■ ROTATING MACHINERY AND CONTROLS LABORATORIES ■

ROMAC

FALL, 1998

Message from the Director

Lloyd Barrett

Once again ROMAC has been busy this past year. In addition to ongoing projects, three new graduate students working on ROMAC projects have joined our laboratory this year: Tom Bernal (compressor aerodynamic project), Robert Prior (bearing test rig), and Pablo Rodríquez (rotor stability with tilting pad thrust bearings). The Annual Meeting in San Antonio last June was well attended and was one of the best meetings we have had. We appreciate the help from Southwest Research Institute, especially Tony Smalley and Bea Moreno, in hosting the meeting including the tour of SwRI and the barbecue dinner. Our meeting next year will be held in Charlottesville.

Work has continued during the past year in making significant improvements to the Shell and Editors for ROMAC computer programs. Our new stability and forced response program, which is nearing completion, will allow us to more easily add additional analysis capability. At the Annual Meeting, Mike Platt of Concepts ETI demonstrated the new RotorLab™ program under development for ROMAC. It offers a much more integrated approach to rotordynamic modeling and analysis using the ROMAC analysis programs and is part of our continuing efforts to improve our computer analysis capability and the ease of use of ROMAC software.

If you have any comments, suggestions, or questions about these efforts or about any of the projects described in this newsletter, please contact the faculty member in charge or me.

We look forward to seeing you next June in Charlottesville

ROMAC Annual Meeting '99

Charlottesville, VA - June 20-24

The 1999 Annual Meeting will be held in Charlottesville at the Doubletree Hotel. The meeting will begin with registration and a reception during the evening of Sunday, June 20 and will end with lunch on Thursday, June 24. Sessions and lunches will be held at the hotel which is just north of Charlottesville with a tour of the ROMAC facilities one afternoon.

There were many positive comments about the 1998 meeting at San Antonio. We endeavor to schedule the Annual Meeting sessions to best accommodate the interests and schedules of our industrial members. At the 1998 Annual Meeting, we expanded the scope of the research overviews at the beginning of the meeting for those attendees who could not attend all sessions. Many of 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. We encourage this interaction and hope that all attendees will take advantage of this opportunity.

Registration materials will be sent to our members in March, 1999. Mark your calendars and plan to join us in June.

ROMAC Programs now available on CD-ROM!

Call the ROMAC Office or send e-mail to jose@virginia.edu to request a copy of the ROMAC CD-ROM with the latest version of all ROMAC programs.

ROMAC Industrial Liaison

José Antonio Vázquez is the 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.

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ROMAC Computer News

José Antonio Vázquez

ROMAC ON-LINE

ROMAC offers a variety of services through our online service. All ROMAC programs are available via FTP (File Transfer Protocol). Our FTP address is:

romacftp.mech.virginia.edu

Users need an account on the ROMAC server in order to have access to the programs. ROMAC is also on the World Wide Web. Members have access to information about ROMAC, ROMAC programs, latest programs and script releases, faculty, staff, students and much more. The address is:

http://www.people.virginia.edu/~romac

Electronic mail (e-mail) is an especially useful tool for providing technical support. All ROMAC faculty, staff and students may be reached using e-mail. ROMAC also maintains a distribution list for notification of program updates. Members that have e-mail but are not included in our mailing list should send e-mail to:

romac@virginia.edu

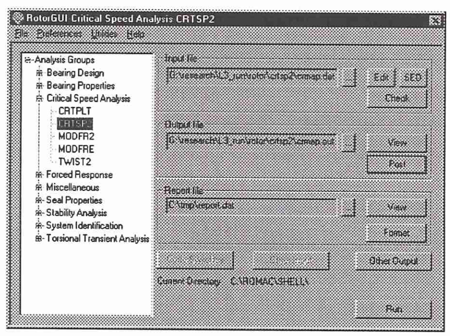
ROMAC User Interface Suite

ROMAC Shell Software

José Antonio Vázquez

The "ROMAC shell" is a collection of support programs that provides an easy interface to the ROMAC analysis codes. The program RomacW is the main component and provides a link to the scripted editor (SED or SEDWIN), the analysis codes, ASCII editors and viewer, rotor geometry plotter (RotorVal) and post-processing capabilities using Tecplot® or other plotting packages to produce final plots.

RomacW is now available for Windows 95/NT. Concepts ETI made the upgrade as part of the agreement reported at last year's annual meeting. The new version was named RotorGUI to differentiate it from the 16 bit version. RotorGUI has the same functionality of the traditional interface but integrates the new looks of Windows 95 and a new comprehensive help file. RotorGUI is distributed as part of the "ROMAC shell" set of programs.



RotorPlot

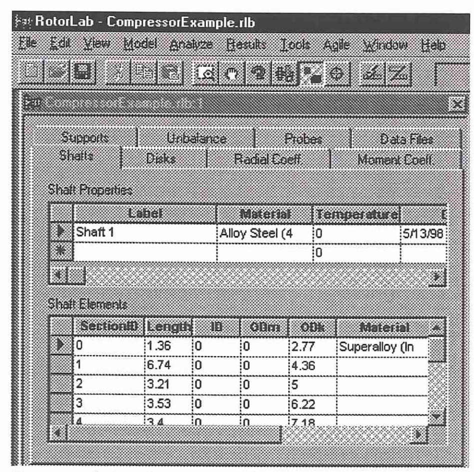
RotorPlot is a generic plotting package developed for ROMAC by Concepts ETI. RotorPlot reads Tecplot data files generated by the ROMAC analysis programs. It provides very simple plotting capabilities and is intended as a temporal solution for those members that have not yet purchased Tecplot.

RotorPlot is distributed as part of the "ROMAC shell" set of programs and can be used through the post-processing feature.

RotorLab™

Mike Platt (Conecepts ETI) and Lloyd Barrett

As part of the software development being performed by Concepts ETI for ROMAC under the agreement reported at last year's Annual Meeting, CETI has been developing an integrated software package, RotorLab, which combines the tasks of design, modeling, analysis, post-processing, and data management into a consistent user interface. The analysis is performed by the standard ROMAC analysis software available to all industrial members. The first version of RotorLab was demonstrated at the last Annual Meeting in San Antonio, and ROMAC and CETI are developing plans for updating and improving this program. The analysis packages currently supported are CRTSP2, RESP2V3, and ROTSTB.

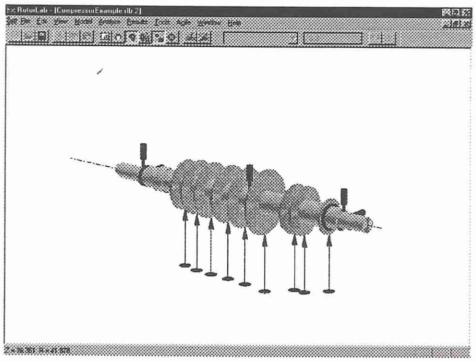


Some of the features of RotorLab include

- Flexible model generation and automatic meshing
- Consistent model definition for a full range of rotordynamic analyses
- Definition of bearing, disk, and support locations by dimension rather than station numbers

- Interactive insertion and movement of elements
- 2D cross-sectional and 3D rendered solid views of rotor assemblies

A survey of the industrial members was taken at the Annual meeting to help us determine new features that you want included in future versions of RotorLab.



ROMAC SED File Releases (Script Files)

MODE_SET.SED *Version 1.0 (07/04/97) by J.A. Vázquez*
Script file that creates setup file for MODEPLT in order to create animated 3D plots.

BRGFILE.SED *Version 1.00 (03/18/98) by J A. Vázquez*
This script is used for THBRG bearing files and is used to import coefficients into RESP2V3.SED.

HCOMB.SED *Version 1.0 (08/13/97) by J.A. Vázquez*
This script is used for data input files in program HCOMB.

SEAL3.SED *Version 1.0 (04/22/98) by J.A. Vázquez*
This script creates the data for SEAL3 version 1.01 and later.

Updated ROMAC Programs

ROMAC Shell

Version 1.33 (03/15/98) updated by T.J. Johnson

- Updated behavior of Shell when launching scripted editor. After using *SEDWIN* under Windows 95/NT, Shell did not enable the run and edit buttons unless the mouse was moved over back window. This behavior was caused by incorrect notification of process culmination in Windows. Problem was solved by adding a timer during operation of scripted editor and then checking condition of editor at each timer event.

THRUST

Version 3.00 (January 1998) updated by Ted Brockett

- Added pad styles of OD shrouded tapered-land bearing and OD shrouded complex tapered-land bearing.
- Corrected thermal boundary condition to the conduction solution in the pad for fixed pad models.
- Improved turbulent models.
- Added pressure boundary conditions to leading edge of tilting pad bearing to model the ram pressure effect.
- Improved tracking of low flow and back flow conditions.

THBRG

Version 2.45 (02/13/98) updated by J.A. Vázquez

- Added more flexible command line options.
- Added plots for bearing coefficients and temperatures for each speed case.
- Moved parameter definitions to file param.inc.
- Changed input, output, console and plot file unit numbers to in,io,ios and ip.
- Moved command line operations and file handling from the READIN subroutine to THBRG.FOR.

Version 2.46 (03/19/98) updated by J.A. Vázquez

- Added an indicator of iteration information.
- Fixed math error that occurred in subroutine FLOW. This error occurred if in flow of the first pad was zero.
- Added output of bearing file. This file contains bearing coefficients and can be used in *ROTSTB* version 7.12 and imported into a *RESP2V3* data file using the scripted editor.

THPAD

Version 2.65 (03/19/98) updated by J.A. Vázquez

- Added full print out file for Tecplot7.
- Eliminated Geograf plot interface.
- Compiled program as 32 bit application.
- Added new command line options.

Version 2.66 (04/17/98) updated by J.A. Vázquez

- Added reduced bearing coefficients to end of bearing file. Program prints a ^Z character and then prints coefficient with same format used by THBRG.

Version 2.67 (07/16/98) updated by L.E. Barrett & J.A. Vázquez

- Added a check to value of stiffness and damping coefficients before calculation of dimensionless damping ratios. This check fixes division by zero error that occurred under certain circumstances.

CRTSP2

Version 2.73 (02/04/98) updated by J.A. Vázquez

- Added option to calculate critical speeds and mode shapes using backward synchronous whirl.
- Added input file description to program source code.

Version 2.74 (03/16/98) updated by J.A. Vázquez

- Corrected problem with mass station number when printing mode shapes if model has two rotors. This problem affected output file but not solution.

ROMAC Short Course

Bearings & Seals

An introductory short course on fluid film bearings and seals in industrial rotating machinery will be offered in mid-May 1999. 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.

Version 2.75 (03/20/98) updated by J.A. Vázquez
- Added output of a plot file. This file is used by *CRTPLT* to produce Tecplot plot files. This modification eliminates need to use *OSED* to create Tecplot files and speeds up the plotting process.

RESPLOT
Version 1.03 (03/31/98) updated by J.A. Vázquez
- Added a check to verify if end of file was reached before reading plot information. If file ended without ^Z command the program reported reading error.

RESP2V3
Version 3.00 (03/23/98) updated by J.A. Vázquez
- Eliminated Geograf subroutines. This modification allows program to be compiled as 32 bit application. Plotting using Geograf is still possible by using program *RESPGEO* distributed with *RESP2V3*.
- Improved command line options.

RESPGEO
Version 3.00 (03/23/98) updated by J.A. Vázquez
- Improved command line options.

ROTSTB
Version 7.11 (01/16/98) updated by J.A. Vázquez
- Modified the way mode shape file was handled. If mode shape file name was not included, the program would not accept name of new file but required name of existing file. This behavior was fixed.
Version 7.12 (03/19/98) updated by J.A. Vázquez
- Added option of including *THBRG* bearing files. Bearing coefficients contained in files are added to list of fixed geometry bearings. Bearings are then organized by station number in ascending order.
Version 7.13 (05/01/98) updated by J.A. Vázquez
- Modified format of plot file to include information used by *MODEPLT* to produce plot files. Data added includes program name, version number, version date and input file name for *ROTSTB*.
Version 7.14 (05/12/98) updated by J.A. Vázquez
- Added switch (-d) to reduce amount of output to console. Using switch causes program to print only the number of iterations needed for convergence to each eigenvalue.
Version 7.15 (08/27/98) updated by J.A. Vázquez
- Corrected printout of coefficients of THBRG bearing files. The Kxy, Kyx, Cxy and Cyx were mixed. This error only affected printout of coefficients. It DID NOT affect operation of program.

MODEPLT
Version 7.3 (05/01/98) updated by J.A. Vázquez
- Changed input format to include *ROTSTB* input file. This gives program much more control and information in case it is required.
- Added rotor geometry to mode shape plots in 2D.
- Added names of input file, output file and mode shape file used in ROTSTB to calculate mode shapes.
- Added ROTSTB version number and version date.

Modified Script Files

THRUST.SED
Version 3.00 (01/25/98) updated by Ted Brockett.
- Allowed for editing of complex tapered land bearings.
- Corrected when relaxation factor and max change value for elastic deformation are modified.
- Added FRACH to list of variables.
- Allowed value of CERR to be up to 100.
- Added variable CRFQ to allow for setting relaxation factor on the fluxes calculated for pad and runner conduction solutions.
- Corrected CRFQ editing so that it must be greater than 0.0.
- Added editing capability for variable JKM that was added to the input data file.

CRTSP2.SED
Version 3.31 (02/04/98) updated by J.A. Vázquez
- Added the option for backward synchronous whirl, consistent with *CRTSP2* version 2.73.
Version 3.32 (03/19/98) updated by J.A. Vázquez
- Improved importation of rotor models from *ROTSTB*. The density of each rotor station is modified to accommodate outside diameter for weight used in *ROTSTB* rotor models.

MODFR2.SED
Version 2.21 (03/19/98) updated by J.A. Vázquez
- Improved importation of *ROTSTB* rotor models. The density of each rotor station is modified to accommodate the outside diameter for weight used in *ROTSTB* rotor models.

RESP2V3.sed
Version 2.3 (03/18/98) updated by J.A. Vázquez
- Added import of bearing coefficients from *ROTSTB*.
- Added import of bearing coefficients from *THBRG* bearing files.
- Added importation of rotor models from *ROTSTB*.
- Script can import a *ROTSTB* file. This includes title files, rotor model and bearing coefficients. Rotor files are imported taking into account outside diameter for weight used in *ROTSTB*. The density at each location is modified to take into account the difference in weight.

ROTSTB.SED
Version 4.5 (03/18/98) updated by J.A. Vázquez
- Added option of importing rotor models from *RESP2V3* files.
- Added option of importing fixed geometry bearing coefficients from *RESP2V3* files.
- Added option of importing full models from *RESP2V3*.
- Added THBRG bearing files.
Version 4.6 (03/19/98) updated by J.A. Vázquez
- Improved import capability for *CRTSP2* and MODFR2 rotor models. Variable weight density is now translated correctly to variable outside diameters for weight.

TECPLOT ® Interface

Starting last year, ROMAC has been migrating plotting from Geograf® subroutines to files compatible with Tecplot®. Plotting capabilities are available for CRTSP2, RESP2V3, ROTSTB, THPAD, THBRG, HCOMB and SEAL3. The Tecplot® interface is normally used through the post processing capability of the ROMAC shell.

Tecplot® has a macro language that performs operations normally done by the user, such as formatting, resizing of plots, creation of XY-maps and data manipulation. ROMAC provides default macros for the creation, formatting and management of plots created with ROMAC programs. Users can modify these macros or write their own to replace the generic plots with ones specialized for their needs. See ROMAC report #423 for more detailed information.

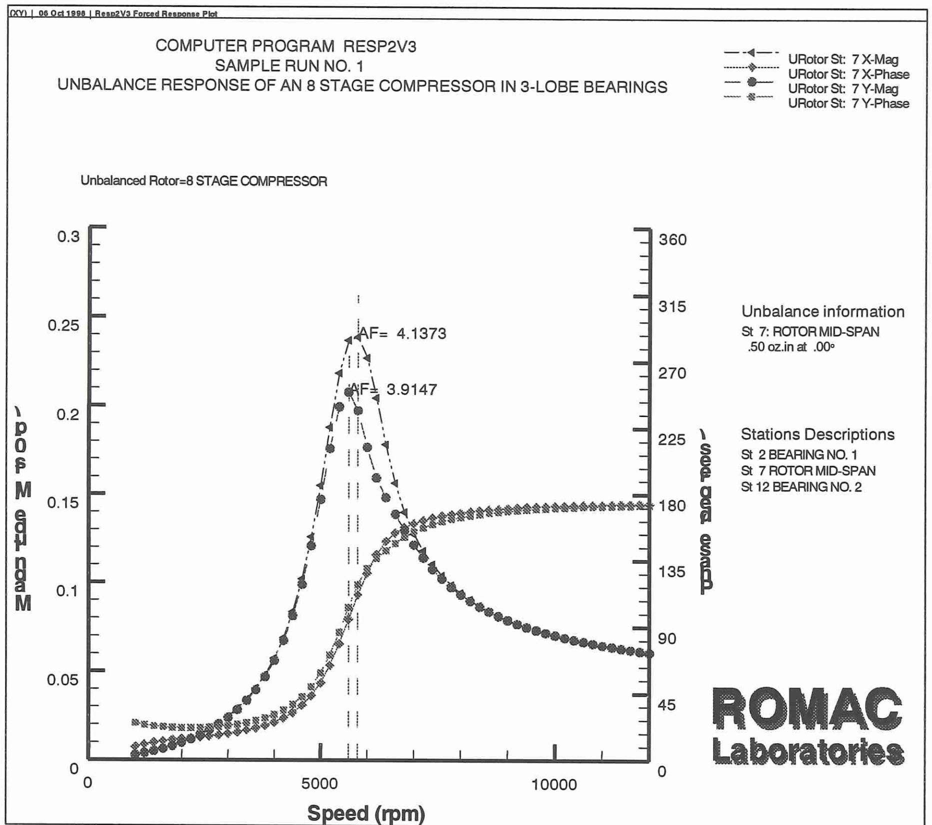
New Tecplot Macros:

HCOMB.mcr

This macro formats axial profile plots calculated by *HCOMB* and provides tools for management of these plots.
Version 1.00 (08/13/97) by J.A. Vázquez
This macro:
- Resizes plot screen.
- Changes fonts of axis titles and labels.
- Changes symbols and colors for maps.
- Creates functions to be run from quick macro function panel.
- Adds ROMAC name on the plots.

THBRG.mcr

This macro provides formatting and management tools for THBRG plots.
Version 1.00 (02/10/98) by J.A. Vázquez
This macro:
- Resizes plot screen.
- Creates X-Y maps.
- Changes fonts of axis titles and labels.
- Creates and displays legend.
- Changes symbols and colors for maps.
- Creates functions to be run from quick macro function panel.
- Adds ROMAC name on plots.



THPAD.mcr

This macro provides formatting and management tools for THPAD plots.
Version 1.00 (02/10/98) by J.A. Vázquez
This macro:
- Resizes plot screen.
- Creates X-Y maps.
- Changes fonts of axis titles and labels.
- Creates and displays legend.
- Changes symbols and color for maps.
- Sets problem for all bearing properties and speed cases.
- Creates functions to be run from quick macro function panel.
- Adds ROMAC name on plots.

SEAL3.mcr

This macro provides formatting and management tools for SEAL3 plots.
Version 1.00 (04/24/98) by J.A. Vázquez
This macro:
- Resizes plot screen.
- Creates new X-Y maps for plots in file.
- Changes fonts of axis titles and labels.
- Creates and displays legend.
- Changes symbols and color for maps.
- Sets problem for all plots.
- Deletes extra X-Y maps.
- Creates functions to be run from quick macro function panel.
- Adds ROMAC name on plots.

Modifications to Tecplot Macros:

CRTSP2_7.mcr

Macro for undamped mode shapes calculated using CRTSP2.
Version 2.01 (05/01/98) by J.A. Vázquez
- Sets ticks to be outside the axes and sets labels at an offset of 3%. This is necessary to better show rotor geometry.

RESP2V3.mcr

Macro that plots the response calculated by RESP2V3.
Version 1.01 (06/16/97) by J.A. Vázquez
- Added drawgraphics cut off instruction. This feature improves speed of macro and avoids multiple repainting of screen before macro finishes.
- Corrected autoscaling for first plot drawn on screen.
Version 1.02 (06/16/97) by J.A. Vázquez
- Added 10\% to vertical axis. This makes room for amplification factors.
Version 1.03 (06/17/97) by J.A. Vázquez
- Fixed problem when only one zone was present.

ROTSTB.mcr
Macro for eigenvectors calculated using ROTSTB (the plotting is done in X-Y coordinates)
Version 1.01 (05/01/98) updated by J.A. Vázquez
- Changed location of tick marks to make space for rotor geometry drawing.
- Lowered location of legend to make space for name of program, date, and version number.

3dROTSTB.mcr
Version 1.01 (05/01/98) updated by J.A. Vázquez
- Resized plot in order to make space for names of input file, output file and plot file.
- Changed location of axis reference in order to make room for version number and date of ROTSTB.

ROMAC3.mcr
Version 1.01 (06/02/98) updated by J.A. Vázquez
Added some variables to make it easier to change name displayed in logo. There are two lines available. User may use this macro or a template to create a logo.

New Computer Programs

BRGPLT
Companion program for *THBRG* that creates a Tecplot data file with a plot of the geometry of bearing. This program is distributed as part of *THBRG*.
Version 1.00b (01/17/98) by J.A. Vázquez
- BRGPLT creates geometry plots including both cuts that can be plotted separately or combined to show final geometry.
Version 1.01 (04/29/98) updated by J.A. Vázquez
- Corrected spelling in output figure.

CRTPLT
Companion program for *CRTSP2* that reads plot file created by *CRTSP2* and creates Tecplot files with plots for critical speed maps or undamped mode shapes depending on the options selected. This program is distributed as part of *CRTSP2*.
Version 1.00 (03/23/98) by J.A. Vázquez
- *CRTPLT* reads *CRTSP2* plot files and produces mode shape plot files and critical speed maps for Tecplot 7. The introduction of this program gives more consistency to plotting process between different rotordynamic programs.
Version 1.01 (05/01/98) updated by J.A. Vázquez
- Corrected problem when creating mode shape plots for single rotor. Program created header for zone with zero elements. Although this is in principle correct, it is not accepted by Tecplot.
- Added rotor geometry to mode shape plots. Rotor geometry is located at bottom of screen but can be moved by selecting rotor and changing Y coordinate.

HCOMB
Honeycomb gas seal program.
Version 0.9b (05/24/97) by Hossein Haj-Hariri
The approach is based on a bulk-flow analysis with special consideration for the role of honeycomb cells. They are viewed as side-branch capacitances and serial resistances. With this simple view of the role of the cells they may be replaced by effective friction effects. Moreover, preswirl effects, as well as entrance losses and exit recoveries, are accounted for.
Version 1.0b (08/11/97) updated by J.A. Vázquez
- Added command line options.
- Modified input format to accept formatted input.
- Made programs *leak* and *force* into a single program *HCOMB*.
Version 1.00 (08/13/97) updated by J.A. Vázquez
- Created output file structure.
- Added options:
  echo input file
  show convergence history.
  show axial profiles.
  conversion routine for old UNIX input files using namelists.
- Changed temporal file used by subroutine Force to be a volatile file that is destroyed at end of program.
- Added plot file for Tecplot.
- gnu plotting was removed since it was not used and required the use of UNIX specific commands.
Version 1.01 (11/10/97) updated by J.A. Vázquez
- Added unit printout to output file.

PADPLT
Companion program for *THPAD* that creates Tecplot data files with a plot of the geometry of the tilting pad bearing. This program is distributed as part of *THPAD*.
Version 1.00b (02/06/98) by J.A. Vázquez
- This program creates a Tecplot file with the geometry of the tilting pad bearing, including pivot locations, preload and offset factors.
Version 1.01 (04/29/98) updated by J.A. Vázquez
- Corrected spelling in output figure.

RESPLOT
Companion program for *RESP2V3*. It reads plot file and input file and creates a Tecplot data file. This program is distributed as part of RESP2V3.
Version 1.03 (03/31/98) updated by J.A. Vázquez
- Added a check to verify if end of file was reached before reading the plot information. If file ended without ^Z command the program reported reading error.

SEAL3
Program for pump seals.
Version 1.0 (03/20/98) by Lucy Zhao and Paul Allaire.
- *SEAL3* uses a bulk fluid flow perturbation analysis to evaluate rotor dynamic coefficients for stiffness, damping and mass coefficients. It can analyze both plain and circumferentially grooved seals. It adds inlet swirl, mass coefficients and surface roughness.
Version 1.01 (04/21/98) updated by J.A. Vázquez
- Changed format of input file to make it compatible with Shell and scripted editor.
Version 1.02 (04/23/98) updated by J.A. Vázquez
- Added more flexible command line options.
- All file control is managed by main subroutine. This subroutine now handles entire opening and closing of files making it easier to track data files.

- Grouped all extra files into a plot file for Tecplot.
- Eliminated file uzn.out and put its information into output file if history option is selected.
- Divided output into "echo of input," written before calculation, and "printout of output," written after calculations.

SEDWIN.
ROMAC Scripted Editor for Windows 95/NT
Version 1.21 (03/20/98) by T.J. Johnson
- This new version of the scripted editor is fully Windows 95/NT compatible. This new scripted editor was demonstrated during the last annual meeting.

Program Development

Development of New Rotor Stability and Forced Response Program FORSTAB - *José Antonio Vázquez and Lloyd Barrett*

The development of the stability program STB has been expanded to include forced response analysis. The program has been renamed FORSTAB. FORSTAB uses modal reduction to reduce the number of equations to be solved. Because the program is modally based, models for various components can be developed using existing critical speed programs or finite element programs or can be measured experimentally. FORSTAB can use transfer function descriptions for bearing supports and casings. This feature permits the use of experimental data in the modeling of these components.

Experimental verification of the results calculated with this program is underway. The program was demonstrated at the last annual meeting and will be released in the first part of next year.

This program includes:

1. Multiple rotors and structures;
2. Foundations (modal description);
3. Flexible supports (8-coefficient models);
4. Flexible supports and casings described using transfer functions;
5. Tilting pad bearings;
6. Magnetic bearings;
7. Fixed geometry bearings;
8. Aerodynamic cross-couplings;
9. Seals (includes mass terms);
10. Gyroscopic effects;
11. Calculation of damped mode shapes for stability and forced response;
12. Interface with Tecplot® for graphic output;
13. 2D, 3D and 3D animated mode shapes;
14. Multiple unbalance locations;
15. Report of absolute and relative unbalance response;
16. Calculation of amplification factors and separation margins following API-617.

RECENT LABORATORY EQUIPMENT ACQUISITIONS

ROMAC participates in the Commonwealth of Virginia's Equipment Trust Fund (ETF) Program, wherein the University is granted matching funds by the State, towards the purchase of new laboratory equipment for use in its teaching and research missions. This is one particular method in which ROMAC funding gets leveraged relative to our laboratory needs. The fund match from the state is typically one-for-one, thus making it possible, in essence, to purchase new equipment at the equivalent of "half-price" to ROMAC. This year, we took advantage of the ETF program to procure a new spectrum analyzer for the ROMAC Laboratories. The specific unit on which we decided was a Stanford Research Systems Model SR785 Two Channel Dynamic Signal Analyzer, which comes with the features we need for use in our many different types of rotor dynamics and bearing testing experiments.

Requests for ETF recommendations are solicited early each Summer, and the School of Engineering's total request is considered by the state in the following Fall. A list of approved equipment is subsequently provided to each of the Department Chairs, and purchase requisitions are then placed near the end of the calendar year. Although this is a long lead-time process, the significant financial benefit to ROMAC and its member companies makes it all very worthwhile. Individual items of capital equipment are also purchased directly on an individual basis by ROMAC during the academic year, on an "as needed" basis.

The purchase and maintenance of capital equipment is an important issue for our laboratory, and especially so with items as costly as general purpose, wide band spectrum analyzers. Only this past Summer, we retired two such measurement systems that had been in virtually continuous use at ROMAC for well over 15 years. These were a Hewlett-Packard 3582A Spectrum Analyzer and a Hewlett-Packard 5423A Structural Dynamics Analyzer system, both of which were essentially worn out from the nearly constant use by several generations of graduate and undergraduate students. We make every effort to maintain our equipment properly and get every penny's worth of serviceable lifetime from it, but even so, all of these items eventually reach the limit of their utility. Therefore, long-term loans and gifts of equipment are very important to ROMAC Laboratories, and we encourage our members to consider this possibility when evaluating their own inventories of test and measurement hardware and software, which might contain surplus items that could be of use to us. Please contact George T. Gillies at (804) 924-6235 for further information.

CURRENT RESEARCH PROJECTS

Fluid Film Bearings and Seals

Tilting Pad Journal Bearing Research - *Karl Wygant, Ron Flack, and Lloyd Barrett*

Work is continuing on the interpretation of several years' worth of data obtained from the fluid film bearing test rig. A series of test bearings with length-to-diameter ratios of 0.75, offset ratios of 0.5, and assembled radial bearing clearances of 2.90 mils, have been tested. All tests were carried out for speeds of 900 rpm, 1650 rpm, and 2250 rpm. The static loads applied to the test rig result in Sommerfeld number range of 0.1 to 2.0. Predictions using THPAD are being compared to measured eccentricities, film thickness, pressure profiles, and dynamic coefficients (reduced from dynamic forces and resulting vibration displacement).

A brief synopsis of the ongoing research areas in the testing of fluid film bearings follows.

The importance of pivot mechanism on bearing performance:

The emphasis of this research is to establish the influence of pivot mechanisms on tilting pad performance. From previously disclosed experimental measurements of ball and socket pivoted bearings, the hypothesis of pivot friction has been presented. Future tests are helping to validate and quantify this hypothesis. Specifically, research is centering on how pad static loading (directions and magnitudes) influence static and dynamic properties.

Influence of Preload and Sommerfeld Number:

A detailed comparison of analytic predictions to experimental measurements is being completed. This research demonstrates the functionality of tilting pad bearings in the negative preload regime. The importance of this work is twofold. First, the validity of analysis codes to predict bearing properties with negative preloads is being validated. Second, this research establishes the measured trends for a range of preloads and Sommerfeld numbers. This again is an important aspect in the validation of THPAD to experimentally derived data.

Significance of Pad Dynamics on Reduced Dynamic Coefficients:

This research establishes the influence of excitation frequency on tilting pad journal bearings. Sinusoidal forcing functions with frequencies ranging from 0.1X to 10X have been applied to a negative preload test bearing. Plots of stiffness and damping versus excitation frequency at constant Sommerfeld numbers show the importance of including pad dynamics in any analytic endeavor.

Repeatability and Uncertainty:

The rigid rotor fluid film test rig offers unparalleled detail on accuracy and repeatability. Comprehensive work is in progress that tracks both repeatability and the uncertainty of all measurements made in the past several years. This work is meaningful because it provides the confidence level to which analytic validation can be claimed. Also, insights into the non-linearity of bearing properties may be gleaned from this work.

Continued Bearing Testing - *Robert Prior, Ron Flack, and Lloyd Barrett*

A new graduate student, Robert Prior, has joined the laboratory this fall. Pursuing an MS degree, Rob will be taking over bearing testing using the fluid film bearing test rig. Rob received his BS degree from the University of Rhode Island in 1991 and worked for EG&G Mechanical Components, Group Research and Development in Cranston, RI until joining us. He has also taken some graduate courses at Worcester Polytechnic Institute and has several AIAA publications in the area of seals.

Besides taking courses, Rob is busy learning how to operate the test rig, and we hope to begin testing by the year end.

Labyrinth Gas Seal Code/Program Development - *Jinghui Chen, Paul Allaire, Ron Flack, and Rainer Nordmann (Darmstadt University)*

A new gas labyrinth seal analysis code, LABY4, is under development to replace LABY3. Labyrinth seals are composed of seal teeth and chambers between the teeth. Conventional seal codes such as LABY3 often do not accurately predict the rotor dynamic coefficient stiffness and damping. A three volume approach has been developed for the seal analysis: volume 1, the volume over the seal teeth; volume 2, the volume over the seal chamber; and volume 3, the seal chamber. Bulk flow equations are used in each volume with a zeroth order centered flow solution and a first order perturbation flow. The perturbation flow is used to evaluate the seal stiffness and damping properties. At this time, the zeroth order code has been written and is being verified. The 3-D fluid flow code TASCflow, by AEA, is being used to evaluate details of the flow and improve the computer code. The first order perturbation section of the code is under development.

Liquid Annular Seals/Helically Grooved Seals/Program Development - *Paul Allaire, Jinghui Chen, and David Brown (Heriot Watt University)*

It is desired by a number of ROMAC companies to continue to improve the annular liquid seal codes. The new seal code for plain and annular grooved seals, SEAL3, was recently developed and released. The new topics under development are inlet swirl and helically grooved seals. The equations of motion are under development. It is expected that a three volume approach, similar to that for gas labyrinth seals, will be employed.

Optimization of Fixed Pad Fluid Film Bearings for Rigid Rotor Machines - *James Byrne, Paul Allaire, and Susan Carlson-Skalak*

A fixed pad fluid film bearing optimization computer code has been developed for the design of low power loss, minimum film thickness and high rigid rotor stability. It is based upon the code THBRG with some enhanced convergence routines. Bearing length, diameter, preload, pad length and other factors in the bearing are adjusted to produce the optimum design. The optimization method is extended to a two bearing rigid rotor such as found in air conditioning compressors and other rigid or nearly rigid rotors. The code will be released in 1999. This project is funded by Carrier Corp. of United Technologies, Inc.

Tilting Pad and Fixed Pad Bearing New Governing Equations and Computer Code - *Minhui He and Paul Allaire*

New, more accurate forms of Reynolds and energy equations with cross film viscosity variations have been formulated. These forms allow for the solution of the equations without having to solve a three dimensional finite element problem. A two-dimensional finite element formulation has been developed for the future bearing code. Further, the formulations allow for treatment of the new industrial type leading edge and other lubrication methods as well as axial pressure gradients in the bearing pads. Test cases are currently being run to verify the accuracy of the new formulations.

Fluids

Plexiglas Pump - *Daniel Baun and Ron Flack*

The Plexiglas pump apparatus has 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 (dynamic) force measurements can be made. All bearings have been calibrated to establish their force versus air gap and coil current characteristics. In addition the uncertainties due to hysteresis and the frequency limitation of the bearings have been determined. The complete control and instrumentation systems (calibrated differential proximity probes, high output power amplifiers, PID controllers, and data acquisition system) have been installed and their functions verified. A digital open loop controller has been added to the apparatus. The digital open loop controller is required such that all the harmonics in the rotor's orbital motion can be controlled. This allows the orbital paths between the reference force measurements and the actual hydraulic force measurements to be duplicated.

Force measurement tests have been run for the single, symmetric double and concentric volute pump geometries using both 4 and 5 vaned impellers. Some of the direct force measurements were compared to the forces previously calculated using LV and pressure data. Reasonably good comparison was observed. In addition comparisons with other published force measurements and standard thrust models were made. An extensive study of the effect of impeller-to-casing relative position on hydraulic force and hydraulic efficiency was made for the 4 vaned impeller operating in the concentric volute. Three very interesting and significant findings from this study are: (1) A concentric volute pump can be made to have the same static force characteristic as a conventional log spiral volute pump. (2) A concentric volute pump can be made to have a comparable or even slightly higher efficiency than that of a conventional log spiral volute pump. (3) The optimal impeller-to-casing relative position to obtain (1) or (2) are the same. Some preliminary studies of the static impeller position stiffness for both the single volute and the concentric volute configurations with a 4 vaned impeller were made. Both casings exhibited negative direct stiffness and destabilizing cross-coupled stiffness characteristics. A testing program designed to measure casing/impeller hydrodynamic interaction coefficients (added mass, stiffness and damping) is currently underway. This program will include an investigation of the effect of static impeller eccentricity on the dynamic coefficients. In addition a comparison between static and dynamic impeller stiffness will be made. Paralleling the experimental work, a computational effort using the commercial CFD code, TASCflow, has been initiated. The goal of this effort is to model the Plexiglas pump and establish good correlation between the forces from the CFD and the direct forces from the apparatus. Some preliminary simulations have been made. Using the experience and knowledge gained from modeling the incompressible flow in the Plexiglas pump, analogous CFD studies will then be conducted for compressible flows.

Torque Converter - *Mark Gruber, Ron Flack, and George Gillies*

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. The internal flow field of different torque converter geometries are studied using laser velocimetry at different measurement planes throughout the pump, turbine and stator at three speed ratios corresponding to significantly different torque converter operating conditions. Both steady and periodic velocities are obtained. The effects of blade angles, passage shapes and operating conditions on the internal flow field and blade interactions are studied. From the experimental data, slip factors, mass flow rates, input/output torques, and incidence angles 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 project was sponsored independently by the Technical Association of the Pulp and Paper Industry (TAPPI) and Black Clawson Company and was completed over the past year. 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 was used to map the internal flow field in a cyclone cleaner at different inflow conditions. Three-dimensional velocity measurements were documented at several different axial planes. Several significant anomalies were identified including backflow and flow asymmetry. The data collected is serving as a benchmark to evaluate computational models of cyclone cleaners used to optimize and assess geometries.

KSB Pump - *Jens Kuss, Daniel Baun and Ron Flack*

Previous research was an investigation into the effects of discharge geometry and impeller/volute relative position on the hydraulic performance (efficiency, power & total head), and radial hydraulic forces in a centrifugal pump. In addition qualitative flow visualization using streak photography of the flow field in the region of the discharge was conducted. The streak photography results were correlated with the measured hydraulic performance parameters and radial thrust distributions. A number of volutes and discharge configurations were investigated and various impeller/volute relative positions were studied. Different specific speed pumps are currently being tested with the inclusion of surface oil flow visualization.

Experimental Compressor Program - *Eric Maslen, Lloyd Barrett, Ron Flack, and Tom Bernal*

A new Master's degree candidate, Tom Bernal, has replaced Ryan Brown who has departed to take a job in Minnesota. Mr. Bernal comes to us with extensive industrial experience having most recently worked as an environmental controls engineer for Johnson Controls. The change in personnel has delayed this project a bit, but it is quickly getting back on track. At this point, all contracts are signed and parts are in production. We expect to assemble the prototype compressor in November and December and have it levitated for bearing checkout by the end of January 1999.

Vortex Visualization - *Eric Maslen, Hossein Haj Hariri, Ron Flack, John DeYoung*

John DeYoung will complete an undergraduate senior thesis detailing his extensive work on this complicated magnetic suspension problem in May 1999. His work has brought the test apparatus to its present state of sphere suspension in refraction index matching oil. We are able to motor the sphere with moderate performance and are presently conducting some experiments to try to resolve a problem leading to torsional jitter and instability at elevated spin rates.

Artificial Heart Pump Hydraulic Performance and CFD Modeling - *Jay Anderson, Houston Wood, Paul Allaire, Naihong Wei, Edgar Hilton, Anthony Curtas, Eddy Miller, Ron Flack, Dan Baun, and Jim McDaniel*

The artificial heart pump is a very small centrifugal pump designed to be implanted and pump blood in humans. The pump is approximately 4 inches in diameter and 1.6 inches long. The design flow rate of 6 to 10 liters per minute and head of 100 to 160 mm Hg was successfully obtained in both water and blood. Pumps in this small size are not commonly discussed in the pump literature and it is not known exactly how they should perform. Computational fluid dynamic (CFD) methods are being used to model the flow in the pump impeller and clearance passages (approximately 40 mils on each side) using the AEA TASCflow code. Washing flow through the clearance passages is required to keep the flow from stagnating and clotting. Analysis indicates that the impeller generates very strong flow but that the existing large clearances allow high backflow rates of as high as 60% of the impeller flow back through the clearance passages to the inlet. A much smaller clearance (15 mils on each side) would greatly reduce this leakage flow but still provide for the needed washing flow. New prototypes are under construction.

Laser Measurements in Artificial Heart Pump - *Steven Day, James McDaniel, Paul Allaire, and Ron Flack*

The artificial heart described above will be employed in laser studies of the fluid flow passages. A planar imaging velocimeter (PIV) state-of-the-art laser system will be used to measure the fluid flow in the front clearance passage to evaluate the critical flow parameters. A full two dimensional sheet of light placed in the passage and carefully timed digital illumination allows for the measurement of all of the fluid velocity vectors to be measured at one time, fully capturing the flow properties.

Magnetic Bearings

Self-Sensing Magnetic Bearings - *Eric Maslen and Dominick Montie*

We now have two funded efforts underway, supported by the National Science Foundation and NASA. The objective of this work is to develop better self-sensing methods and to demonstrate them on a high speed rotor. We expect to be spinning a levitated rotor by early next year in magnetic bearings with a neural network based self-sensing estimator. In later work for NASA, we will explore self-sensing in highly loaded bearings where magnetic saturation substantially modifies the actuator properties, complicating the self-sensing task.

In a recently completed preliminary study of self-sensing using multi-input - multi-output parameter estimation, we have demonstrated that a single parameter estimator can provide accurate position sensing even when a portion of the actuator and/or drive mechanism has failed. This holds strong promise for increasing the level of integration of fault tolerant systems since the mechanism for actuator fault tolerance will automatically provide sensor fault tolerance.

Control of a High Speed Milling Spindle - *R. Fittro, C. Knospe, and E. Maslen*

Over the past few years, in cooperation with an industrial sponsor, we have designed, fabricated, and tested a new high speed milling spindle equipped with active magnetic bearings. This spindle has been magnetically levitated first with decentralized PID feedback control and later with multivariable controllers developed via application of μ-synthesis.

The spindle has three radial magnetic bearings as well as a thrust bearing for controlling the motion in the axial direction. The spindle uses differential optical sensors to determine the radial and axial position of the shaft and is controlled by a parallel processing digital controller designed and built at the University of Virginia. Four Texas Instruments TMS320C40 digital signal processors are employed for control algorithm computations. This hardware platform permits the execution of a 7 input, 7 output, 75th order controller with a throughput rate in excess of 12 Khz.

In the last year we have demonstrated some extremely sophisticated multivariable feedback controllers on the spindle. The results indicated that we can expect to achieve a 30 to 50% improvement in performance (reduction in dynamic tool compliance) over the best that could be achieved by conventional decentralized control methods. This work has greatly advanced the state-of-the-art in magnetic bearing feedback control. The spindle has been operated up to 20,000 rpm.

Low Bias Control of Magnetic Bearing Losses - *J. Lindlau and C. Knospe*

Active magnetic bearings (AMB) are currently under consideration for application to energy storage flywheels (ESFs). These bearings quite often suffer from high operating losses due to the rotation of the magnetic bearing journal in the stator's magnetic field. Such losses may provide a significant obstacle to the application of AMBs to ESFs unless very unorthodox, new approaches are employed.

Our research seeks to develop the theory and practical knowledge for the employment of gain-scheduled, nonlinear controllers for the minimization of rotating losses so as to achieve stable and robust magnetic suspension of high-speed, flexible rotors.

Our approach to design the nonlinear feedback controllers takes advantage of the recent breakthroughs in the theory of gain-scheduled control. Using Linear Matrix Inequality (LMI) methods, robust, feedback control algorithms can be synthesized that are a continuous function of time-varying parameters. This eliminates the need for large controller look-up tables and the interpolation between entries in these tables. This method also guarantees performance even with quickly varying parameters, unlike earlier gain scheduling approaches based on look-up tables. Most importantly, these techniques can be applied to the development of a controller for nonlinear systems via a quasi-LPV formulation.

Over the past year we have constructed one DOF test rig and have very carefully identified its dynamics. We are now prepared to design and implement the nonlinear control laws.

Control of Reaction Wheel Jitter - *C. Knospe*

Magnetic bearing reaction wheels are currently being considered for attitude control for the Next Generation Space Telescope because of the increased control that they provide for the attenuation of transmitted vibration. This jitter will be induced through both imbalance and sensor runout. While the imbalance forces will be synchronous (1X) with the wheel speed, the sensor runout will have both synchronous and harmonic components (2X, 3X, etc.). Over the past 5 years, we have developed a technique, known as

Adaptive Vibration Control (AVC), for greatly reducing synchronous vibration in rotating machinery on active magnetic bearings. This method is essentially an adaptive feedforward approach specifically tailored for the problem of rotating machinery vibration. We will apply this technique to a magnetic bearing reaction wheel (MASAREDI) at NASA Goddard Space Flight Center so as to reduce the synchronous and harmonic forces transmitted.

The AVC algorithm has been successfully applied to several different rotating machinery applications including turbomolecular pumps and a large hydrogen compressor. Both UVA researchers and Revolve Magnetic Bearings have now demonstrated the reduction of transmitted synchronous forces by over 40 dB. An extensive theory for the robustness of AVC has also been developed.

Magnetic Bearing Loss Measurements - *Andy Braden, Paul Allaire, George Gillies, and Mary Kasarda (Virginia Tech)*

The high speed bearing loss test rig continues in operation. A series of bearings with equal pole face area, equal bias flux, and other comparable properties has been tested. The results so far have shown that the rotor power loss in magnetic bearings is approximately proportional to the bias flux density squared and inversely proportional to the air gap thickness. In contrast to previous theoretical expectations, the loss is independent of the number of poles in the bearing. At this time, a vacuum chamber is being fitted to the test rig to remove the losses due to air drag and concentrate on the magnetic losses in the rotor. Future bearings to be tested include cobalt iron rotors, thin laminations (7 mil thickness) in the existing heteropolar/homopolar stators. A new homopolar stator has also been obtained from an industrial manufacturer of magnetic bearings. This project is funded by NASA Lewis Research Center.

Magnetic Bearing Finite Element Loss Computer Program - *Robert Rockwell, Paul Allaire, Catherine Lebiedzik, Mary Kasarda (Virginia Tech), Andy Provenza (NASA Lewis) and Gerry Brown (NASA Lewis)*

A 2-D finite element computer code was developed for magnetic bearing configurations. It included the effect of moving magnetic material in the rotor to evaluate the eddy currents generated in the rotor and the power losses. The calculated values gave good correlation to experimental measurements when an effective axial conductivity was used to model the lamination effects. Material saturation effects are currently being added to the code.

A 3-D finite element computer code is under development for computing iron losses in laminated magnetic bearings. It is capable of modeling both heteropolar and homopolar bearings. Eddy current losses in laminated rotors are modeled using an analytical solution for the magnetic vector potential in the rotor. This analytical solution will be coupled to the finite element solution in the rotor to allow for a full solution of the eddy currents in each lamination. This project is funded by NASA Lewis Research Center.

Adaptive Magnetic Balancing of Flexible Rotors Using Singular Value Decomposition Methods - *Williams Foiles, Paul Allaire, Edgar Hilton, Jihao Luo, and Takis Tsiotras*

Adaptive magnetic balancing of high speed flexible rotors supported in magnetic bearings is under development. It uses the singular value decomposition, coupled with an influence coefficient method, to determine the optimum magnetic balancing method for flexible rotors. The Moore-Penrose generalized inverse is employed to solve the problem. The minimum number of balance planes, as well as minimum balance weights, can be used to effectively balance the rotor. The method will be implemented on the magnetic bearing controls test rig. This work is sponsored by NASA Goddard and American Flywheel Systems.

Linear Parameter Varying Controls for High Speed Flexible Rotors - *Jihao Luo, Edgar Hilton, Paul Allaire, Edgar Hilton, Takis Tsiotras (Georgia Tech), Zongli Lin and Hai Zhang*

High speed flexible rotors such as those used for high speed energy storage flywheels have properties which are not time independent. This is due to gyroscopic effects and other changes in the rotor such as centrifugal growth. A new linear parameter varying control method for use with such rotors has been developed. The method produces an overall reduction in vibration amplitude or other rotor parameters over a wide speed range. An algorithm has been developed for a test rig rotor in the controls test rig. At this time, rotor and bearing properties are being evaluated and uncertainties are being estimated. The controller will be experimentally implemented in the near future. This project is sponsored by NASA Goddard and American Flywheel Systems.

Real Time Control of High Speed Magnetic Bearing Systems - *Edgar Hilton, Paul Allaire, Marty Humphrey, and Naihong Wei*

Computer control of magnetic bearing systems requires high speed real time control. The computer system must have high through put rates that should be modular in nature. Newer and faster computers are continually coming online and other components such as A/D and D/A devices are improving as well. A methodology is being developed for implementation of high speed magnetic bearing real time controls using Unix based systems which can include new more advanced hardware as it comes along while only a minimum of software changes need to be made in the system. A system of this type is under development for the controls test rig for rotor operation up to approximately 20,000 rpm. Three suitable computers have been selected and purchased, as described below. This project is sponsored by NASA Goddard and American Flywheel Systems.

Magnetic Bearing Controls Test Rig - *Edgar Hilton, Paul Allaire, Naihong Wei, Marty Humphrey, and Takis Tsiotras (Georgia Tech)*

A vertical magnetic bearing controls test rig is under development. It has three bearings: two are employed as magnetic bearings and the third is used as a force actuator. The rotor has been modeled and rap tested extensively for characterization. Also, the rotor has been levitated and characterization of the levitated magnetic bearing/rotor system is underway. A set of three high speed computers will be employed to implement the control system: 1) a system processor, 2) the lateral x,y magnetic bearing controllers, and 3) the axial magnetic bearing controller and the adaptive magnetic balancing system. This project is sponsored by NASA Goddard and American Flywheel Systems.

Artificial Heart Pump Prototype: Electromagnetic Bearings - *Michael Baloh, Paul Allaire, Edgar Hilton, Naihong Wei, Jeff Decker, and Roger Fittro (Aston University)*

The magnetic bearing supported artificial heart project has successfully operated the current prototype (CF3) in both water and blood under a wide variety of operating conditions. The pump is approximately 4 inches in diameter and 1.6 inches long. It is intended to be implanted in humans as a cardiac assist device. The pump hydraulic performance is described in some detail in another section.

There are magnetic bearings in the pump: 1) an inlet side thrust/ moment bearing divided into 8 segments and 2) a discharge side radial/thrust bearing, also divided into 8 segments. The bearings performed well in centering the impeller in the clearance passage in most cases; however, improvements are underway. The former CF3 bearings were constructed of a combination of materials which proved to have some problems so new bearings consisting of all silicon iron are under construction. Also, the load capacity of the very small bearing will be enhanced. The magnetic bearing coil currents were perturbed to identify the bearing and fluid characteristics of the operating pump under a number of operating conditions.

An advanced dedicated compact controller is currently being constructed for this pump using the new TI C60 chip and associated A/D, D/A boards. The new controller will be approximately the size of a textbook. Advanced robust controls work to improve pump performance under various fluid forces acting on the impeller is underway. This project is sponsored by Medquest Products, Inc. and is carried out jointly with the Artificial Heart Lab of the University of Utah.

Electromagnetic/Permanent Magnetic Bearings Design for Artificial Heart Pump - *Jeff Decker, Paul Allaire, Michael Baloh and Brad Pantuck*

A new electromagnetic/permanent (EM/PM) magnet design has been developed for the artificial heart pump prototype number 4 (CF4). The bearings have a ring configuration which is very compact and efficient. A major objective in this design is to minimize the bearing power consumption due to coil losses. The bearings have a permanent magnet bias flux generation but are controlled with electromagnetic coils. The bearing rings are divided into eight poles each, one for the inlet side of the pump and one for the outlet side of the pump, constructed in such a way as to largely uncouple the ring quadrants from one another. Saturation links are employed to minimize the lift off forces needed to start up the pump. Some simple circuits with similar design have been constructed and are undergoing testing.

One strong candidate for the control approach is that of sliding mode controls. This method provides robust control for nonlinear magnetic bearings using high speed switching amplifiers. It is also suited to self sensing as seen by the successful implementation (listed above). A development effort on sliding mode controls for the rigid heart pump rotor is underway. This project is sponsored by Medquest Products, Inc. and is carried out jointly with the Artificial Heart Lab of the University of Utah.

Physiologic Control of the Artificial Heart Pump - *John Ingraham, Paul Allaire, Milton Adams, Gang Tao and Michael Baloh*

It is necessary to adjust the speed of the artificial heart motor to match the physiologic needs of the human body. Typical activities are 1) sleeping or resting, 2) sitting or other moderate activity, and 3) stair climbing or other highly active needs. The adjustment of the motor speed to these activity levels should be carried out automatically, without patient intervention. A model of the human circulatory system, the artificial heart and a physiologic controller has been developed and is being improved. It has been found that the controller developed so far can effectively control motor speed under certain conditions.

Sliding Mode Controls for Rotors in Magnetic Bearings - *Paul Allaire Alok Sinha (Penn State University), Jun-Ho Lee, Michael Baloh, and Gang Tao*

Sliding mode control algorithms were developed for a planar rotor. A detailed study was carried out to evaluate the stability limits of the rotor-magnetic bearing system with structured uncertainty in the bearing properties and rotor unbalance. This work is currently being extended to include a rotor with degrees of freedom in both x and y directions and including gyroscopic effects. Eigenvalue separation and assignment methods are also being investigated.

Self Sensing Magnetic Bearings Using Sliding Mode Control - *Jun-Ho Lee, Paul Allaire, Satoshi Ueno (Ibaraki University), Yoiji Okada (Ibaraki University), and Gang Tao*

Sliding mode control methods using linear and nonlinear approaches have been developed for magnetic bearings with physical sensors and with self sensing. A state space approach governing the magnetic bearing to operate on a hyperplane has been developed and implemented experimentally in a magnetic bearing balance beam test rig. Work continues on robust boundary layers and reaching conditions.

Self Sensing of Magnetic Bearings Using Observer Based Optimal Regulator Theory - *Jun-Ho Lee, Paul Allaire, and Gang Tao*

Controller synthesis methods are being developed to obtain magnetic bearing control with self sensing. Discrete time control is used to stabilize a plant using an observer based optimal regulator. The magnetic bearing current is measured using an LEM and the signal is used to evaluate the air gap thickness in the magnetic bearing. The resulting state space control is being implemented on a simple single-input single-output balance beam test rig at this time. The method will be extended to multiple-input multiple-output systems in the future.

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, PCs, and any type of transducers (position, pressure, acceleration, etc.) would be greatly welcomed and appreciated, especially since our equipment budget is always small. In return, you may get an immediate capital write-off on taxes from the gift donation.

Rotor Dynamics

Testing of Flexibly Mounted Bearings Supporting a Flexible Rotor - *José Antonio Vázquez, Lloyd Barrett, and Ron Flack*

Work continues on the flexible test rig. This rig has been modified to use flexible bearing supports. The stiffness of these supports can be modified in the horizontal direction while the stiffness in the vertical direction remains almost constant. Characterization of the supports has been done using frequency response functions (FRF's). The FRF's were obtained using electromechanical shakers and performing a frequency sweep over the range of interest. Transfer functions can be obtained from these FRF's using the parameter estimation program TF_IDENT. These transfer functions are then used as the description of the supports in analysis programs such as FORSTAB, ROTSTB and FRESP2.

The rig has been tested with tilting pad bearings and three lobe bearings. The measured unbalance response and stability thresholds are used for the experimental verification of the program FORSTAB. Comparisons between predicted and measured unbalance response were presented at the last annual meeting. The predicted and measured location of the first and second critical speed agreed within 2% for all support configurations. A full report of the results and comparisons is underway.

Experimental Measurement of Rotor Instabilities - *C. Hunter Cloud, Lloyd Barrett, and Eric Maslen*

Hunter is continuing his research into the measurement of rotor instability. The project involves the use of magnetic actuators for studying the stability of rotors mounted on fluid film bearings, in particular, tilting pad bearings. There are several areas of this research. One area to be studied is the experimental examination of how common system non-linearities, i.e. unbalance and misalignment, and tilting pad bearing design characteristics (preload, offset and pivot type) influence actual stability threshold versus the predictions of current modeling techniques. In this area, magnetic actuators will be utilized to generate variable and measurable cross-coupled stiffness to drive the rotor/bearing system unstable.

The other main focus of this project is to develop an analytical method for determining a rotor/bearing system's stability threshold and sensitivity through the results of non-synchronous forced excitation. It is hoped that the methodology and techniques developed will provide an inexpensive alternative to shop testing at full pressure, density and speed to verify stability thresholds and margins. Experimental verification of this method will be accomplished with the use of magnetic actuators generating non-synchronous forced excitation.

Hunter has been busy designing the test rig and performing background research in the analytic areas of the project.

Rotor Stability Analysis Including Tilting Pad Thrust Bearings -*Pablo Rodríquez and Lloyd Barrett*

Pablo Rodríquez has joined the laboratory as a new graduate student pursuing an MS degree. Pablo comes from Venezuela and is on leave from PDVSA where he is a senior project engineer. He received a BS degree in Mechanical Engineering from Instituto Universitario Politecnico in Caracas in 1983.

Pablo's research topic involves the inclusion of tilting pad thrust bearing models into rotordynamic stability analyses. This work is similar to that performed earlier for tilting pad journal bearing and magnetic bearing modeling in ROTSTB. The thrust bearing analyses will be included in the new stability and forced response program, FORSTAB, developed by José Antonio Vázquez. The analyses will include all of the pad dynamics of the thrust bearings and extends the earlier work performed to include fixed geometry thrust bearings in stability analyses. Pablo is currently taking courses and performing background research into his research topic. This project has ramifications for future modeling for including disk flexibility into stability and forced response analyses. Some elementary formulations for including these effects were presented at an earlier Annual Meeting and the present project will provide the basic research necessary for future extensions. The approaches taken are based on frequency response function models and are consistent with the formulations used in FORSTAB.

Singular Value Decomposition Methods for Balancing and Forced Response Analysis of Rotors - *William Foiles, Paul Allaire, and Edgar J. Gunter*

A new method of balancing flexible rotors has been developed. It uses singular value decomposition, coupled with an influence coefficient method, to determine the optimum balancing method for flexible rotors. The Moore-Penrose generalized inverse is employed to solve the problem. The minimum number of balance planes, as well as minimum balance weights, can be used to effectively balance a rotor in the field. The method can also be used to evaluate the worst case unbalance response in the rotor. The method has been applied to some industrial rotor balancing cases and will be verified by application to flexible laboratory rotors. An extensive literature survey on balancing has been assembled and will be published in the Shock and Vibration Digest. A computer code to be employed in industrial balancing is under development.

Correction of Subsynchronous Vibration Problem in Industrial Compressor - *Paul Allaire, Edgar J. Gunter, and John Nicholas (Rotating Machinery Technology)*

A new high performance industrial compressor experienced high vibrations during testing. The characteristics included subsynchronous vibration at operation below the first critical speed and other unusual phenomena. A full rotordynamic analysis of the compressor was carried out with the OEM. New bearings, a center honeycomb seal, and other changes were successfully implemented to solve the problem and obtain a compressor with low vibrations. A report on the case history will be presented next year.

Analysis and Solution of High Vibration in an Industrial Steam Turbine - *Paul Allaire, Adhemar Castilho (Petrobras), Augusto Gomes (Petrobras), John Nicholas (Rotating Machinery Technology), William Foiles, Minhui He, and Jim Byrne*

A critical path steam turbine used in refinery applications has had a recent history of high vibration problems of a synchronous nature. A very detailed analysis of the rotor, steam turbine casing, and support structure has indicated several problems: 1) operation of the machine near the second critical speed, 2) non-optimized fluid film bearings, 3) an outdated coupling design and 4) an overly flexible support structure. A redesign of the problem components has been carried out and will be implemented soon.

Rotor Drop Analysis of Magnetic Bearing Supported Machines - *William Foiles and Paul Allaire*

Some rotor drop analysis of magnetic bearing supported rotors was carried out to determine the transient response of the rotor following impact. An important aspect is the tendency of some rotors to go into full clearance whirl in the back up bearings. Several papers were published on this topic.

Finite Element Analysis of Multilevel Rotor/Structural Systems - *Guoxin Li, Giorgio Calanni, Paul Allaire, and Edgar J. Gunter*

A new finite element modeling procedure and computer code is under development for use with multi-level rotors and structural systems such as casings. Applications include gas turbine engines, steam turbines and compressors. The objective is to use beam and shell finite elements in a finite element code to model rotating machines. Many rotating machines have non-beam like properties that need to be modeled with other finite element types. The shell element is the most useful one to add to beam elements. Currently, errors in predicting critical speeds of gas turbine engines are often over 10%. Equations of motion for this type of modeling process are underway. A computer code will be developed for industrial use.

Rotor Critical Response Estimation - *Eric Maslen and Chris Sortore*

Chris Sortore will defend his PhD Dissertation in Rotor Critical Response Estimation in November or December. This work has been very successful in that it has developed methods and tools for determining the predictive accuracy of a combination of rotor response modeling and experimental calibration. Originally intended as a method of obtaining rotor response at critical clearance locations for use in online adaptive balancing (as developed by Carl Knospe), this work has produced an organized approach for reconciling theoretical models to experimental measurements and for assessing the ability of the theoretical model to determine rotor response at locations which cannot be directly measured.

FOR MORE INFORMATION

We want to hear from you!

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