■ ROTATING MACHINERY AND CONTROLS LABORATORIES ■

ROMAC

FALL, 1996

Message from the Director

Lloyd Barrett

Recently Hossein Haj-Hariri stepped down as ROMAC director to permit more time for his research activities. He has also been asked to be the Director of Graduate Studies for the Mechanical, Aerospace and Nuclear Engineering Department which is an important, but time-consuming position. Hossein will continue to perform research with ROMAC, initially emphasizing the analysis of honeycomb seals. We appreciate all Hossein has done as ROMAC director, and look forward to the results of his seal research.

I have been asked to assume the position of ROMAC director, and I look forward to serving in that capacity. I have been associated with the industrial program since its inception in 1971, and was ROMAC director from 1986-1989. Please call or e-mail me (leb@virginia.edu) with any questions you may have concerning ROMAC.

Ted Brockett has left ROMAC to take a position in industry. We wish him well, and thank him for all he has done for ROMAC in his positions as graduate student, Research Engineer, and Research Professor. José Antonio Vázquez is now one of our Laboratory Research Engineers (Dan Baun is the other) and is the principal contact person for questions related to the ROMAC computer programs. We are looking to share a position with the University for maintenance of our computers and computer network so that José and others in the lab can spend more of their time addressing the needs of our membership on technical issues.

The annual membership fees for ROMAC will be increased to $14,000 beginning January 1, 1997. This was discussed at the last Annual Meeting where it was pointed out that there had been no increase in fees for several years. However, part of the fee increase will be used to defray the costs of the Annual Meeting, so that each member company will be allowed to send two members to the Annual Meeting without paying a separate registration fee. For the past several years the registration fee has been $550 per person. We hope this new policy will lead to even better attendance at the Annual Meeting.

ROMAC Annual Meeting `97

Wintergreen, VA - June 22-26

The 1997 Annual Meeting is scheduled to begin with registration on Sunday, June 22 and end on Thursday, June 26. The meeting will be held at Wintergreen Resort in Wintergreen, Virginia. Following the last Annual Meeting, we investigated conference facilities in Las Vegas but found them too expensive at that time of year.

The Annual Meeting was last held at Wintergreen Resort in 1990 and it was one of our best attended meetings. We are hoping that this location, in addition to our new policy of including two meeting registrations in the annual membership fee, will make this meeting even better attended. Wintergreen Resort is located on the top of the beautiful Blue Ridge Mountains around 40 miles south of Charlottesville. Recreational facilities available include golf courses, indoor and outdoor pools, tennis courts, horse-back riding, hiking, saunas and exercise rooms. Accommodations will be in studio apartments in the lodge at $98/single or double occupancy. The studios have kitchenettes and small living rooms plus the usual amenities.

We had many positive comments about the 1996 meeting in Charlottesville. We had a good turnout for the 1996 meeting and hope to have an even better one for 1997. We understand that the research areas of ROMAC are quite diverse, and we recognize that few of our members are truly interested in all facets of our research program. Therefore our core work of rotor dynamics, fluid film bearings and seals is scheduled at the center of the conference with the specialized topics of magnetic bearings and fluids placed at the end. This is done intentionally to permit members with more restricted interests to attend only those parts of the conference that are of most interest to them. However, many of

INDEX

our members tell us that one of the most significant benefits of attending the ROMAC Annual Meeting arises from the interactions that occur among members from different organizations. Since this is of benefit to our members, we want to try to encourage this interaction and hope that the attendees will take advantage of this.

Registration materials will be sent to our members in March, 1997. At that time we will also be providing you with information about the many activities available at Wintergreen Resort. Mark your calendars and plan to join us in June.

ROMAC Industrial Liaison

José Antonio Vázquez, who many of you already know as a ROMAC doctoral student, has been appointed ROMAC Theoretical Lab Engineer. He is responsible for liaison with industrial members on technical issues with our programs. He works directly with graduate students and faculty in finding answers to your questions. If you have any questions concerning ROMAC programs, please call José at (804) 924-6234 or contact him via e-mail at jose@virginia.edu.

ROMAC Short Course

Basics of Rotor Dynamics

An introductory short course on the Basics of Rotor Dynamics will be offered in May 1997, probably the week of May 19th. The course will develop formulations and concepts, as well as provide familiarity with ROMAC codes. We will also be using the ROMAC Scripted Editor and the Shell. As in the past, there will be no registration charge but meeting space will limit the number of attendees. More information will be provided around the first of the year. Please contact us with your requests or suggestions for short courses.

ROMAC Computer News

José Antonio Vázquez

ROMAC continues to improve our existing programs, as well as the ROMAC User Interface Suite of programs.

ROMAC ON-LINE

In order to facilitate access to ROMAC programs and technical support, we recommend that all members make use of our services on the Internet. All ROMAC programs are available via FTP (File Transfer Protocol) and Electronic Mail (e-mail). E-mail is an especially useful tool for providing technical support. All ROMAC faculty, staff, and students may be reached using e-mail. Members who have e-mail are notified immediately of any updates to ROMAC programs.

ROMAC is also on the World Wide Web. Members have access to information about ROMAC, ROMAC Programs, faculty, staff, and students, and much more. The address is:
http://kelvin.seas.virginia.edu/~romac

ROMAC User Interface Suite

ROMAC Shell and Scripted Editor

Eric Maslen, José Antonio Vázquez, and Lloyd Barrett

During the past year a number of improvements have been made to the Shell and Scripted Editor. In order to assist ROMAC members in getting started with these programs, an installation program was developed and is now available. This routine automatically sets up both the Shell and Editor to interact with ROMAC programs already stored on the user's hard drive, and performs other tasks to provide less troublesome interaction between the analysis programs, data files, editor, and script files. ROMAC plans to provide a Windows™ version of the Scripted Editor, and has developed a plan for this to be accomplished before the next Annual Meeting. A new version of the Shell will be released at the next Annual Meeting which will conform to the Windows™ standard for Multiple Document Interfaces (MDI). This enhancement will permit simultaneous management of several different analyses.

At the last meeting the topic of plotting was discussed with the membership. There was a strong consensus for interfacing the output of the ROMAC analysis programs to a commercial plotting package. The package selected was Tecplot™. The plan is for the Shell to provide generic Tecplot™ graphs which the user could then modify on line. This would require each user to purchase a copy of Tecplot™. The generic plots would be created using macros which would be read by Tecplot™ to produce the graphs. Users could modify these macros or write their own to replace the generic plots with ones specialized to their needs.

ROMAC is continuing discussions with Concepts, ETI on their proposal to provide ROMAC computer programs to ROMAC members. A presentation on the proposal was made by Concepts to the ROMAC members at the last meeting, and a number of ideas were presented by the membership. The goal is to develop a plan under which there are no disadvantages to any ROMAC member and which provides an improved graphical user interface (GUI) for ROMAC analysis programs for use by all ROMAC members.

In addition, several new script files are available for ROMAC programs. These new scripts, together with new versions of older scripts are listed in this newsletter under the following section.

ROMAC SED File Releases (Script Files)

CRTSP2.SED Version 3.22 by J.A. Vázquez.
DTRANSF.SED by J.A. Vázquez.
PADFEM.SED by T.S. Brockett.
PDAM2D.SED by T.S. Brockett; modifications by W.T. Korn.
RESP2V3.SED Version 2.0 by T.S. Brockett and P. Allan; modifications by T. Johnson.
TURSEAL.SED by T.S. Brockett.
TWIST2.SED by T.S. Brockett and P. Allan; modifications by T. Johnson.

Updated ROMAC Programs

CRTSP2 Version 2.50 (04/04/96; update by T.S. Brockett):
- Secant search algorithm changed to bisection (more stable).

CRTSP2 Version 2.60 (09/24/96; update by José Antonio Vázquez):
- Bisection method changed to "false point" method. This is a faster method and also removes a bug inadvertently introduced in the previous release.
- Small change in the output format.

FJBCOF Version 3.00 (09/24/96; update by Lloyd Barrett)
- Replaced the input file by an iterative input.
- The input pressure can now be set by the user.

FRESP2 Version 2.60 (03/25/96; update by T.S. Brockett):
- General code clean-up.
- Fix plot bug.

LABY3 Version 1.11 (06/28/96; update by T.S. Brockett):
- Lowered the tolerance for the condition number.

ROTSTB Version 6.00 (01/30/96; update by T.S. Brockett):
- Addition of fixed geometry thrust bearing models.

SEAL2 Version 1.40 (02/14/96; update by T.S. Brockett):
- General code clean-up
- Fix a bug on multiple speed cases.

THBRG Version 2.40 (11/14/95; update by T.S. Brockett):
- Removed unused line of code causing overflow problems.
- Bug Fix: supply pressure updated at end of each speed/load case.

THPAD Version 2.63 (04/04/96; update by T.S. Brockett):
- Modification to the description E/C to E/Cp.
- Added unit to the output plots.

THRUST Version 2.00 (06/05/96; update by T.S. Brockett):
- Added thrust disk thermal deformation.
- Added dynamic coefficient calculations.
- Pin-point data extraction.
- Faster algorithm.
- Better initial convergence.
- Better element mapping.
- Easy development of design charts.
- "Chi" editing.
- Effective crown calculations.

TURSEAL Version 2.12 (05/29/96; update by T.S. Brockett):
- Modified the size of the variable for the input file name.

TWIST2 Version 3.02 (02/09/96; update by T.S. Brockett):
- General code clean-up and plot bug fix.

New Computer Programs

TORTRAN3 Version 1.0

Scott Orsey and Lloyd Barrett

TORTRAN3 is a transient response program for torsional rotor systems. TORTRAN3 can analyze rotor systems with non-linear couplings that are driven by synchronous machines, variable frequency drives, or any other torsional forcing function that can be expressed as a function of time or rotor speed. One important feature of TORTRAN3 is its cumulative fatigue analysis. Rotors that undergo large periodic loading, such as synchronous motor driven machines during startup, may fail after a finite number of starts.

ACCDES and PREDES Version 3.0

Deb Dhar and Lloyd Barrett

ACCDES and its associated preprocessor PREDES find suitable hydrodynamic bearing coefficients and magnetic transfer functions based on designer supplied acceptable stability criteria. The stability criteria includes minimum logarithmic decrements, operating speed separation margins and restriction in the bearing coefficients within certain bounds.

MSUPPORT Version 1.0 and DTRANSF Version 1.0

José Antonio Vázquez and Lloyd Barrett

MSUPPORT and DTRANSF calculate polynomial transfer functions from modal information. MSUPPORT takes ROTSTBMS support modal files and writes the corresponding polynomial transfer function file in the format needed for ROTSTB Version 7. DTRANSF is an enhancement to MSUPPORT. It handles zero frequency modes and accepts several input file formats. DTRANSF can read the modal input files for ROTSTBMS, FRESP2 rotor files and FRESP2 substructure files. The output format can be any of the above file formats plus support files for ROTSTB Version 7.

Polynomial transfer functions can also be calculated from experimental data using the program TFIDENT (see next section on the magnetic bearing suite).

Magnetic Bearings Modeling and Analysis Suite

Eric Maslen, Christopher Sortore, and David Meeker

Overview

This is a modular package of interacting codes designed specifically for analyzing the performance of rotor systems with magnetic bearings. Most of the components of the suite will also be useful to analysts not involved with magnetic bearings. In this suite, rotor systems are viewed as a collection of generic interacting (linear) components - any number of rotors, casings, bearings, seals, and so forth. The components are all modeled using a standard state space form with linear parametric dependence on speed; this format easily supports gyroscopics and the models are compatible with MatLab in either an ASCII or binary format.

Analysis Procedure

The analysis procedure is sequential: first, you develop dynamic models of the components. Next, you assemble the components into the overall system. Finally, you evaluate stability or forced response of system. This sequential approach speeds up the analysis process because models are not regenerated for each analysis. Further, it expedites modification of system components and subsequent analysis of the resulting modified system. Modeling and assembly are automated by the program GLUE. This program is similar to a MAKE facility as would be used in the development of large software codes.

Codes in the Suite

The suite presently contains ten codes designed to work together. These include:

AUXBRG - auxiliary bearing performance
BODE - forced response, transfer function computation
CRTSP_2 - enhancement of existing CRTSP2
EIGS - stability analysis
FILTER - modeling of cascaded controller filters
GLUE - incremental model compiler, linker
HARMOPT - forced response minimization analysis
MAGAUDIT - magnetic bearing dynamic capacity analysis
MODAL - rotor modeller: modally truncated models
TF_IDENT - extracts transfer functions from experimental data

Syntax Notes

All of these codes use a standard syntax:
code_name <command line options>

A list of the valid command line options can be queried with:
code_name /?

Most of the codes support the command line options /m and /f:
- /m displays a manual file if "code_name.man" exists
- /f displays information about the data file format.

All of the codes display the version number when invoked without arguments.

Code Source

All of these codes are written in standard C. This was done primarily because Maslen and Meeker are much more competent in C than in FORTRAN, but, in fact, several of the codes probably cannot be ported to FORTRAN. We apologize to those who are unfamiliar with C and may prefer to see source in FORTRAN, but believe that it is in the best interest of ROMAC and of the members to leave these codes in C.

Synopses

The remainder of this report is a series of brief synopses of the purpose, status, and future plans for each of the codes in the suite.

AUXBRG

Purpose: computes likely whirl speeds for circularly isotropic rotors on circularly isotropic auxiliary bearings with specified stiffness, damping, clearance, and friction characteristics
Status: released as Version 1.1
Plans: extend to compute whirl response at specified critical clearance points

BODE

Purpose: computes transfer functions, forced response, and unbalance response for system models assembled by GLUE. Includes gyroscopic effects. Output includes plot files and textual summaries.
Status: released as Version 1.1
Plans: (completed)

CRTSP_2

Purpose: a port of the existing CRTSP2 to C with substantial extensions: automatic critical speed map generation, command line control of output file verbosity, improved convergence
Status: released as Version 4.1
Plans: add automatic generation of Campbell plots, fast process support of single level rotors

EIGS

Purpose: complex eigenvalue computation, including both forward and backward modes of gyroscopic models at a given shaft speed. Models are generated by GLUE or MODAL: state space form with linear dependence on speed (gyroscopics)
Status: released as Version 1.0
Plans: (completed)

FILTER

Purpose: generates standard format state space models of cascaded filters from a simple description file
Status: released as Version 1.1
Plans: extend to permit more complicated filter structures with branches

GLUE

Purpose: incremental model compiler/ linker

- components are identified in SYSTEM file through defining data files and executable modeling code, dependencies are listed
- on launch of GLUE, file times are checked to determine which component models need to be updated
- component interconnections are identified in SYSTEM file
- end result is updated component models and assembled system model

Status: released as "alpha" version: presently only supports planar models

Plans: extend to support two-plane models with anisotropy and cross-coupling

HARMOPT

Purpose: computes the control effort and rotor response required by various combinations of mass imbalance and/or sensor run out. It is assumed that the control is designed to minimize a weighted quadratic sum of the control effort and rotor response, where the weights are specified by the user.

Status: released as Version 1.0

Plans: (complete)

MAGAUDIT

Purpose: computes the dynamic capacity of a radial actuator/amplifier system in Class "A" or Class "B" operation as a function of frequency.

- assumes four quadrant organization, negligible coupling
- uses experimentally derived magnetic model, permits saturation
- uses simulation and harmonic analysis to extract capacity in the presence of significant nonlinearity

Status: released as Version 1.1

Plans: extract magnetic model parameters directly from experimental data, generalized to stators without four quadrant organization

MODAL

Purpose: Generates a modally truncated state space model of a free-free (or pinned-free) single shaft rotor.

- Uses the transfer matrix approach to compute flexible modes and an ad-hoc method to compute rigid body modes.
- Retains any number of specified physical input or output degrees of freedom (can be more than the number of modes retained).
- Model is compatible with GLUE and with MatLab.
- Data file is easily derived from CRTSP2 models

Status: released as Version 1.4

Plans: allow mode dependent damping (rather than fixed percent damping in all modes)

TF_IDENT

Purpose: Generates a transfer function model of specified order which matches the magnitude and phase of a measured transfer function.

Status: released as Version 1.0

Plans: force stable solutions: presently CAN generate unstable transfer function models, but generally doesn't.

Program Development

ROTSTB Version 7

José Antonio Vázquez and Lloyd Barrett

A new version of ROTSTB (Version 7) includes the capability of representing flexible supports using a transfer function representation. This new addition was checked against the program ROTSTBMS. Experimental comparison is underway. This new feature permits the inclusion of flexible support models that contain multiple resonances in the range of interest. This representation of the support model has the advantage that it can be obtained experimentally.

Development of New Rotor Stability Program

José Antonio Vázquez and Lloyd Barrett

ROMAC is developing a new rotor stability program using modal reduction to reduce the number of equations to be solved. It is similar in construct to ACCDES which is our new program for finding suitable hydrodynamic bearing coefficients and magnetic transfer functions based on designer supplied acceptable stability criteria. This new program is being developed to permit easier expansions to include additional effects.

Because it is modally based, models for various rotors and structural components can be developed using existing critical speed or structural finite element programs. In addition the use of transfer function descriptions of bearing supports and casings permits the use of experimental data in the modeling.

This program will include:

1. Multiple rotors and structures.
2. Foundations (modal description).
3. Flexible supports (8-coefficients).
4. Flexible supports and casing described using transfer functions.
5. Tilting pad bearings.
6. Magnetic bearings.
7. Thrust bearings.
8. Fixed geometry bearings.
9. Aerodynamic cross-couplings.
10. Seals.
11. Gyroscopic effects.

Future expansions include:

1. Flexible disks.
2. Tilting-pad thrust bearings.
3. Secondary Rotors (described as transfer functions).

Some of these were discussed at the last ROMAC Annual Meeting.

THPAD

Karl Wygant and Lloyd Barrett

Enhancements to THPAD are being developed. See "Enhancements to THPAD" under Current Research Projects: Fluid Film Bearings and Seals.

SEAL3

Lucy Zhao, Paul Allaire and David Brown (Heriot Watt University)

Development of SEAL3 is nearing completion. See "Annular Seal Program" under Current Research Projects: Fluid Film Bearings and Seals.

Hydrostatic Bearing Code

Paul Allaire and John Kocur (DEMAG Delaval)

We have completed final development of the hydrostatic bearing code for low viscosity liquid lubricants based upon John Kocur's Ph.D. Thesis. Documentation is under development.

Finite Element Magnetic Bearing Modeling

Robert Rockwell, Paul Allaire and Mary Kasarda

A two-dimensional finite element code is being developed for magnetic bearing analysis. See "Finite Element Magnetic Bearing Modeling" under Current Research Projects: Magnetic Bearings.

Equipment Donations

Keep ROMAC in Mind

If you have any surplus instrumentation lying around which you're about to discard or are not using, please consider a donation to our ROMAC labs. It may be quite useful in our experimental research in fluids, rotordynamics and magnetic bearings. Such usable and relatively recent equipment such as FFTs, oscilloscopes (DSO or analog), DVF-2 or DVF-3, 486 PCs, and any type of transducers (position, pressure, acceleration, etc.) would be greatly welcomed and appreciated, especially since our equipment budget is always quite small. In return, you may get an immediate capital write-off on taxes from the gift donation.

Current Research Projects

Fluid Film Bearings and Seals

Tilting Pad Journal Bearing Research

Karl Wygant, Lloyd Barrett and Ron Flack

Testing of 5 shoe tilting pad journal bearings continues on the rigid rotor test rig. This series of test bearings has an L/D ratio of 0.75, offset ratio of 0.5, and an assembled clearance of 2.90 mils. Various preloads are being tested, preloads will range from 0.6 to -0.2. Eccentricities, film thickness, thermal properties, damping, and stiffness characteristics are being compared to predicted values.

A brief synopsis of the research to date: A preload of 0.348 has been tested. Good agreement exists between measured and predicted stiffness and damping coefficients for multiple Sommerfeld numbers. Also, the static operating conditions tend to agree well, particularly at high eccentricity ratios. Two areas are being studied to improve the correlations. The first area is friction in the ball and socket assembly of tilting pad journal bearings. The second influence is fluid shear force on the pad moment balance.

At the moment testing is concentrated on the study of individual pad motion. Button type proximity probes have been installed to measure the dynamic motion of individual pads. It is this pad motion that leads to the dependence of dynamic bearing coefficients on the excitation frequency of the rotor and leads to reduction in cross-coupled stiffness forces. The additional pad dynamic information will help to clarify any discrepancies between measured and predicted coefficients.

A time transient non-linear tilting pad bearing program is being developed to study several interesting areas of bearing performance. The emphasis is to examine how high eccentricity ratios and/or the interaction of multiple excitation frequencies influence stiffness and damping coefficients.

Enhancements to THPAD

Karl Wygant and Lloyd Barrett

The latest release of THPAD is Version 2.63, which was released in late June.

Correlation of measured and predicted bearing properties has led to the investigation of several future enhancements to the predictive capabilities of THPAD. Some of these enhancements are listed below:

1) An improved film thickness model is being incorporated into THPAD. Currently THPAD assumes that pivoting occurs at the pad-fluid interface. This new model accounts for the pad pivoting at a specified location beyond this point.

2) Research is being conducted to examine the best method for including the influence of friction in pivot assemblies. Friction in the pivot assembly can effect pad dynamics as well as film thickness.

3) Under certain loading/speed conditions the shearing of lubricant at the pad-fluid interface can alter the equilibrium position of the pad. It is this same shearing effect that leads to power loss in a bearing. THPAD is being modified to handle this fluid shearing effect in the pad moment balance.

Comparison of Thermal Measurements in Tilting Pad Bearings to THPAD Predictions

Michael Witt and Lloyd Barrett

At the last Annual Meeting a presentation was made on some comparisons of measured temperature data in tilting pad journal bearings supplied by one of our member companies to theoretical predictions made by THPAD. Included in the comparisons was a rudimentary uncertainty analysis in the predictions based on uncertainties in the bearing geometry, lubricant viscosity, and thermal boundary conditions. This work is continuing, and is now focusing on some additional data provided by a member company. In addition to the effect of these uncertainties on the prediction of bearing temperatures, their effect on the predicted stiffness and damping coefficients is also being investigated.

Annular Seal Program

Lucy Zhao, Paul Allaire, and David Brown (Heriot Watt University)

The development of turbulent flow equations for annular seals in plain and grooved seals is continuing. Equations for the stiffness and damping coefficients have been obtained and a computer code SEAL3 written. The results have been favorably compared to experimental results supplied by Prof. Brown. The new code will be released at the next Annual Meeting.

Optimization of Fluid Film Bearings

James Byrne, Paul Allaire, and Susan Carlson

A Master's Thesis project will be conducted by Mr. James Byrne of Carrier Corp. This will consist of a computer modeling of fluid film bearings with existing ROMAC computer codes. A separate optimization code will be developed to select bearing parameters such as length, diameter, number of pads, preload or others to attain desired characteristics such as a given level of load capacity, stiffness, damping or other bearing operational parameters.

Honeycomb Seals

Hossein Haj-Hariri

During the Annual Meeting I presented a plan of attack for the investigation of the flows and forces in honeycomb seals, using a combination of bulk flows, and physical intuition. The crux of the method is the utilization of the aspect ratio of the planform of the honeycombs, and performing a momentum and mass balance for control volumes having such planforms and extending from the base of the honeycomb and spanning the depth of the seal. The fluid interface between the flow-through region and the recirculating flow trapped in the honeycomb is assumed flat and fully developed. Moreover, the highly three-dimensional flow in the honeycomb is viewed as a tensor product of two two-dimensional flows. The equations were presented at the Annual Meeting. The reasoning seems to be on a sound footing. Also, some preliminary two-dimensional simulations of the ideas involved seemed to correctly predict the effects of the honeycomb depth on the performance of the seal.

Based on the above observations, I would like to develop the method for the analysis of straight-through honeycomb seals. First the case of incompressible flows will be studied. Even though most applications of honeycomb seals involve compressible flows, it is much easier to get started with the incompressible case. There exist some experimental results for comparison. Next, I will move to the compressible case.

This work will be conducted by myself originally. If there is indeed the promise that I think it will have, then we may assign a student to the project for the further development of the code.

Fluids

Plexiglas Pump

Daniel Baun and Ron Flack

Over the past few years, tests were completed for the double volute Plexiglas pump. Velocities (from LV data) and pressures were collected. Impeller loads were found for both the single and double volute geometries. Also from the LV data, volute losses and slip were calculated for the double volute case.

The pump has now been modified and magnetic bearings/load cells have been installed which can directly measure the reaction loads at the bearing locations. Both average (static) and instantaneous force measurements can be made. The magnetic bearings have been calibrated to establish their force versus air gap and coil current functions. In addition the nonlinear effects such as hysteresis and eddy currents have been investigated in order to assess their effect on the accuracy of force measurements. Detailed uncertainty analysis will be performed on each calibration relation such that meaningful uncertainties can be determined for *in situ* impeller force measurements. The complete control and instrumentation system (calibrated differential proximity probes for shaft position sensing, high output power amplifiers to drive the bearings, PID controller, and data acquisition system) has been installed and each function verified. On-going improvements in the instrumentation and data acquisition systems have been made on the single volute pump geometry for which LV and pressure data have already been taken. The direct force measurements compared well with previous force measurements from pressure data and also with force predictions from standard thrust models. In addition, measurements have been made with the impeller operating at various positions within the volute. These measurements demonstrated significant variation in the hydraulic forces as the impeller was moved from its centered position. In addition to static force measurements for various impeller/volute geometries, a primary research objective is to measure casing/impeller dynamic influence coefficients: stiffness and damping. A parallel computational effort is also planned. Preliminary work on this aspect of the research effort will commence shortly with a commercial CFD code.

The new system meets expectations of being a quick and relatively accurate method of directly measuring impeller generated hydraulic forces. The flexibility of the design allows for relatively easy modifications to pump geometries.

Torque Converter

Warren Claudel, Alexander Yermakov, and Ron Flack

This is an independently sponsored industrial project that has been used to expand ROMAC's experimental flow visualization capabilities and understanding of the mixed flow in multi-element turbomachines. Laser velocimetry is used to map the internal flow field of seven different torque converter geometries at eleven measurement planes throughout the pump, turbine and stator at three speed ratios corresponding to significantly different torque converter operating conditions. Both steady and transient velocities are obtained to investigate the effect of geometrical design parameters and operating conditions on the internal flow field and element interactions. From the experimental data, slip factors, mass flow rates, input/output torques, and flow angles at element interfaces are determined. Results show highly unsteady element interface flows, large separation regions, and circulatory secondary flows in all elements. These inefficiencies can be minimized through valid geometry modifications supported by the experimental results. Collected experimental data is used to validate computational results obtained by a commercially available 3-D Navier-Stokes code.

Cyclone Cleaner

Mark Fisher, Daniel Baun, and Ron Flack

This new project is sponsored independently by the Technical Association of the Pulp and Paper Industry (TAPPI) and Black Clawson Company. Cyclone cleaners are widely used in the paper industry to separate pulp sludge from water that is used as a transport fluid. The water and pulp sludge mixture enters the cyclone cleaner tangent to the inside radius. This causes the fluid mixture to follow the inside surface of the cleaner wall. The result is a swirling flow that produces high tangential velocities. The conical shape of the cleaner causes the inside surface to have a decreasing radius. This decreasing radius generates higher tangential velocities as the fluid moves downward toward the cleaner outlets. These tangential velocities produce centrifugal forces that cause the more massive pulp sludge to move to the outer surface of the cleaner, while the less massive water collects in the center. The separated pulp sludge and water exit the cleaner through two separate outlets at the bottom. Laser velocimetry is being used to map the internal flow field in a cyclone cleaner at different inflow conditions. Velocity measurements will be made at several different planes inside the cleaner. The data collected will serve as a benchmark to evaluate computational models of cyclone cleaners used to optimize and assess geometries.

Compressor Bearing Forces and Aerodynamic Couplings

Eric Maslen, Ron Flack, Lloyd Barrett, and Dan Baun

At the last Annual Meeting a round table discussion on aerodynamic forces and instability was held. Also, Professor Abraham Engeda of Michigan State University made a presentation of some of his compressor research. ROMAC is developing plans to perform some work in this area.

Prediction of bearing loads from aerodynamics and aerodynamic cross coupling forces in centrifugal compressors is presently, at best, empirical based on only a few data sets. The resulting equations used to predict these properties are quite old and are virtually without experimental corroboration. Consequently, there is significant room for valuable contributions to this field and the ROMAC membership has indicated a strong interest in obtaining high quality experimental data in conjunction with improved (and experimentally validated) modeling.

In the past, ROMAC has been reluctant to enter this research area because we didn't feel that we could establish a credible experimental compressor facility with our available resources, especially space. However, we have begun to explore a collaboration with Dr. Engeda which would provide us with access to such a facility. Dr. Engeda has two centrifugal compressor test stands, each capable of operating at up to 400 horsepower presently and with plans to expand to an 800 horsepower capability. Such an experimental facility is quite expensive to establish so we see collaboration with Dr. Engeda as extremely beneficial to ROMAC.

Our objective is to establish an experimental facility at Michigan which is capable of measuring bearing loads and aerodynamic couplings as well as an advanced computational facility at ROMAC which can model the experiments for model validation and refinement. To construct the experimental facility, we plan to retrofit one of Dr. Engeda's compressors with magnetic bearings calibrated to yield accurate bearing force information in much the same manner as we have done in our own lab with the plexiglas pump rig. The computational facility is presently being established through the acquisition of a high performance computational platform (200 MHz Pentium Pro with 128 MB of RAM) as well as two commercial compressible flow CFD packages: TASCflow and FLOWPLUS.

During the next six months, we will do some initial modeling of a selected impeller/volute/diffuser combination as well as explore the engineering required to carry out the necessary modifications of Dr. Engeda's compressor. At the end of this preliminary period, we hope to have clear enough hardware and analytic plans to be able to pursue the large initial funding required to implement the full scale effort.

Magnetic Bearings

Optimal Control of a Magnetic Bearing without Bias Flux

Charles Yang and Carl Knospe

Conventional active magnetic bearings are operated using a bias current (or flux) to achieve greater linearity and dynamic capability. The disadvantage of operation with a bias is the rotating loss due to eddy currents and hysteresis associated with it. For high speed rotating machinery, this loss may result in excessive rotor heating. Moreover, it results in decreased machine efficiency. Thus, operation without bias is appealing in applications where efficiency is critical, e.g. energy storage flywheels. While control without bias flux is an attractive alternative, it is considerably more complex due to both force slew rate limitations and actuator nonlinearity.

A single degree-of-freedom system consisting of a mass and two opposing electromagnets has been investigated. The optimal control problem is solved for a cost function that represents a trade-off between regulation and energy loss. The result is an optimal variable structure feedback controller which may also be applied to many other applications which contain opposing quadratic actuators. This controller is not practical for implementation since it does not consider system uncertainties or disturbances. Nevertheless, the investigation yields valuable insights into the nature of the problem. More importantly, it provides a benchmark of the optimal control of magnetic bearing without bias, which can be used for evaluation of the performance of a practical feedback controller designed via other methods.

The design of a practical optimal and robust controller for nonlinear systems is challenging due to lack of unified general nonlinear design methodology. Various methods have been investigated such as feedback linearization, sliding mode, backstepping, etc. None of those methods can handle robustness and optimality simultaneously in general. Current research focuses on fairly recent theoretical results, namely, Linear Parameter Varying (LPV) control theory. The nonlinearity and saturation can be treated as varying parameters which are measured on-line. A gain scheduled controller can be synthesized using Linear Matrix Inequality (LMI) methods. Theoretically, this controller can stabilize the rotor and optimally reject disturbances. Our next task is to design such a controller for testing on a flexible rotor test rig.

Robust and Gain Scheduled Controllers for Magnetic Bearings

Steve Fedigan, Carl Knospe and Ron Williams

Algorithms are currently under development that synthesize magnetic bearing controllers which guarantee performance in the presence of both parametric and dynamic uncertainties in the rotor-bearing system. These algorithms will be used to synthesize controllers which will be scheduled on uncertainties which can be measured and robust to those which cannot be determined. Commercial software is currently available which synthesizes controllers that are robust to complex parametric and dynamic uncertainties. This software synthesizes conservative controllers since it is necessary to cover physical parameters which are real quantities by complex numbers. Performance is also sacrificed since the controllers are robust to even those uncertainties which can be measured. The new software will synthesize robust gain scheduled controllers for both real and complex uncertainties. With these extended capabilities, controllers can be developed which offer greater performance in magnetic bearing systems.

Finite Element Magnetic Bearing Modeling

Robert Rockwell, Paul Allaire, and Mary Kasarda

A two-dimensional finite element code has been developed for magnetic bearing analysis. The model includes rotation of the magnetic material in the rotor for proper modeling of the losses as well as upwinding for high velocities. It has the capability of calculating magnetic flux, force on the rotor, rotor eddy currents, and rotor power loss. A user friendly preprocessor allows for easy input of a particular magnetic bearing geometry. This code is suitable for heteropolar magnetic bearing geometries. It will not handle homopolar magnetic bearing geometries. Version 1.1 of the code will be released at the Annual Meeting.

Magnetic Bearing Loss Measurements

Mary Kasarda, Paul Allaire, Eric Maslen, and George Gillies

A NASA funded project on magnetic bearing rotor losses continues. Extensive magnetic bearing rotor loss measurements have been made on four different magnetic bearing configurations: heteropolar and homopolar. Analytical/ empirical modeling of the results has produced a breakdown of the losses into eddy current losses, windage losses, alternating hysteresis, rotating hysteresis, and eddy current skin effects.

Mobil Test Rig

Chris Sortore and Eric Maslen

We have been developing a fault tolerant magnetic bearing demonstration rig for Mobil Oil Corporation for the past five years and expect to have the first real demonstration of this technology in

December. The six foot long rotor is levitated in three radial bearings and one thrust bearing, all magnetic, and has a variable frequency drive kindly donated by Reliance Electric. The rotor weight is about 100 pounds and each of the radial bearings has a capacity of approximately 1200 pounds of force. Development of this machine has been particularly welcome in ROMAC because of its relatively large scale: it is much closer than its predecessors in size and dynamics to the kinds of machinery used by ROMAC members.

The controller for this rig is the ROMAC version 4 digital controller which is designed to be highly fault tolerant. This controller runs identical control algorithms for the magnetic bearings on each of three active CPU's. The outputs from these CPU's are compared to detect discrepancies indicative of a CPU fault. When (if) faults are detected, the faulty CPU is isolated and replaced electrically with a fourth standby unit. This provides the opportunity for CPU replacement on the fly, leading to extremely long MTBF.

In addition to controller fault tolerance, the rig will demonstrate amplifier/coil fault tolerance as well as sensor fault tolerance. The actual currents delivered by the amplifiers are compared to the requested currents. If the detected error for a given amplifier exceeds a reestablished threshold for more than about 3 milliseconds, the controller will assume that that amplifier or its associated coil or cabling/connectors has failed. It will then reconfigure itself to use the remaining amplifiers and coils differently in such a manner as to nearly (as nearly as possible) recover the original bearing performance. This capability is the outcome of David Meeker's dissertation studies which are now available as ROMAC Report No. 392.

Sensor fault tolerance is the easiest of the three to obtain -- the rig simply implements three sets of sensors for each sensed motion. The outputs of the three sensors are compared and the output of one of the two which most closely matches is reported as the actual position. This is essentially an analog voting scheme, similar to what is done in the digital controller.

With the successful demonstration of this test system, we hope to prove the capability of several important component technologies which will lead to a class of extremely reliable magnetic bearing based rotating machines.

Artificial Heart Pump Prototype

Michael Baloh, Edgar Hilton, Ramy Awad, Tim Waters, Dan Baun, Paul Allaire, Eric Maslen, Ron Flack, and George Gillies

This is an ongoing project to develop a continuous flow magnetically supported artificial heart pump as a ventricular assist device. A new prototype, CF3, has been designed and constructed. It has only two magnetic bearings and employs self-sensing so that no physical sensors are used. It is currently undergoing testing at the University of Virginia. Following completion of this work, it will be sent to the Artificial Heart Laboratory at the University of Utah. There it will undergo tests in pumping blood and life support of a cow.

Magnetic Bearing Supported Turbine Generator Modeling

William Foiles, Edgar Hilton, Paul Allaire, Lloyd Barrett, and Eric Maslen

Modeling of a magnetic bearing supported turbine generator set is in progress. The primary objectives are 1) the analysis of rotor drop on auxiliary bearings and the likelihood of rotor whirling and 2) modeling of the rotor/bearing/substructure system with regard to control algorithms.

Foil/Magnetic Bearing Modeling

Minhui He and Paul Allaire

Modeling of foil/magnetic bearings has begun as a small development project within ROMAC. An NSF SBIR contract to model a combined foil/magnetic bearing has been awarded to Cho-Bra Engineering with a subcontract to UVA for some of the work. The objective is to develop a working prototype.

Rotor Dynamics

Rotor Dynamic Effects Due to Thrust Bearings

Lloyd Barrett

At the last Annual Meeting a presentation was made on the effects of fixed geometry thrust bearings on stability of rotor systems. Results were based on a preliminary study for a particular rotor model to gain some insight into the importance of including thrust bearing stiffness and damping effects. It was shown that a logarithmic change of 0.2 due to thrust bearings is not unrealistic. Work is progressing to establish a research program to more systematically assess the effects of thrust bearings. This program will focus on looking at a wider range of rotor models and operating speeds to help provide additional insight into these effects.

During the past year a new release of ROTSTB was made that includes the ability to incorporate fixed geometry thrust bearing models into rotor stability analyses. The new research program being established will also include tilting pad thrust bearing models. One issue that is to be addressed is a better understanding of the frequency dependent effects of pad motion on the reduced stiffness and damping coefficients. This same issue has been of concern in tilting pad journal bearings and arises from the way the bearing models are incorporated into the rotor dynamic analyses. Our goal is to develop ways in which tilting pad thrust bearing dynamics can be effectively included and permit future expansions of the rotor dynamic programs to include other effects such as pivot flexibility and leveling devices.

Effects of Bearing Pivot Flexibility on Rotor Stability and Forced Response

Lloyd Barrett and Karl Wygant

As part of the testing of tilting pad journal bearings underway in ROMAC, we are continuing to look at the effects of pivot flexibility. This project also involves assessing the effects of friction on tilting pad pivots. A transfer function description of tilting pad journal bearings has been developed that will permit inclusion of pivot flexibility effects into rotor dynamic analyses along with the usual tilting pad hydrodynamic stiffness and damping effects. The transfer function description is in conjunction with the work in the project by José Antonio Vázquez (see "Testing of Flexibly Mounted Bearings Supporting a Flexible Rotor") which is aimed at developing a consistent modeling approach for rotor dynamic analyses that will more easily allow expansion for including support, casing, and flexible disk models including models based on experimental measurement.

Testing of Flexibly Mounted Bearings Supporting a Flexible Rotor

José Antonio Vázquez, Ron Flack, and Lloyd Barrett

Work continues on the flexible test rig to experimentally test the effects of bearing supports on the effective stiffness and damping capability of bearings. This rig has been modified to utilize flexible bearing supports. The stiffness of these supports can be modified in the horizontal direction while the stiffness on the vertical direction remains almost constant. Characterization of the supports has been initiated using frequency response functions (FRFs). The first results of these studies were presented in the last Annual Meeting. The effects of the support characteristics on the forced response of the rotor were also presented at the Annual Meeting. Currently, we are obtaining polynomial transfer functions from the FRFs of the supports and will use these transfer functions as the description of the supports in analysis programs like ROTSTB and FRESP2.

Boiler Feed Pump Analysis - Dow Chemical

Paul Allaire, Kelly Fort (Dow Chemical), Curt Reynolds, Lucy Zhao, William Foiles, and David Brown (Heriot Watt University)

Rotor/bearing/seal analysis of an industrial boiler feedpump is underway in cooperation with Dow Chemical Co. The pump has undergone vibration problems in recent years. Modeling of the rotor has been completed. Bearing and seal coefficients are being evaluated using ROMAC codes. The vibration analysis of the pump is in progress.

Including Flexible Disks and Other Attached Components in Rotor Dynamic Analyses

Lloyd Barrett and José Antonio Vázquez

At the last Annual Meeting a presentation was made on a basic formulation for including flexible disk and other attached rotor component models into rotor dynamic stability and forced response analyses. Based on transfer functions, the approach can be applied to a number of existing rotor dynamic code formulations used by ROMAC. With this formulation, the models can be obtained from both analysis and testing. The analytic models suitable for ROMAC programs can be developed from the results of other programs such as general purpose finite element structural programs.

Work is continuing on further developing the formulation to include gyroscopic effects and unbalance forces. A plan for including this formulation into ROMAC computer programs is also being developed.

For More Information

We want to hear from you

Write to ROMAC at the address on the next page. The telephone number to reach our Office Manager is (804) 924-3292. Our FAX number is (804) 982-2246. We can receive Internet electronic mail at romac@virginia.edu. Visit our homepage at http://kelvin.seas.virginia.edu/~romac. Your inquiries, comments, and suggestions will be appreciated. Updates to keep our Industrial Contact List current are always welcome.