Update on the Rotating Machinery Stability Test Rig

Above: Startup Bode Plot of Stability Test Rig
Below Right: Stability Test Rig Updates on Page 9)

Temperature Distribution across Film and Pad (Film Thickness x 1000) See Maxbrg article on page 4
ROMAC NEWSLETTER/ANNUAL MEETING SUMMARY

Dear Romac Member:

The 23rd Annual ROMAC Meeting was held June 2-4, 2003. To me and other ROMAC faculty members, it is pretty amazing that we have made it through 23 years. A number of companies were not able to make it to the meeting so we are sending out this newsletter to let you better know what is going on, as well as to those who were there.

ANNUAL CURRENT MEMBERSHIP AND MEETING ATTENDANCE

First, let us thank you for being long term industrial members of the Rotating Machinery and Controls Industrial Program. We have 27 industrial members which has been reasonably stable in recent years following quite a few company mergers and generally tough economic times. There were 26 industrial attendees at the annual meeting representing 17 companies. There are six ROMAC faculty members and we support about six or seven students with ROMAC funds.

The company members are: AC Compressor, Boeing, Concepts, GE Connec, Cooper, Curtiss-Wright, Siemens Demag, Dow Chemical, Dresser Rand, Dupont, Elliott, Exxomobil, Framatome, Flowserve, KAPL, Kobe Steel, Mechanical Solutions, Mitsubishi, Petrobras, Pratt & Whitney, Rockwell, RMT, Rolls Royce, Solar Turbines, Hamilton Sundstrand, TCE, and Waukesha Bearings.

The ROMAC faculty members are Paul Allaire, Lloyd Barrett, Ron Flack, George Gillies, Carl Knospe, and Eric Maslen. The new/old ROMAC Director is Paul Allaire for the next three years. This is the first time he has been the Director since his first term in 1980 to 1983.

ANNUAL FEES AND FINANCIAL POSITION

Our membership fee of $16,000 per year is unchanged for next year. The total income to ROMAC is estimated at $344,000 with net income after UVA overhead (20%) of $292,000. The expenses are faculty summer salary $90,000, student support $165,000, travel $11,000, part time staff $18,000, office expenses $33,000, and annual meeting expenses $21,000. We are about on budget for this year. Many of this year’s expenses will be similar to last year’s expenses and there are other companies interested in joining ROMAC.

A former ROMAC company member, Turbocare, has informed us that they are rejoining for next year. We are also discussing renewed membership with Kingsbury, Inc.
ROMAC SHORT COURSES

Three ROMAC short courses were taught in mid May of 2003 free to ROMAC members. They were 1) magnetic bearings, 2) fluid film bearings, and 3) rotordynamics. A total of 19 people attended including quite a few younger engineers. Much to our surprise, several more experienced individuals attended as well. The courses were taught by ROMAC faculty members and students.

The courses seemed to be quite popular. One feature we included in the courses was some detailed information on new ROMAC computer programs such as MAXBRG. We plan to teach short courses similar to this again in the future.

FUTURE RESEARCH

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

PROJECT RESULTS AND FUTURE DEVELOPMENTS

We have developed several new computer modeling programs, associated manuals, experimental results, as well as various theses and published papers. A series of articles in this newsletter highlights the progress on the various topics and expected future developments. We have included both directly funded ROMAC projects and related projects which are funded by other sources. If a project is funded directly through ROMAC funds, it is so stated at the beginning of the article.

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<th>Topic</th>
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Fluid film journal bearings are widely used in rotating machinery and their modeling is critical to machine design and analysis. First, the bearings’ stiffness and damping greatly affect a machine’s rotor dynamics. Second, some bearing parameters, such as minimum film thickness and maximum temperature, are very important concerns for reliable operation. The objective of this project is to develop a state of the art thermo-elasto-hydrodynamic (TEHD) algorithm for industrial journal bearing analysis.

Many advanced methods are utilized throughout the modeling process. The pressure is calculated from the generalized Reynolds equation that includes radial viscosity variation. A special form of the two-dimensional energy equation was developed for MAXBRG to achieve computational efficiency and broad capability. The differential equations are solved by the finite element method and the turbulent effects are handled automatically. Pad temperature is calculated by a coupled film-pad approach that improves numerical robustness. Pad elasticity is modeled by a two-dimensional finite element method. The deformations of journal, shell and pivot are all taken into account.

This comprehensive algorithm can be used to analyze directly lubricated bearings (inlet groove or spray bar) as well as conventional fixed geometry and tilting pad bearings. Pressure dam bearings can also be analyzed with an adiabatic thermal model. In addition to the usual flooded lubrication condition, the bearings can be modeled under starvation, high ambient pressure or axial flow situations. Moreover, the algorithm allows great flexibility to suit different analytical needs. For example, a user can choose isoviscous analysis, or include either adiabatic or full thermal effects; the pads may have different axial lengths or inlet tapers.

Progress in the Past Year:

The computer code MAXBRG that implements this algorithm was finished and the version 1.0 was released on July 1, 2003. Specifically in the past year, the pressure dam bearing was added in the analysis; the models for the conventional bearings under flooded condition were extensively validated through comparisons with test data; the directly lubrication, starvation and other special flow models were preliminarily verified with good results; a few corrections and updates were made according to the comments from users. The complete dissertation, a user’s manual and the code are now available from ROMAC.

Future Work:

Because of high demand from the ROMAC members (all companies at the meeting requested this), the second version is currently under development. Based on the survey at the annual meeting of 2003, several features will be added to MAXBRG, including hydrostatic bearings, hydro-lift pocket effects, a second groove mixing model, and improved turbulence and starvation models. The new version is expected to be released next summer. Meanwhile, we are collecting feedback and refining the code. Your input is very important and highly appreciated.
LABYRINTH GAS SEAL CODE/PROGRAM DEVELOPMENT

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

Project Objectives:

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

Progress in the past year:

The set of equations to describe the flow in labyrinth seals has been obtained. A dimensionless analysis of the differential equation primary flow equations and a perturbation of these equations were developed. A preliminary computer program has been written for the set of differential equations. The initial version of LABY4 works now. Before a test version to some industrial firms can be delivered, more development on the program stability and accuracy are underway to ensure that all current available experimental data sets are reasonably well modeled by the code.

At this time, we are trying to understand the flow in labyrinth seals more accurately. Our current series of CFD simulations will focus on a 3D eccentric seal model. Some key parameters used in three-control-volume method, such as the ratio between the second and third control volume axial velocity, and boundary conditions such as inlet loss coefficient, exit recovery coefficient and land loss coefficient are expected to improve with detailed modeling capability from Tascflow. This will allow us to improve LABY4.

NEW FLUID FILM BEARING TEST RIG

Student: TBD  
Advisors: Ron Flack, Lloyd Barnett, and Eric Maslen  
Funding: ROMAC  

Over the past years significant advances have been made on the ROMAC fluid film bearing test rig. For example, redesign work and updating of hardware and sensors led to an increase in maximum testing speed from 2250 rpm to 7840 rpm. Updates included, overhaul of lubrication system to handle high flow rates, sensor and load cell updates, and replacement of journal support bearings with high precision higher speed ball bearings.

Basically, static testing at journal speeds up to 7840 rpm has occurred (8000 rpm is the limit due to the drive timing belt) and dynamic testing is limited to 4900 rpm (due to shakers which are over heating except for short tests). The maximum static load is 1000 lb and dynamic loads are limited to 150 lb. Furthermore, testing at higher speeds may be difficult due
to structural resonances (there are several at lower speeds but have been out of the vicinities of testing speeds). Specifically, the stinger has resonances above 5000 cpm. The current design also requires the operator to be in the test cell for initial alignment – at higher speeds this becomes a safety hazard. If the rig were to be run at higher speeds, static and dynamic loading devices as well as load cells would have to be replaced (very expensive), the structure would have to be redesigned, and an out-of-test-cell alignment procedure would have to be developed. All of the above have forced the lab to seriously consider the next generation of test rig.

One configuration under consideration is a twin magnetic bearing excitation system, similar to the new ROMAC rotordynamic stability test rig and similar to the smaller scale bearing test rig at Universität Darmstadt and headed by Dr. Professor R. Nordmann. The design retains single bearing setup of current test rig, but the rigid mounting of fluid film bearing eliminates alignment concerns. The rig would be driven by high speed electric motor with VFD. The magnetic “bearings” would load the test bearing both statically and dynamically. They would act as load cells and the motion sensors would be an integral part of the system. The use of these “bearings” would allow the rig to be much smaller and concise and would eliminate many of the resonances.

Design specifics would be to test bearings at least 3 in in diameter up to speeds of at least 12000 rpm and up to large eccentricity ratios. Tilt pad and other bearings will be tested. At this point a detailed optimization study is needed. Namely, the speed and or load need maximized (one cannot get both for dynamic testing). Required loads and sizes of the magnetic bearings need to be determined. The specific eccentricity range needs to be set. And a full dynamic analysis of the possible rig needs to be done including static and dynamic constraints which dictates journal, bearing, and magnetic bearing diameters and masses.

A component analysis will be needed as very few of the components on the current rig will transfer. This will be a dedicated effort by a new graduate student, hopefully starting in January. Included in the analyses are: Magnetic Bearing System (Two Magnetic Bearings, Lamination Stacks, Custom Controller, Computer Interface Boards), Fluid Film Bearing System (FFB split housing, Test bearing, Oil seals), Drive System (High Speed Motor (~25 hp), Variable Frequency Drive, High Speed Coupling), Lubrication System (Lube Oil Supply Pump, Electric Heater, Shell and Tube Counter Flow Heat Exchanger, Flow Meter with automatic flow control), Instrumentation (Proximity Probes, Hall Sensors, Thermocouples, A/D Boards), Computers/Accessories (Magnetic Bearing Control Computer, Data Acquisition Computer).

With a project this large member interest is imperative. Input from interested members must be incorporated into any further design, in order to satisfy the current industrial demands several companies have already made suggestions. Furthermore, financial support and “donations” will be necessary. Again, several companies have already volunteered with hardware contributions and we will look for this to continue.
Rolling element bearing stiffness and damping properties is a topic that many ROMAC companies are interested in. However, ROMAC faculty members have not conducted research in this area before. In our ROMAC Annual Meeting last summer, half of the companies present voted for us to conduct research on the topic and it is thought that a number of other companies that were not present would like this work. This number of votes is about the same as several other topics such as the work on the rotor/bearing stability test rig and the high speed bearing rig. A preliminary assessment of codes such as the JB Jones code indicates that the currently available rolling element bearing codes do not meet the needs of ROMAC companies.

Paul Allaire is willing to undertake research on the topic to develop a rolling element modeling code over the next few years with suitable supporting staff. Part of the analysis involves the operating conditions of the rolling element bearings where some recent research has been found. Recent research by Bercea, Neliș, and Cavallaro [2000] in laboratories Romania and France discussed the equilibrium problem of double-row rolling bearings. Zupan and Prebil [2001] of a university in Ankara Turkey, discussed carrying angle and carrying capacity of large single row ball bearings.

Other work is more concerned with stiffness and damping properties with some example work obtained from the literature. Dietl, Wensing, and van Nijen [2000] conducted an experimental and theoretical study of damping in rolling element bearings at SKF in the Netherlands. Wensing and van Nijen [2001] developed modeling of the stiffness and damping of rolling bearings. Akturk [2003] of Gazi University in Turkey determined the effects of preload and number of rolling elements on angular contact ball bearing stiffness and how it affects rotor natural frequency. An SKF engineer in the US has provided Paul with a tutorial on rolling element bearings to get us started and SKF is interested in cooperating with us on better understanding of rolling element bearing properties.

As this is a new area for us, we will have to work with the companies which desire this new code to determine priorities on which bearing types and other details of the bearing analysis that need to be carried out. We hope that work in this area will bring in several new ROMAC members who need this type of analysis.
Student: C. Hunter Cloud
Advisors: Lloyd Barrett, Eric Maslen
Project Start Date: January 1990
Funding: ROMAC/ExxonMobil/Petrobras

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:

Test rig has achieved 10,000 rpm with bearing overall vibration levels of less than 0.25 mils p-p. The data acquisition system for basic machinery measurements such as orbits, Bode plots and spectrums is almost fully operational. Current efforts are focused on the magnetic actuator cross-coupling and excitation control system development and commissioning to make the rig fully operational for stability testing. Analytical efforts are focused on evaluating which system identification/modal analysis techniques are most appropriate for measuring a rotor’s stability level. In conjunction, software is being developed to implement these techniques on the test rig.
The ultimate objective of this work is to develop a reasonably automated mechanism for correcting engineering models of rotordynamic systems to better match experimental data for real machines. An important feature of the approach pursued here is that it can capture dynamic effects completely missed in the model, like foundation dynamics. Thus it could be used to better model existing machines. We refer to the method as model reconciliation (MR). The underlying idea is to introduce localized modifications to analytic rotordynamic models to make them match experimental data. When finally developed, the method should have the following properties:

1) It should permit extrapolation: a corrected transfer function from one set of system inputs to one set of outputs should imply an accurate transfer function from another set of inputs to another set of outputs. This means, for instance, that correcting the model using data from an instrumented hammer and accelerometers would improve the prediction of response at a seal location to excitation at unbalance locations.

2) The method should account for uncertainties in the data, the finite frequency range of the data, engineering assumptions about where error or unmodelled dynamics are likely to enter the model, and engineering assumptions about where error or unmodelled dynamics are likely to enter the model.

The work is central to any engineering process where some unknown machine parameter needs to be estimated from experimental data. For instance, in Hunter Cloud’s work, we seek to identify bearing properties from forced response data - a process which neatly falls under the rubric of model reconciliation. Indeed, a significant question that Hunter raises is whether the extracted model should be synchronously reduced or full tilt pad coefficient - a dynamically more complex model. MR can address this question directly because it doesn’t assume, a priori, that the bearing dynamics have any particular character (K and C, for instance) but instead produces a transfer function representation of the bearing dynamics. This transfer function can be interpreted either as a close fit K and C or as a more complex dynamic system (full tilt pad model).

Progress in the Past Year:

In the past year, we proposed a "robust model reconciliation" (RMR) method which incorporates the effects of the experimental uncertainty (bounded, spectrally characterized noise). We also developed a method to examine the validity of the reconciliation process, which uses extra data as a reference to compare with the data produced by the reconciled model. Both simulated data and experimental data have been used to demonstrate the results of the method. The error model permits the synthesis to ignore spurious features of the identified model, thereby producing more reasonable results. Finally, a recent development promises to greatly reduce the computational complexity of the method, resulting in a much more reliable numerical tool. The work is designed to be useful to Romac companies and we request your input in the development of the methods.
BALOPT—NEW BALANCING CODE

Student: Guoxin Li and Bin Huang
Advisor: Paul Allaire and Zongli Lin
Project Start Data: January 2002
Funding: ROMAC

Project Objectives:

Since the 1950s balancing has been an important technology for engineers concerned with synchronous vibration problems. While the technology has improved over the years, there is still no efficient computer program to solve some of the basic balancing problems, such as the minmax balancing problem. In many cases, the conventional least squares method of balancing is not optimum for balancing high-speed flexible rotors. The objective of this research is to develop a new generalized approach to rotor balancing with a convex optimization technique. This formulation not only solves the minmax balancing problem, i.e., the maximum vibration amplitude is minimized, but also allows balancers to deal with various kinds of practical constraints and data uncertainty. Furthermore, this formulation can be extended to a unified approach in which the modal trial weight distribution is obtained by solving inequality constraints.

Progress in the Past Year:

A beta version of the new ROMAC balancing code, BALOPT, is complete. A friendly user interface using Script Editor is developed. This version of BALOPT contains the following basic functions: influence coefficient estimation, run out compensation, weighted minmax, weighted least squares, correction weight constraints and orbit constraints. The code is being tested numerically. The beta version is also being verified by some of the ROMAC members who participated in this project.

Future Work:

BALOPT will be tested both numerically and experimentally on the laboratory test rigs and the industrial rotors. New functions such as the robust balancing, stochastic influence coefficient estimation and unified approach with modal balancing as well as the pre-processing and post-processing functions will be added. Different solvers will be tested, and the user interface will be enhanced. Members are encouraged to try the beta version and feedback is needed to improve the code. The final version will be released in June 2004 before the annual meeting.

“A beta version of the new ROMAC balancing code, BALOPT, is complete”
Project Objectives:

This test facility has several objectives in study of high speed centrifugal compressors. The first is to collect bearing load data for on- and off-design conditions. This data will be used to validate and improve computational tools. Secondly, testing will investigate the sensitivity of flow instabilities to adjusting compressor parameters (tip clearance, volute size, etc). The last objective is to develop an active surge control algorithm to be used in industrial scale centrifugal compressors. This control scheme will modulate the tip clearance to stabilize surge (see Surge Stabilization in Centrifugal Compressors).

The test rig will incorporate two radial active magnetic bearings (AMB) and one thrust AMB to constrain five degrees of freedom. The AMBs will provide a direct measurement of the bearing forces by measuring the coil currents. Later work will include mounting flux sensors on the pole faces to obtain more precise force measurements at the bearing locations. In addition, the AMB will allow active manipulation of the rotor position and, hence, impeller tip clearance.

Progress in the last year:

All design work is complete for test rig. All machine parts have been released to machine shops. The impeller/volute/diffuser set, supplied by Kobe Steel, has been completed and tested. We have started to move equipment into our new test facility. The machine foundation has been installed, as have most of the utility services. Instrumentation design for the test facility has been completed and purchase of the required transducers has been initiated. A data acquisition system has been specified and bids are currently in evaluation. Testing is expected to start by the beginning of 2004.

Surge Stabilization in Centrifugal Compressors

Student: Dorsa Sanadgol
Advisors: Eric Maslen and Ron Flack
Project Start Date: Fall 2001
Funding: ROMAC
Project Objectives:

The safe range of operation in 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, potentially mitigating the hazards associated with operation near the nominal surge line. For compressors with un-shrouded impellers, 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 have 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 advantage of our approach. 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 one dimensional incompressible flow model including the effects of tip clearance variation on the compressor characteristic has been derived. Using a proper Lyapunov function a stability condition for mass flow feedback gain was also derived. Due to impracticalities of mass flow measurements, subsequent research has focused on applying different estimation techniques to substitute pressure measurements for direct mass flow measurement. Among the nonlinear estimators, extended Kalman filter (EKF) method is used because of its high performance and robustness. Simulation results show that EKF is able of accurately estimating the true mass flow rates. These estimates are further used as the input to the controller. Results from simulation of this control scheme 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 with reasonable control authority.

EFFECT OF REYNOLDS NUMBER ON PERFORMANCE OF A SMALL CENTRIFUGAL PUMP

Students- Steven Day, Phillip Lemire
Advisors- Ron Flack, Jim McDaniel
Funding: None

Project Objective:

A study of a small centrifugal pump has been made to address the effectiveness of traditional pump affinity laws and the influence that viscous effects, as characterized by the Reynolds number, have on the pump performance. This was investigated both experimentally and numerically on models of a small centrifugal pump, which has an impeller diameter of 46 mm with a log spiral volute. In the experiments, the Head-Capacity curves were determined for speeds between 500 and 3000 rpm and for two fluids with different viscosities. Design point Reynolds numbers ranged from 90 to 2800. Results showed that lower Reynolds number flows did not adhere to conventional pump affinity laws, whereas higher Reynolds number flows scale very effectively according to traditional pump affinity laws. The numerical study consisted of comparing the generated head and internal flow field of the pump scaled based on traditional affinity laws with and without consideration of the Reynolds number. Like the experimental results, the numerical simulations indicate that consideration of the Reynolds number is necessary to insure accurate scaling in this small pump.
Project objective:

Self-sensing magnetic bearings offer the potential advantage of reducing hardware cost and complexity in commercial AMB systems. Experience with this technology over the past 15 years has been modest, suggesting that the achievable performance of self-sensing AMB’s is likely to be poor relative to position-sensed systems. The goal of this project has been to develop a commercially feasible approach to self-sensing that answers this concern of poor relative performance.

To realize this goal, the project has explored a specific paradigm for exploiting amplifier-induced switching ripple in the AMB coils to estimate airgap dimension. This exploration has followed numerous lines including electrical realization as well as sensitivity to hysteresis, eddy currents, magnetic saturation, and other sources of uncertain gain in the system. Numerous experiments have been conducted including physical levitation of a rotor in self-sensing AMB’s at speeds up to 60,000 RPM and simulation studies aimed at revealing details of hysteresis sensitivity.

The main findings of this work are that the paradigm developed at ROMAC is viable and that sensing resolution can be quite fine: on the order of 0.04 mils with high permeability stator materials. Further, rough measures of relative stability suggest that our sensing technique can yield a system with nearly as high gain margins as are realized with eddy current sensors.

Progress in the past year:

In the past year, a formal analysis framework for studying the stability robustness advantages of exploiting switching ripple was developed and explored. The exciting conclusion of this work is the observation that self-sensing AMB’s are not, in fact, fundamentally touchy and there is emerging technology to realize very robust systems. The bulk of the technical details of the analysis and interpretation of the results are too cumbersome to present here in the newsletter, but the main finding is that tolerable gain uncertainty can typically be increased by a factor of more than 10 by properly exploiting switching ripple. This means that, if sufficient levels of switching ripple are acceptable in a given AMB system, then it will be very reasonable and commercially viable to implement the system as self-sensing.
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 of different controllers. First, an accurate nominal model including the substructure modes was developed from physical laws and refined by experimental data. An uncertainty representation and a performance criterion were developed for the model AMB system. The influence of gyroscopic effects on the stability and performance of AMB system under a MIMO controller was analyzed.

**Progress in the Past Year:**

We tested different controllers. The results were used to validate the model and the control design. Of special interest is the control of the flexible rotor modes and substructure dynamics. The objective is to add more damping into the flexible modes while minimize the force transmitted to the substructure. The work will be completed this year, and the results will be released in ROMAC report.
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:

Experiments for measuring the material properties of the magnetic alloy used to build the non-laminated magnetic actuator have been carried out. The magnetization curve, and major and minor hysteresis loops for the magnetic alloy have been plotted from the experimental data. Finite element analysis using the magnetization curve produced frequency responses very similar to those generated from dynamic tests on the magnetic actuator.

An analytic model for a non-laminated cylindrical magnetic actuator including eddy current effects was developed. Due to the complexity of this complete analytic model, a simplified model was given. Both the complete and the simplified models are explicitly dependent on the actuator material and geometric properties. Thus, the influence of each of the actuator properties on its performance can be easily calculated. Comparison of the frequency responses of the two analytic models to that resulting from finite element analysis demonstrates good accuracy for a wide range of material and geometric properties. The analytical modeling approach employed is being applied to non-laminated magnetic actuators of other geometries, such as C type, to generate accurate analytic models for these actuators.
Student: Min Chen
Advisor: Carl Knospe
Project Start Date: September 1999
Funding: None

Project Objectives:

High speed machining, which combined with higher spindle speed, machine feedrates and greater depth of cut, increases the metal removal rate and productivity. However, this aggressive cutting operation makes “chatter” a more significant concern. Self-excited chatter adversely affects machining operations by causing tool failure, increased tool wear, and scrapped parts. Most current techniques are to alter machining conditions (e.g. spindle speed) to avoid the occurrence of chatter.

Active magnetic bearings (AMBs) provide a new solution for chatter free high speed machining, due to its active control capability. Advanced control techniques can be designed and employed in AMBs, so as to optimize the tool/spindle dynamics catering to current cutting conditions. Compared to conventional approaches, AMB based chatter control is more flexible and can achieve greater depth of cut in machining operations.

Progress in the Past Year:

Advanced control design techniques require an accurate mathematical model of the cutting process. In the past year, a new experimental approach to identify the cutting dynamics was proposed. This method treats the problem as a closed-loop gray-box identification case and is based upon spectral analysis and least squares estimation. Active magnetic bearing is employed both to excite the system and to increase the tool’s damping. The key of this method is to break the inherent time delay feedback loop in machining process by limiting the observation period to less than one workpiece revolution. A relationship between cutting dynamics and depth of cut at certain machining conditions has been identified using this new method. The models built could be used to predict machining stability and guide tool controller design.

Both speed-independent and speed-dependent controllers have been synthesized and implemented in AMB system. Speed-independent controllers optimize the tool/spindle dynamics at the worst case cutting speeds, while the speed-dependent controllers optimize the tool/spindle dynamics at one specified cutting speed. They can be used in different cutting applications.

A controller switching technique has been investigated and implemented in the dSPACE control board to achieve bumpless transfer between controllers. This technique can be used to select controllers automatically or manually according to different cutting conditions without affecting the current cutting operation.
SOFTWARE HIGHLIGHTS

**CRTSP2**
Corrected a variety of bugs associated with third rotor
In CRTSP2.SED, corrected interpolations for differential bearings between rotors

**FORSTAB**
Added labels to output stations for plotting purposes
Updated separation margin calculation with latest API standard paragraphs
Added chapter to manual explaining how to generate rotor files using CRTSP2

**HYDROB**
Corrected bugs related to some versions being created in parallel with different capabilities
Replaced some subroutines with LAPACK subroutines
Incorporated circumferential grid spacing capability
In HYDROB.SED, corrected errors with viscosity inputs and expanded help descriptions

**SEAL3**
Corrected fluid properties unit conversions, specifically, those surrounding kinematic viscosity

**THBRG**
Corrected rigid rotor stability threshold calculation
Added warning in output for the case where gravity load is zero.
This results in rigid rotor stability threshold becoming automatically zero rpm.

In THBRG.SED, changes the names of loads to better differentiate the type and expanded their descriptions in Help.

**TORPLOT3**
Converted from FORTRAN to C
Converted all plotting from GEOGRAF to TECPLOT
Run directly through POST in ROMAC GUI
Added TOR3ELE.SED editor for defining the geometry and material properties for the elements of interest

**MAXBRG**
Released version 1.0
Additional research and capabilities are in progress (see other newsletter section).

**ROTORLAB**
After some negotiating, we have worked out a development agreement with Concepts NREC which will restart the Rotorlab work. The first step is to complete the DLL based version parallel to the ExxonMobil code. This will provide a hook for incorporating new rotordynamic and bearing solvers. In addition, 3D modeshape/forced response plots will be added as well as the bearings case manager, which permits examination of worst/best case performance across bearing parameter ranges. The target is to have a first version completed in time for the 2004 Annual Meeting. Progress to-date is good: we are currently slightly ahead of the milestone established at the project’s inception so we are optimistic about the Annual Meeting roll out.

**FUTURE WORK**
Add penetration factor calculation to TWIST2
Expand stiffness models for elastomeric couplings in TORTRAN3
Increase maximum number of pads in THRUST
Create speed case output capabilities in SEAL3 for use with rotordynamic codes

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![Graph and Diagram](image-url)
Our new prototype axial flow magnetically suspended artificial heart pump is now under construction. It is intended for left ventricular assist in persons with congestive heart failure to work in parallel with the diseased heart. It pumps at a design flow of 6 liter/min and produces a pressure rise of 100 mm Hg. It has dimensions of approximately 65 mm long by 35 mm in diameter. The axial flow pump has an inlet with 6 blades inducer, the impeller has 4 vanes and the diffuser has 3 vanes. The magnetic suspension system is composed of one permanent magnet radial bearing, one active control electromagnetic radial bearing and one permanent magnet thrust bearing. The rotor position sensors are Hall effect sensors used for both feedback to the active control bearing and flow control through estimating the pressure drop in the pump impeller.

It is expected that we will have the first few prototypes for testing in November or December of this year. A simulated cardiac test loop consisting of a pneumatic pulsatile heart mock heart, fluid filled tubes modeling the veins and arteries, and an adjustable resistance to simulate states of resting (sleep), low level activity such as sitting upright, and higher level of activity such as walking. The pump will be tested for its performance and reliability.

The past work on this project has been funded by the National Institute of Health over the past five years in a large grant funded through the Utah Artificial Heart Institute and UVA. A large grant application is pending with NIH for support of this project through the next five years. We expect to hear if the grant is funded early next year. We think we have a very good chance.

ANNUAL MEETING

Charlottesville, VA
June 6 – 9, 2004

The 2004 Annual Meeting will be held in Charlottesville, VA at the DoubleTree Hotel (www.charlottesville.doubletree.com) at a nightly rate of $60.00 single/double room plus taxes. The DoubleTree is located on 29North and offers an elegant setting as well as convenience to many businesses, shops and attractions. The hotel provides free shuttle to and from the Charlottesville airport, as well as to some UVA locations.

The meeting will begin with a welcome reception on Sunday afternoon. Lunch and breaks will be provided during the week, as well as a dinner buffet on Monday night. Registration packets will be mailed out at the beginning of March. Details are also provided on our web at http://virginia.edu/romac. Make plans now to attend the 2004 ROMAC Conference!
There are a number of mechanisms through which ROMAC obtains research instrumentation and other equipment for its laboratories. These include:

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

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

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

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

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

Special points of interest:
* Plans for Annual Meeting now under way
* Annual ROMAC Fee unchanged for 2004
* New companies joining Romac
* Software Highlights

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