution from a continuous domain of the correction weights and have tried successfully it on several numerical simulations and an experiment using AFS test rig. Now, we are working to an improve version of our program for finding an optimum solution for correction weights from an available discrete set of values of correction weights. Also we are trying to build a friendly interface between computer and user, and to translate our code in a widespread programming language.

Dynamic Analysis of Rotor with Gyroscopic Effects
Student: Tetsu Konishi
Advisor: Paul Allaire
Project Start Date: March 2001
Project Objective:

The objectives of this research are to develop an efficient code using modal analysis for the analysis of a large turbine-generator system with foundation and gyroscopic effects and model optimum designs for the system.

There is a finite element method for this analysis. However this method is not efficient for optimization because it has many degrees of freedom and solves many equations. Modal analysis reduces the number of equations and allows for calculation of the system vibration properties efficiently.

Progress in the last year:

The modal analysis code has almost completed. The effects of foundation and gyroscopics on geinvalues in a typical rotor foundation system have been found. The unbalance response calculated by this code showed good agreement with that of conventional rotor dynamics codes. I plan to modify FORSTAB code in order to deal with large and complicated rotor foundation systems and verify the new code.

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

Model reconciliation is a technique that allows the modification of models to make them match experimental data. For this method to be effective, the modification to the model must be sensible to the engineer and the method must allow the engineer to control the character of the modifications and where they operate. The resulting models will make better prediction of the internal behavior of the system (not only at the locations where experimental data was available).

It is proposed that models of real systems can be composed of a high confidence nominal model combined with unknown dynamic mechanisms acting at specific locations. The objective of the reconciliation process is to identify the transfer functions of these unknown dynamic mechanisms.

Progress in the Past Year:

In the past year, we have completed a series of experiments aimed at exploring the strengths and shortcomings of our approach. The work has revealed the importance of solving the "diagonal synthesis" problem which permits extraction of uncoupled dynamic mechanisms (the present technique tends to introduce non-physical coupling effects). In addition, the work has shown that the extracted dynamics tend to exhibit excessive complexity, particularly at high frequencies. Introduction of synthesis cost functions aimed at diminishing this problem have not proved effective. On the theory side, we have made progress toward a diagonal synthesis procedure and have also begun work on explicit identification of uncertainty in the experimental data and incorporation of that uncertainty into the reconciliation process. Since the annual meeting, we have made significant progress toward a ROMAC program aimed at encapsulating this analysis process. We hope to release a preliminary version by next spring. A primary objective of the first release will be to get member feedback on the input data structure: how appropriate to your testing methods is this code?

ROTORDYNAMICS CONT.

ANALYSIS OF INSTABILITY IN STEAM TURBINE

Advisor: Paul Allaire

A stream turbine with Petrobras in Brazil is experiencing instability, probably due to laby seals. An analysis is just starting to determine the cause and evaluate design changes.

ROTATING MACHINERY STABILITY TEST RIG

Student: C. Hunter Cloud
Advisors: Lloyd Barrett, Eric Maslen
Project Start Date: January 1990
Sponsor: Exxon Mobile

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 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.

Progress in the Past Year:

With research funding issues finalized in January, much of the test rig's hardware is on hand and efforts are currently focused on rig assembly. Ring testing of the bare shaft has been completed. Additional testing will be conducted in the next few months to verify the fully assembled rotor (with actuator sleeve assemblies) and the support characteristics of the actuator housings and fluid film bearing housings. The objective is to have the rig commissioned during the first of the year.

From the analytical perspective, some simple studies have been completed to examine the problem of determining a machine's stability MARGIN from the same test data used to determine stability LEVEL. These studies indicate that robustness assessment may be possible especially when more advanced model reconciliation and robust control techniques are applied

HEART PUMP PROJECT

ARTIFICIAL HEART PUMP PROJECT

Students: Steven Day, Phillip Lemire, Yi Wu, Amy Throckmorton, Sonna Patel.
Advisors: Paul Allaire, Houston Wood, James McDaniel, Gang Tao, Milton Adams

Progress in the Past Year:

UVA continues to develop new artificial hearts under a large four year NIH grant. We are working on a small ventricular assist heart pump that will be used in parallel to the existing damaged heart in heart disease cases. We are continuing to carry out laser velocimetry flow measurements in our existing centrifugal flow/ magnetically suspended pump and have designed a new, smaller centrifugal flow pump for potential use in children and small adults. The next activity is likely to be the development of a new, very small, axial flow pump in collaboration with the Utah Artificial Heart Institute in Salt Lake City, collaborating with Dr. Donald Olsen. We are also working on the physiological control algorithm to adjust the pump speed during different human requirements such as sleeping, sitting, walking and climbing stairs.

SOFTWARE HIGHLIGHTS

ROTORLAB

Work continues on extending the RotorLab architecture to encapsulate the rotordynamic, bearing, and seal solvers inside of a dynamic link library (DLL). By isolating the solvers from the GUI, and having them operate on a standardized data structure, the program will be more adaptable to future changes in, or additions to, the list of ROMAC solvers. Sponsored by ExxonMobil Research & Engineering, these improvements will also allow ROMAC members to use their own proprietary solvers for specific analyses as needed.

Other recent changes since the annual meeting include:

- Improving the disk elements to automatically calculate mass and inertia when the effective length and outer diameter are input.
- Updating the interface for the bearing and seal solvers so the user does not need to specify all of the intermediate file names – these are now pre-defined based on the input file name.
- Adding a switch to the stability analysis to allow the user to choose full or reduced bearing coefficients when a THPAD file is used for input.

HYDROB

- Released in July 2001
- Hybrid journal bearing code for applications where hydrostatic and hydrodynamic effects are present
- Predicts operating characteristics including load capacity and dynamic coefficients
- Based on ROMAC Report # 309, "Dynamic Analysis of Liquid Lubricated Hydrostatic Journal Bearings"
- Scripted editor capabilities for use with ROMAC GUI

TWIST2

- Command-line options added
- Geograf plotting routines replaced with Tecplot capabilities
- Tecplot mode shape and forced response plots available

ANNUAL MEETING

San Diego, CA - June 9-13, 2001

The 2002 annual meeting will be held in San Diego, CA at the Humphrey's Half Moon Inn & Suites (www.halfmooninn.com) at a nightly rate of $125.00 plus taxes. Humphrey's Half moon is located on Shelter Island and is conveniently located to most sites and attractions. Free airport shuttle to and from the hotel is also provided.

The meeting will begin with an evening reception with hors d' oeuvres on Sunday, June 9th. A tour of member company Solar Turbines will be given at the beginning of the week. Lunch and breaks will be provided daily with the sessions ending on Thursday, June 13. Registration material will be mailed out early in March. Complete details will be posted to http://www.virginia.edu/romac/ as they develop. Make plans now to join us in San Diego!

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 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 completed a series of recalibrations on our collection of Bentley probes and sensor heads, with each probe and the associated data organized for easy access by our students. This task was begun at the beginning of a major reorganization of the layout and use of our laboratory space (still in progress), and several other maintenance-related projects were carried out at the same time.

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. Please contact George T. Gillies at (804) 924-6235 for further information.

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