■ ROTATING MACHINERY AND CONTROLS LABORATORIES ■

ROMAC

FALL, 1997

Message from the Director

Lloyd Barrett

This past year has been a busy one for ROMAC. We have begun several new projects that were reported at the Annual Meeting as well as continuing ongoing work. The Annual Meeting in Wintergreen, VA last June was well attended and was one of the best meetings we have had. This was the first meeting since ROMAC began including registration fees for two attendees from each member company for the Annual Meeting. This policy is working well and hopefully is reducing paperwork for everyone. We look forward to having a good turnout at next year's meeting in San Antonio, TX. We thank Southwest Research Institute for helping us host next year's meeting.

During the past year some significant improvements have been made to the Shell and Editors for ROMAC computer programs. Included in these are new graphical post processing capabilities for several of the programs using TECPLOT®. We have also formalized our agreement with CONCEPTS ETI to develop future enhancements to the graphical user interface for ROMAC programs. Development is well underway and we anticipate demonstrations and new releases at the next Annual Meeting.

In response to interest from a number of member companies we are evaluating the requirements and costs associated with enhancing the capabilities of the fluid film bearing test rig by increasing the speeds. This is a major upgrade with significant costs. Our immediate goal is to determine how to best accomplish this in a cost effective way with minimal interruption to the testing program already underway.

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 in San Antonio!

ROMAC Annual Meeting '98

San Antonio, TX - June 21-25

The 1998 Annual Meeting is scheduled to begin with registration on Sunday, June 21 and end with lunch on Thursday, June 25. The meeting will be held at the Menger Hotel in San Antonio, Texas.

The Menger is an historic hotel adjacent to the Alamo and Rivercenter Mall on San Antonio's River Walk. Accommodations will be $110 for single or double rooms. The meeting will be held at the hotel with a visit one afternoon to Southwest Research Institute followed by a Texas barbeque.

We had many positive comments about the 1997 meeting at Wintergreen. We understand that the research areas of ROMAC are quite diverse, and we recognize that not all of our members are 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 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, 1998. Mark your calendars and plan to join us in June.

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

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://kelvin.seas.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

Eric Maslen, José Antonio Vázquez, and Lloyd Barrett

As most of you know, ROMAC is in the midst of transition from writing our own Graphical User Interface (GUI) to providing a more comprehensive and powerful environment written by Concepts ETI (CETI). Initially, CETI's offering will look essentially the same as the collection of tools already provided by ROMAC: a central shell for launching analyses and the associated scripted editor. Other tools include the graphical previewer for rotor models and a postprocessing interface to the commercial plotting package, TECPLOT®. Ultimately, CETI will develop a more polished but less generic interface to the more central software (like CRTSP2, RESP2V3, ROTSTB, etc.) which will be even easier to use and substantially more graphical. However, in order to protect our investments in other, more peripheral or developmental codes, the present generic interface will continue to be maintained.

This process will be officially inaugurated with the release of a Windows 95 based version of the scripted editor (SED). This software is presently running at ROMAC in an alpha version and will be released well in advance of the next Annual Meeting, after a few usability and compatibility issues get worked out. When this code is completed, it will be turned over to CETI and ROMAC's internal GUI development efforts will essentially cease - with the exception of script writing and enhancement. From then on, we will be heavily involved with CETI's development through periodic meetings to discuss code functionality, database structure, and usability.

The first of these meetings took place at the end of September when Lloyd Barrett, Eric Maslen, and José Vásquez of ROMAC met with Michael Platt of CETI. The primary focus of this meeting was to define the structure of a database "superset" which embeds the data presently distributed across many different data files. The objective of this restructuring is to eliminate the need to enter descriptions of physical objects (shafts, bearings, seals, and so forth) more than once. At the same time, considerable effort is being made to ensure that existing files can be used within the new structure so that your considerable standing investment in modeling is not lost. A significant theme underlying this database structure is to model machinery components in the same manner as they are inventoried: as parts which can be combined to form machines. In this way, your investment in modeling the geometry of a particular shaft or the inertia properties of an impeller wheel or the dynamic properties of a seal can be capitalized when you reuse these models in describing subsequent machines. In actual execution, CETI's GUI will use the superset database to generate data files for individual executables, like CRTSP2 or ROTSTB.

We also discussed the graphical element of the new interface and explored some of the issues in using AutoCad or other

CAD generated files as a basis for geometric definition of rotors and other mechanical elements. Again, the motivation is to eliminate redundant input of data: once you've created a computer readable description of the rotor geometry, why should you have to type the description in all over again?

CETI plans to show at least a demonstration version of their more polished interface at the next Annual Meeting. This demonstration version will establish the form of the interface and illustrate its functionality. Our September meeting with Mike Platt left us very excited about the prospects for the new CETI interface; it will considerably streamline the modeling and analysis process, allowing the analyst to focus more on the analysis itself and less on the mechanics of setting up the software.

ROMAC SED File Releases (Script Files)

CRTSP2.SED Version 3.23 (25 Mar 1997) *by J.A. Vázquez*
Added the debug option that exists in CRTSP2 2.61.

CRTSP2.SED Version 3.24 (16 May 1997) *by J.A. Vázquez*

- Added the interpolated bearing coefficients.
- The Script will provide a default dummy second rotor when the number of elements in the second rotor is equal to zero.

CRTSP2.SED Version 3.25 (06 June 1997) *by J.A. Vázquez*
Modified the script to allow only 1 rotor. If rotor 2 has no elements it will set the first and last element to be zero.

FINBRG.SED Version 2.02 (01 Apr 1997) *by J.A. Vázquez*

FRESP2.SED *by J.A. Vázquez*

MODE_SET.SED *by J.A. Vázquez*
Script file that creates the setup file for MODEPLT in order to create animated 3D plots.

MODFR2.SED Version 2.10 (23 Apr 1997) *by J.A. Vázquez*
The script can now import rotor models from ROTSTB files.

MODFR2.SED Version 2.20 (01 Sept 1997) *by J.A. Vázquez*
The script can now import unbalance rotor models from RESP2V3 files.

RESP2V3.SED Version 2.2 (17 June 1997) *by J.A. Vázquez*
The script includes extra information used by RESPLOT to create the TECPLOT® input file.

RESP2V5.SED *by J.A. Vázquez*

ROTSTB.SED Version 4.1 (06 Dec 1996) *by J.A. Vázquez*
Added the output plotting file for the mode shape.

ROTSTB.SED Version 4.2 (01 Apr 1997) *by J.A. Vázquez*
The script was updated to be compatible with the enhancements to ROTSTB version 7.01. Namely, a relaxation factor and a maximum number of iterations were added to the script.

ROTSTB.SED Version 4.3 (05 May 1997) *by J.A. Vázquez*
Added the option of importing rotor models from MODFR2 files.

THPAD.SED Version 2.56 (28 Mar 1997) *by J.A. Vázquez*
Made the script compatible with THPAD 2.64. Added the option of printing the full dynamic coefficients of the bearing to the output file.

THPAD.SED Version 2.57 (02 May 1997) *by J.A. Vázquez*
Under certain conditions old files were not read correctly. This caused problems updating old files. In particular the variable prnfull was not being defined.

TWIST2.SED Version 2.11 (28 Feb 1997) *by J.A. Vázquez*
Added the capability of handling shaft element multiplying factors and disk models.

Updated ROMAC Programs

CRTSP2 Version 2.61 (25 March 1997) *by J.A. Vázquez*
The modal file now includes the description of the rotor. This information is going to be used in a stability program under development. Added a literal description of the options used in the program. Added the option of printing the convergence information.

CRTSP2 Version 2.62 (16 May 1997) *by J.A. Vázquez*
Added interpolated bearing coefficients. When the number of Speed Cases is negative the program reads two sets of bearing coefficients for each bearing. These sets will be the coefficients for the first and last speed cases and the program will perform a logarithm interpolation for the rest of the cases. This feature is useful when calculating critical speed maps because the user only has to specify the beginning and end of the stiffness range. The logarithm interpolation provides equally spaced points when using log scale. The number of interpolation points is limited to the size of the bearing coefficient arrays (8 at the moment).

CRTSP2 Version 2.72 (01 Oct 1997) *by J.A. Vázquez*

- A single rotor can be run without specifying a dummy rotor
- General code clean up (eliminated most of the goto commands)
- Compiled as a 32 bit application
- Eliminated the Geograf Plotting subroutines
- Changed the order of the equations to solve. This modification makes the program easier to follow and understand and separates the calculation for both rotors.
- Enhanced the command line options. The new command line options are:

-i fileName	use fileName as input file name
-o fileName	use fileName as output file name

-m fileName	use fileName as the output modal file name.
- fileName	use them in the following order if not defined before: input, output, plot, modal.
- g	print the command to include ROMAC.ORG file in order to run the program
-?	print the command line options available
- @fileName	use fileName as the response file for CRTSP2

Note: Switches can be preceded by "-" or by "/" and can be either upper or lower case (processing is not case sensitive).

MODFR2 Version 2.34 (27 March 1997) *by J.A. Vázquez*
Added the rotor model at the end of the modal file output. This addition helps identify the rotor model that generated the modal file. This modification does not have any effect on the operation of FRESP2.

MODAL Version 1.5 (02 Sept 1997) *by E.H. Maslen*
The program is now able to handle up to 20 pinned or spring loaded boundary conditions.

MODEPLT Version 7.0 (09 Dec 1996) *by J.A. Vázquez*
MODEPLT is a companion for ROTSTB version 7.x. It plots the mode shapes in 2D using GEOGRAF® routines.

MODEPLT Version 7.1 (29 May 1997) *by J.A. Vázquez*
Added an option to output Tecplot® files. The command line option was changed to include a more flexible interaction with the program. The new command line options are:

- file_name	if no input specified yet, use file_name as input file; otherwise, if no output specified yet, use file_name for output file
-i file_name	use file_name as the input data file
-p file_name	use file_name as the plot data file
-m+/-m-	do/do not use Geograf to plot the modes |default: DO
-g	display the entries in the romac.org file necessary to run this program
-?	show this text and exit
@file_name	read command line arguments from file_name

Note: Switches can be preceded by "-" or by "/" and can be either upper or lower case (processing is not case sensitive).

MODEPLT Version 7.2 (03 July 1997) *by J.A. Vázquez*
Added 3D mode shapes. For the 3D animated mode shapes, MODEPLT uses the script MODE_SET.SED.

RESPGEO Version 2.31 *by J.A. Vázquez*
RESPGEO plots the forced response calculated by RESP2V3 using the GEOGRAF® libraries.

RESPLOT Version 1.0 (09 April 1997) *by J.A. Vázquez*
Program RESPLOT reads the input and plot files from RESP2V3 and generates a plot file to be used in TECPLOT® 7. The TECPLOT® plot file is in ASCII format in case a change is necessary. If the user so desires, the output format can be changed to binary format using the TECPLOT® input requirements. This program plots the response at the output stations where a plot was requested (RESP2V3 input data).

RESPLOT Version 1.01 (16 June 1997) *by J.A. Vázquez*
- Added the possibility of handling semi-major-minor axis plots.
- Added the orientation of the X-probe angle.

RESPLOT Version 1.02 (20 June 1997) *by J.A. Vázquez*
Added the calculation of the amplification factor and separation margin following the API 617 (sixth edition).

ROMAC SHELL Version 1.31 (11 Dec 1996) *updated by J.A. Vázquez.*
When using the menu command *Edit/Scripted/Editor* a strange behavior occurred under certain circumstances. The problem was fixed by this update. The help file for the shell is now a Windows help file.

ROMAC SHELL Version 1.32 (27 Feb 1997) *updated by J.A. Vázquez and W.T. Korn.*
Added the variable $w to the list of possible file names that can be passed to other programs during post-processing.

ROTORVAL Version 0.84, *by J.A. Vázquez*
- Updated to handle the changes introduced in ROTSTB versions 6 and 7.
- Added the possibility of including interpolated bearing coefficients for CRTSP2 files.
- Can handle single rotors for CRTSP2 files.

ROTPLT *by J.A. Vázquez*
ROTPLT reads ROTSTB input files, performs error checking and plots the rotor model using GEOGRAF® routines. This program is intended as a preprocessor for ROTSTB 7.00 for those users with DOS operating systems.

ROTSTB Version 7.00 (09 Dec 1996) *by J.A. Vázquez*
Added the capability of using a transfer function to represent flexible supports. This required changes to several files in the code. The transfer functions representing the flexible supports are input to the program by means of an external file. Slightly changed some output the code produces.

ROTSTB Version 7.01 (01 April 1997) *by J.A. Vázquez*
- Added relaxation factor for the eigenvalue search and a variable maximum number of iterations.
- The program now prints to the screen a summary of the eigenvalue search. This helps to identify potential convergence problems and gives some feedback on the search behavior.

ROTSTB Version 7.03 *by J.A. Vázquez*
- Added more general command line options.
- Added the imaginary information of the eigenvectors to the plot file generated by ROTSTB.

- If a plot file name is supplied, the program will write the eigenvector information to this file even if the plot eigenvector option is turned off in the program.

ROTSTB Version 7.10 (02 Oct 1997) *by J.A. Vázquez*
Changed the way tilting pad bearings are included in the calculations. Changed the second order equations plus residual approach to a direct approach using complex coefficients. This change helps the convergence when tilting pad bearings are present.

TF_IDENT Version 3.1 (23 Jan 1997) *by E.H. Maslen*

THPAD Version 2.64 (28 March 1997) *by J.A. Vázquez*
Added a print-out of the full bearing coefficients.

TORTRAN2 Version 1.11 (14 Feb 1997) *by J.A. Vázquez*
Check that the time dependent torques are input in ascending order.

New Interface with TECPLOT®

At the last Annual Meeting the new plotting interface with TECPLOT® was presented. ROMAC provides some generic TECPLOT® graphs which the user can then modify on line. This will require each user to purchase a copy of TECPLOT®. The generic plots are created using macros which are read by TECPLOT® to produce the graphs. Users can modify these macros or write their own to replace the generic plots with ones specialized to their needs. Plotting capabilities for CRTSP2, RESP2V3 and ROTSTB were released at the Annual Meeting. Two different approaches have been used to create the TECPLOT® data files. The first approach, used in CRTSP2, uses the output script editor to create the file. A report script was created that translates the information in the output file of CRTSP2 to a format that TECPLOT® can understand. The second approach, used in RESP2V3 and ROTSTB, was to create a separate program that reads the input and plot files and creates the TECPLOT® file. In either case, the operation is handled through the Shell post-processing feature and is completely transparent to the user. Macro files are an integral part of the interface with TECPLOT®. These files manipulate the default graphic presentation of TECPLOT® and create a format according to each application. Macro files also contain functions that permit the automatic operation of several options in TECPLOT®.

New Report Scripts:

CRTMTEC.RPT Version 1.00 (27 May 1997) *by J.A. Vázquez*
This script creates a report file with the format of an input data file for TECPLOT®. The input file contains the mode shapes read from the CRTSP2 output file. The mode shapes are organized as blocks of mode shapes divided by speed case. The mode shapes for each rotor are written in independent blocks so that they can be plotted independently. The script also identifies the location and value of external and differential bearings for each rotor at the different speed cases.

CRTMAP.RPT Version 1.00 (27 May 1997) *by J.A. Vázquez*
This script creates a critical speed map file from the data available in the output file for CRTSP2. The map is created for each bearing location. In general each critical speed map has the same natural frequencies but the horizontal axis changes with each bearing. The critical speed map information is stored by bearing. At this moment there are no provisions in the case of missed critical speeds. In the cases where critical speed are not found the output script of CRTSP2 will not run successfully, indicating that an error has occurred.

Macro Files:

CRTSP2_7.MCR Version 1.00 (27 May 1997) *by J.A. Vázquez*
This macro is used to format the mode shape plots for CRTSP2. Several functions are available to make the display of these plots easier. The most important macro functions are the plotting of the different speed cases for each rotor. The macros presented here plot all of the mode shapes for each speed case and for one rotor at a time. This was determined to be the default behavior; however, the user can change this behavior by changing the macro or by using the TECPLOT® features directly.

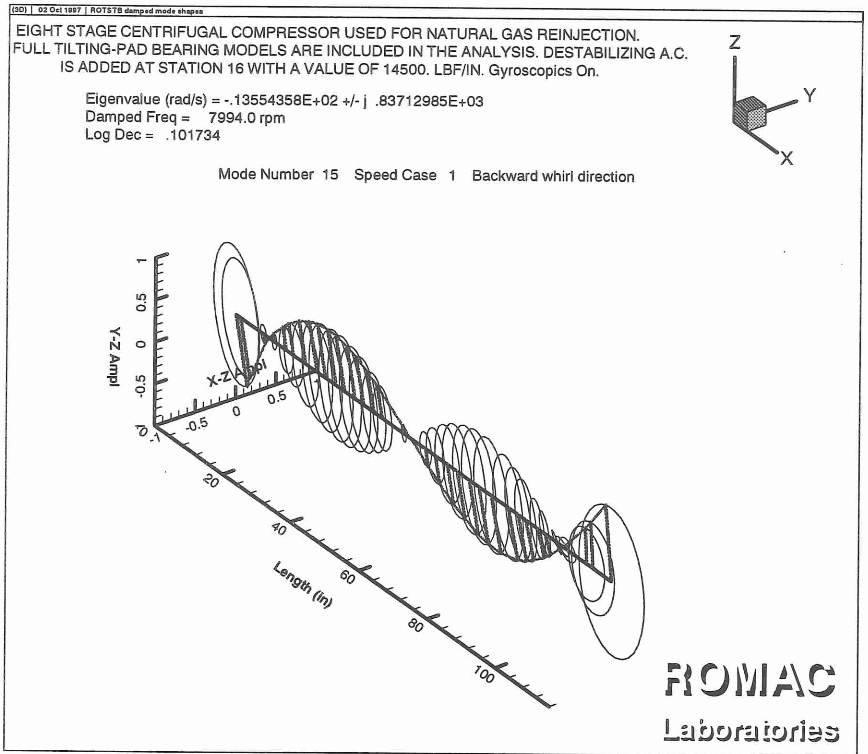
CRTSP2_M.MCR Version 1.00 (27 May 1997) *by J.A. Vázquez*
This macro is used to format the critical speed map plots. By default, all of the critical speeds calculated in CRTSP2 are used in the critical speed map creation.

CRTSP2_7.MCR Version 2.0 (20 June 1997) *by J.A. Vázquez*
The macro was modified to accommodate single rotor problems. This modification makes the macro much simpler.

RESP2V3.MCR Version 1.00 (27 May 1997) *by J.A. Vázquez*
This macro is used to format forced response functions from RESP2V3. All data contained in the plots is extracted from the input and plot files. Most of the labels are extracted from the input file for RESP2V3. The macro contains several macro functions that permit an easier operation and manipulation of the plots.

ROTSTB.MCR Version 1.00 (27 May 1997) *by J.A. Vázquez*
This macro is used to format damped mode shape plots from ROTSTB. The TECPLOT® file is created using MODEPLT version 7.1 or later. By default the major axis, minor axis, ellipse angle, X-Z amplitude, Y-Z amplitude and phase angle are plotted. The macro functions provided with the ROTSTB.MCR macro allow changes to the plotted damped mode shape and plotting of the station numbers.

Some macro functions also allow the plotting of the major and minor axis with



the ellipse angle and the X-Z amplitude and Y-Z amplitude with the phase angle to be turned on and off.

3DROSTB.MCR Version 1.00 (04 July 1997) *by J.A. Vázquez*
This macro is used to format 3D mode shape plots with or without animation. The TECPLOT® file is created using MODEPLT version 7.20 or later with the 3D option. The above figure shows an example of a 3D mode shape plot.

ROMAC.MCR Version 1.00 (27 May 1997) *by J.A. Vázquez*
This macro writes the ROMAC name at the bottom of the plots. It writes the name twice, the first time it writes the name in black, offsets the position and then writes the name again in white, that way obtaining the effect shown in the different figures. This macro is called from within the different macros. This macro was written as an example of writing logos. Members can either modify this macro or create their own using this macro as a template.

New Computer Programs

SEAL3 - Liquid Annular Plain and Grooved Seals

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

SEAL3 is a new pump seal program replacing SEAL2. It is ready for release. It uses a bulk fluid flow perturbation analysis to evaluate rotor dynamic coefficients for stiffness, damping and mass coefficients. A perturbation method was employed using a zeroth order evaluation of the centered seal and a first order perturbation was used to evaluate the stiffness and damping properties. Both plain and circumferentially grooved seals can be analyzed. The advantages over SEAL2 are that inlet swirl, mass coefficients, additional terms in the governing differential equations, and surface roughness have been added. Significantly better agreement was obtained with experimental data with SEAL3 as compared to SEAL2.

HCOMB Version 1.0

Hossein Haj-Hariri

The computer program, HCOMB, which analyzes honeycomb seals, is ready for release. See "Modeling of Honeycomb Gas Seals" under Current Research Projects: Fluid Film Bearings and Seals.

Program Development

THRUST Version 3.00

Ted Brockett and Lloyd Barrett

Work is ongoing to improve the thrust bearing program, THRUST. Updates underway for the code include:

1. Allow for inlet pressure boundary conditions to all pad styles (including tilting pad styles) to model ram pressure effect.
2. Turbulence to be limited by that in turbulent pipe flow.
3. Modify printout of turbulence information.
4. Add the necessary subroutine to model the tapered-land bearing with O.D. dam and the complex tapered-land bearing with O.D. dam.
5. Add backflow and low flow tracking to the code. Low flow can lead to convergence problems in the energy solution in the film.
6. Add a scaling factor for the convection coefficient on the outer periphery of the pad. This will allow different convection coefficients to be applied on these parts of the pad.
7. Include the periodic boundary condition to the pad temperature solution when modelling fixed pad bearings. Before, the pad leading edge temperatures could differ from those of the trailing edge.
8. Modify convergence routine to relax the flux values calculated from the energy mesh that are used as boundary conditions in the pad thermal solution. This should aid thermal convergence.

Development of New Rotor Stability and Forced Response Program

José Antonio Vázquez and Lloyd Barrett

ROMAC is continuing with the development of a new rotor stability program using modal reduction to reduce the number of equations to be solved. This program has been currently expanded to include forced response calculations. Because this program 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 casings described using transfer functions;
5. Tilting pad bearings;
6. Magnetic bearings;
7. Fixed geometry bearings;
8. Aerodynamic cross-couplings;
9. Seals;
10. Gyroscopic effects;
11. Calculation of damped mode shapes for stability and forced response;
12. Interface with Tecplot® for graphic output;
13. Multiple unbalance locations;
14. Report of absolute and relative responses.

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.

CURRENT RESEARCH PROJECTS

Fluid Film Bearings and Seals

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

Research continues on the influence of pivot friction on tilting pad journal bearing performance. The series of test bearings has a length to diameter ratio of 0.75, offset ratio of 0.5, and an assembled radial bearing clearance of 2.90 mils. Testing has been completed on bearings with rocker-back pivots and preloads of 0.35, 0.20, 0.00, and -0.20. Testing of a spherical seated ball and socket pivoted bearing with a preload of 0.35 has also been completed. Eccentricities, film thickness, pressure profiles, stiffness and damping characteristics are being compared to predicted values.

A brief synopsis of the research to date: Good agreement exists between measured and predicted values of eccentricity and pad temperature rise. Measured stiffness and damping characteristics follow the same trends as predictions. On a quantitative level, good agreement is also seen with individual values. All tests are carried out for Sommerfeld number ranges of 0.1 to 2.0 and speeds of 900 rpm, 1650 rpm, and 2250 rpm.

At the moment, testing is concentrated on the influence of pad dynamics. A range of forcing functions with frequencies from 0.1X to 10X are being applied to the -0.20 preload test bearing. Plots of stiff ness and damping versus excitation frequency at constant Sommerfeld numbers will be generated and compared with predictions. This research will establish the influence of excitation frequency on tilting pad journal bearings.

Testing in the next couple of months will concentrate on tilting pad journal bearings with spherical seated ball and socket pivots. The emphasis of this research is to establish the influence of pivot mechanisms on tilting pad performance. From previous experimental measurements of ball and socket pivoted bearings the hypothesis of pivot friction has been presented. Future tests will help to verify and quantify this hypothesis.

Enhancements to THPAD - *Karl Wygant and Lloyd Barrett*

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

- Non-dimensionalization of the rotational stiffness was changed to correctly match the non-dimensionalization for the pad moment balance.
- Calculation of the pad tilt angle has been modified to account for the pad tilting at a point beyond the oil film.
- Additional option has been added to provide more flexibility to the user to control convergence criteria. This new option should further improve convergence for THPAD users.
- Pressurized housing formulas are solved in THPAD. Input options for seal, inlet, drain geometry, and inlet pressure now allow for THPAD to balance flow equations. Housing pressure and flow are then automatically calculated and used in the thermo-elasto-hydrodynamic solution for THPAD.

Labyrinth Gas Seal Code/Program Development - *Jinghui Chen, Paul Allaire, and Ron Flack*

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. First, a commercial 3D flow solver will be used for some simple labyrinth seals and compared to results from LABY3 to determine the limitations. Next, a three-volume method will be considered to develop the seal operational equations of motion: volume 1 - the volume over the seal teeth, volume 2 - the volume over the seal chamber, and volume 3 - the seal chamber. A perturbation method will be employed using a zeroth order evaluation of the centered seal and a first order perturbation to evaluate the stiffness and damping properties. The equations of motion are under development and will be coded into a computer program.

ROMAC Short Course

Bearings & Seals

An introductory short course on fluid film bearings and seals in industrial rotating machinery will be offered in mid-March 1998. 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.

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

It is desired by several industrial members of ROMAC to develop a computer code for liquid helically grooved seals. These seals can be used to pump against the pressure gradient in pump seals and reduce leakage flow substantially. The code will be an extension of the new code, SEAL3. A three volume method, similar to that to be used for the gas labyrinth seals will be employed. The equations of motion are under development.

Optimization Of Fluid Film Bearings/Program Development - *James Byrne, Paul Allaire, and Susan Carlson*

A computer code for the optimization of fluid film bearings for minimum power loss, design minimum film clearance, and stability is being developed. Large compressors and other rotating machines need to have optimized fluid film bearing parameters such as length, diameter, number of pads, and preload. Nonlinear optimization methods will be employed for this analysis. Equations of motion for rigid rotor machine stability have been developed. Applications include refrigeration compressors, natural gas compressors, steam turbines and other machines. This project is funded by Carrier Corp.

Pressure/Thermal Effects in Fluid Film Bearings/Program Development - *Minhui He and Paul Allaire*

Many new fluid film bearings have directed lubrication or cool oil supplies added by various means. Current industrial bearing computer codes do not model the new designs. A new computer program to model these effects is in progress. A finite element method of solving the Reynolds equation and the energy equation is being developed to apply to these bearing designs.

Modeling of Honeycomb Gas Seals - *Hossein Haj-Hariri*

The computer program HCOMB has been developed for the modeling of honeycomb gas seals. The approach is based on a bulk-flow analysis with special consideration for the role of the 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. Preliminary results which were presented at the Annual Meeting demonstrated acceptable predications of the leakage flow while providing superior predictions of the dynamic coefficients. The code takes a few seconds to run on a low-end workstation.

At the present time, the manual is being prepared. I also plan to extend the methodology to the modeling of labyrinth gas seals.

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 the bearings have been calibrated to establish their force versus air gap and coil current characteristics. In addition the uncertainties due to hysteresis and the frequency limitation of the bearings have been determined. The complete control and instrumentation system (calibrated differential proximity probes, high output power amplifiers, PID controllers, and data acquisition system) have been installed and their functions verified. Currently a digital open loop controller is being added to the apparatus. The addition of this system is required for the control of higher rotor harmonics. In addition, it will provide user control of the whirl ratio. These enhancements are necessary to achieve better accuracy of the dynamic coefficients.

Force measurement verification tests have been run for the single and symmetric double volute pump geometries. The direct force measurements using the magnetic bearings compare well with the forces previously calculated using the LV and pressure data. In addition comparisons with other published force measurements and standard thrust models were made. Some preliminary studies on the effect of impeller eccentricity on the static forces for the single volute have been made with more studies planned in the future. A testing program designed to measure casing/impeller hydrodynamic interaction coefficients (added mass, stiffness and damping) is currently underway. This program will include a study of the effect of volute geometry and static impeller eccentricity on the dynamic coefficients. A parallel 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. 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, Bernd Christen, Michael Hotho, 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 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. Three-dimensional velocity measurements have been made at several different planes inside the cleaner. Thus far several anomalies have been seen 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 - *Daniel Baun and Ron Flack*

This 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 an end suction 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. In total two volutes and five different discharge configurations were investigated. For each discharge configuration, various impeller/volute relative positions were studied. Different specific speed pumps will likely be tested in the future.

Experimental Compressor Program - *Eric Maslen, Lloyd Barrett, Ron Flack, Ryan Brown and Stephanie Blanch*

A joint effort between ROMAC, McQuay International, and SKF Nova has finally taken form for the development of a test compressor on the scale of 200 horsepower. Despite the substantial investment from the industrial partners, the resulting equipment will be the property of ROMAC and any experimental results will be available to the entire membership. We salute the industrial partners (Paul Butler and Earl Champaigne at McQuay; Anders Lindskog at SKF) for their willingness to support this work in so open a manner.

The compressor will initially be fitted with a McQuay stock impeller/volute pair intended for refrigerant compression. With a 30,000 RPM variable speed drive and magnetic bearings for load sensing and impeller orbiting, this facility should have the flexibility and information content to explore better predictive models for aero performance and for bearing loading. It is expected that the first levitation of this compressor will occur in early June, 1998, shortly before the ROMAC Annual Meeting.

Meaningful experimental work with this compressor will rely heavily on input from ROMAC industrial members. Our intent is to put together a technical steering committee within ROMAC to help provide direction. We will arrange a special meeting of this steering committee at next year's Annual Meeting. If you wish to join the steering committee, please contact Eric Maslen (804-924-6227 or ehm7s@virginia.edu).

Magnetic Bearings

Control of Magnetic Bearings with Low Bias Flux - *Charles Yang, Jeff Lindlau 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 with low bias is appealing in applications where efficiency is critical, e.g., energy storage flywheels. While control with low bias flux is an attractive alternative, it is considerably more complex due to both force slew rate limitations and actuator nonlinearity.

We have nearly completed our theoretical efforts with the design of controllers for a single degree-of-freedom system consisting of a mass and two opposing electromagnets. Controllers were designed via the use of new results in gain-scheduled control using Linear Parameter-Varying (LPV) sytem theory. This involves posing the control problem as an infinite-dimensional Linear Matrix Inequality (LMI) and solving through convex optimization techniques. Since the previously developed theory in this field does not include any robustness with respect to model uncertainties, we have extended the theory to cover both time-varying and time-invariant dynamic uncertainties via the use of scaled small gain conditions. The controllers we have obtained so far appear to give quite good performance but high frequency disturbances may result in instability, a serious problem if these controllers are to be applied to high speed rotating machinery. We believe that a reformulation of the performance function used will alleviate this problem.

We are now constructing a very simple test rig to demonstrate these nonlinear controllers.

Gain Scheduled Control for Substructure Properties - *Steve Fedigan, Carl Knospe and Ron Williams*

In many active magnetic bearing (AMB) systems, the dynamics of the substructure (i.e. the object to which the control system's actuators and sensors are mounted) have a significant impact on the effectiveness of the control system. In the past, these support dynamics have been handled by re-tuning or even re-designing the controller. This is an expensive process and usually involves field-trained personnel. The current research seeks to eliminate this time-consuming process by designing a controller which is gain-scheduled on the support properties. After the machine has been installed, excitation forces are applied to the system through the bearings, and the response is recorded with existing position sensors. Based on this I/O data, the support properties (such as compliance and natural frequencies) are estimated, and these estimates are entered into the gain-scheduled controller. This approach offers performance superior to controllers which are robust to the variation in support properties, and guarantees a certain level of performance unlike many adaptive methods. The auto-tuning method is particularly attractive for systems such as turbomolecular pumps which are manufactured in large quantity, as it reduces the cost of installing such systems.

Self-Sensing Magnetic Bearings - *Eric Maslen, Carl Knospe, and Dominick Montie*

Efforts at developing self-sensing technology for magnetic bearings are finally funded! Working with a neural network company in Charlottesville - Barron Associates - we have now completed two Phase I SBIR contracts and are in the midst of a Phase II. The parallel funding from NSF and NASA seeks to develop methods for self-sensing which will work even in the face of substantial saturation of the stator or rotor iron. The solutions that we are examining are a hybrid of the linear techniques developed in Daniel Noh's PhD dissertation (now ROMAC Report No. 387) and the neural network techniques in which Barron Associates specializes. The neural networks permit a methodical approach to identifying and incorporating the nonlinear effects central to saturated stator behavior.

The Phase II (NSF) program presently underway will culminate in leviation of a high speed rotor using the self-sensing schemes explored in the Phase I. This technique offers noise performance which is substantially superior to other techniques to be found in the literature. With the extension to accommodation of stator saturation, we believe that self-sensing technology will finally be commercializable.

Magnetic Bearing Losses - *Lance Fujita, Paul Allaire, George Gillies, Mary Kasarda (Virginia Tech), Bob Rockwell, Pam Norris, and Christina Mastrangelo*

Measurements on magnetic bearing rotor power losses, sponsored by NASA Lewis Research Center, continue. Mary Kasarda graduated with her Ph.D. and is now an Assistant Professor at Virginia Tech (I created a Hokie!). Lance Fujita, who worked on the test rig as an undergraduate student, is now the main person on this rig. We are currently installing a vacuum chamber on the test rig. This will allow us to remove the air drag on the rotor to separate these from the iron (eddy current and hysteresis) losses. We have new bearing configurations including a 7 mil silicon iron rotor and a cobalt iron rotor that will be tested. Also, a low loss homopolar magnetic bearing is being purchased from Avcon for testing in the loss test rig.

Some startling results in heteropolar bearings were obtained in the past year. It was found that losses were larger, in bearings with the same pole face area and air gap flux density, when the magnetic bearing clearance was larger. More unexpectedly, an 8 pole bearing and a 16 pole comparable heteropolar bearing were tested and the rotor power loss measurements were found to be nearly identical. All previous publications and opinions of experts in the field had predicted that the power loss would be much higher in the 16 pole bearing because of the higher number of poles (or pole edges) that the rotor "sees" as it passes the poles. It was felt that the higher number of fluctuations of magnetic flux in the 16 pole bearing would produce a higher loss but this was not the case.

Linear Parameter Varying Controls for Flexible Rotors - *Steve Mason, Edgar Hilton, Paul Allaire, and Takis Tsiotras*

Research on linear parameter varying controls for flexible rotors has been carried out under funding from NASA Goddard. The gain scheduling control for flexible rotors utilized a linear parameter varying control method to account for the rotor plant variation due to gyroscopic effects.

Finite Element Modeling of Magnetic Bearings - *Bob Rockwell and Paul Allaire*

Finite element modeling of magnetic bearings continues. A two-dimensional computer code for evaluating the magnetic vector potential, magnetic flux density, eddy currents, and power losses due to eddy currents has been developed. Advances in the code are currently being made by benchmarking the results with the measurements of rotor loss from the test rig. Progress on the three-dimensional version of the code is being made. Issues concerning three-dimensional modelling of moving magnetic materials continue to be a subject of research in finite elements, including major firms such as ANSYS which recently withdrew the magnetic elements with this analysis capability.

Artificial Heart Pump Prototype: Magnetic Bearings - *Michael Baloh, Naihong Wei, Edgar Hilton, Jeff Decker, and Paul Allaire*

The magnetic bearing supported heart pump joint project, with the Artificial Heart Laboratory at the University of Utah and Medquest Products, continues. A three-year grant of $3,000,000 has been secured for the development of the heart pump. The following discussion is limited to the UVA group; the very considerable contributions by the Utah team are not detailed here. The objective is a heart assist device to assist the normal heart when it loses performance. The design life following implantation is 15-20 years. It will have to be powered by batteries external to the body, similar to laptop computer batteries, which will provide 8 to 10 hour operation before recharging.

The third prototype, called CF3, has approximate dimensions 4 inches in diameter and 1.6 inches long. It was constructed last year. It employs a thrust/moment magnetic bearing divided into 8 poles and a radial/thrust magnetic bearing, also divided into 8 poles. Eddy current sensors were temporarily installed to levitate the rotor and conduct some pump testing. The impeller was levitated this summer in all five axes; however, noise was found in the sensor signals due to the interaction between the magnetic bearing switching amplifiers and the sensors. These problems have now been largely eliminated by the introduction of better sensors, sensor relocation, and some amplifier redesign. Testing continues.

A new prototype, CF4, has been designed. It is approximately 50% of the size of CF3 and should better fit into the space for a heart assist device. It will employ hybrid magnetic bearings using a combination of electromagnetic and permanent magnet components.

Parameter identification methodologies for self sensing of the magnetic bearings are being employed in the heart pump. This will allow for the eventual removal of the eddy current sensors in the prototypes.

Artificial Heart Pump Prototype: Pump Design and Performance Bearings - *Jay Anderson, Dan Baun, Jim McDaniel, and Ron Flack*

During preliminary testing, the artificial heart pump impeller pumped approximately 3 liters/min, out of an expected eventual 6-10 liters/min, using water. More pump testing will be conducted very soon. Most performance testing will be carried out at the University of Utah and Medquest Products; however, a performance test loop is being constructed in the ROMAC Lab.

Good fluid performance is very important to the pump. Plans are underway for laser velocity measurements of the pump flows to be made in the ROMAC Labs.

Artificial Heart Pump Prototype: Physiologic Control - *Tim Waters, Paul Allaire, and Gang Tao*

Proper operation of the motor driving the artificial heart pump must be matched to the body's needs. The required pump flow rates and head will vary when the body is at rest or in activities. A physiologic controller, to adjust the pump motor speed, is under development. It will employ the magnetic thrust and radial bearing currents as a feedback signal in an electronic control loop.

Magnetic Bearing Controls Test Rig - *Justin Shute, Edgar Hilton, Bill Foiles, Paul Allaire, and Takis Tsiotras*

The magnetic bearing controls test rig construction is nearly completed after a couple of years of development and low funding. The original design was carried out by Katsuya Yamashita of Mitsubishi Heavy Industries. Initial funding of the magnetic bearing controls and amplifiers was contributed by Mitsubishi Heavy Industries as well, and component construction was contributed by Rotating Machinery Technology. The vertical frame and base have now been constructed and are being solidly attached to the walls. Initial testing of the free-free modes of the rotor has resulted in a match to the theoretical model of within 1% for the first three modes. The project will test control algorithms for industrial applications of rotating machines supported in magnetic bearings.

Sliding Mode Controls - *Paul Allaire and Alok Sinha (Penn State University)*

The use of sliding mode control provides a means of using robust nonlinear control for magnetic bearing supported rotors. This work explores the development of sliding mode algorithms for uncertainties in regard to bearing properties such as actuator gain and amplifier saturation. The methods are not as computationally involved as some other advanced control algorithms which can assist in minimizing the hardware needed to implement the control algorithms.

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 to experimentally test the effects of bearing supports on the effective stiffness and damping capability of bearings. 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 on the vertical direction remains almost constant. Characterization of the supports has been done using frequency response functions (FRFs). The FRFs are obtained using electromechanical shakers and performing a frequency sweep over the range of interest. Some of these results were presented at the last Annual Meeting. Transfer functions can be obtained from these forced response functions using the parameter identification program TF_IDENT. These transfer functions are then used as the description of the supports in analysis programs like ROTSTB, FRESP2 and STB_FOR.

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

With rotor instability being a major concern among machinery manufacturers and users, ROMAC is pursuing a research project involving 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.

The experimental portion of this project is being planned with the use of the magnetic bearing test rig developed as part of the project with Mobil. Major additions to this rig will include fluid film bearing pedestals and journal configurations suitable to utilizing bearings tested in the fluid film bearing test rig, a variable frequency drive and motor capable of speeds up to 10,000 rpm, oil system and vibration data acquisition system.

Rotor Drop Analysis of Magnetic Bearing Supported Machines - *Bill Foiles, Paul Allaire, Lynn Tessier (Revolve Technologies), and T. Miyaji (Ebara Corp)*

Rotor drops are important events for magnetic bearing supported machines. It is desired to determine if the rotor will simply drop to the bottom of the clearance with small oscillations or go into full whirl in the clearance circle. Nonlinear transient rotor dynamics was performed on two different rotors; one of them had a tendency to go into full whirl while the other did not. It is not clear what are the rotor/bearing/support parameters which might create the situation.

Work on this type of analysis is continuing. In a cooperative industrial project, the nonlinear transient analysis approach is currently being extended to another compressor rotor by Ebara, supported in magnetic bearings constructed by Revolve Technologies. Rotor drop experimental evidence has been obtained for this rotor under various drop conditions and the results of the nonlinear analysis will be compared to these results.

Rotor Finite Element Analysis Code/Program Development - *Bill Foiles, Paul Allaire, and E. J. Gunter*

A new rotor dynamics finite element analysis and capability computer code is under development. Equations of motion for a multilevel rotor code for stability and unbalance response have been derived. The new modeling includes new elements such as tapered elements and disks with relief in the shrink fit.

Industrial Boiler Feedpump Modeling - *Paul Allaire, Kelly Fort (Dow Chemical), Minhui He, David Brown (Heriot Watt University), and Lucy Zhao*

Rotor dynamic modeling of the industrial boiler feedpump is in progress. The six stage boiler feedpump operates at 3600 rpm in industrial service with Dow Chemical. Six of these pumps operated with mechanical packings for many years. Upon removal of the mechanical packing in one pump, the pump exhibited subsynchronous vibration at 1800 rpm. Rotor dynamic modeling was evaluated to include a shaft model, bearing analysis, and seal analysis. One additional purpose was to evaluate the results of the new annular seal code SEAL3.

When all of the seals were included in the boiler feed pump analysis, the first bending mode predicted frequency was 1800 rpm but the predicted log decrement was strongly positive (it should have been negative) when the seal model had the stiffness and damping terms but not the mass term. Including the mass terms produced a first mode negative log decrement but a very low frequency. The reason for this and how to properly model the effect of the mass terms is unknown at this point in time. Checking with knowledgeable other industrial people has not produced a solution to this problem. Research efforts continue.

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 the 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. Some examples of recent acquisitions include a Hewlett-Packard 4263A LCR meter, a Walker Scientific MG-30 gaussmeter, and a Hewlett-Packard 3324A frequency synthesizer.

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 Autumn. A list of approved equipment is subsequently provided to each of the Department Chairs, and purchase requisitions are then placed at or 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 routine course of the academic year, on an "as needed" basis. Long-term loans and gifts of equipment are also important to the ROMAC Laboratory, and we encourage our members to consider this possibility when evaluating their own inventories of test and measurement hardware and software.

FOR MORE INFORMATION

We want to hear from you!

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Your inquiries, comments, and suggestions will be appreciated. Updates to keep our Industrial Contact List current are always welcome!

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