■ ROTATING MACHINERY AND CONTROLS LABORATORIES ■

ROMAC

FALL, 1995

Message from the Director

Hossein Haj-Hariri

The 1995 annual meeting marked the end of Ron Williams' 3-year term as the ROMAC Director and the start of mine. It has been a very interesting 4 months so far. Over the summer we devoted most of our weekly meetings to budget and research planning. We carefully considered your needs which were communicated to us either publicly during the annual meeting, or privately otherwise, and prioritized our on-going research areas. Student funding was then allocated based on this prioritization. As the size of the group has increased over the years, the budget and research planning process has become more structured. On behalf of all the ROMAC faculty, I thank my predecessor for implementing much of this structure.

Now on to research. We devoted several sessions of the Williamsburg meeting to research planning, where we laid out the ongoing projects, as well as those we were considering. There were extensive discussions, capped by the traditional feedback session at the conclusion of the meeting. It was our sense that this exchange process was particularly fruitful. There were many constructive and relevant comments from the members, and we certainly appreciated that. The bulk of the summer's planning process was then devoted to optimal resource allocation based on your feedback. The narrative research descriptions which follow state the research projects for this year.

Our labs. The lab space continues to receive full usage. As many of you are aware, George Gillies joined ROMAC last year as Research Professor. George has done a phenomenal job of organizing and cataloguing our labs and supplies. He has been an invaluable addition to the group, and his knack for organization and reduction of entropy is in a class by itself. Klaus Brun, our outgoing (read graduating!) lab engineer, has helped George -- and Bob Humphries before George -- with the organization and general upkeep of the labs. Klaus deserves many thanks for a job well done, and we wish him well on his post-ROMAC endeavors. Dan Baun will take over the duties of the lab engineer starting in January. Finally, we continue upgrading the computers and lab equipment to enhance the productivity of our graduate students. You will have a chance to see all these at the 1996 annual meeting in Charlottesville (more on this later).

Other items of note. Ted Brockett continues in his position as a Research Faculty member. Most of you know Ted very well. He too has been an invaluable addition to the lab. His expertise and experience with most of the ROMAC codes is a great source of reference for many of our members. This knowledge coupled with Ted's personality make him uniquely qualified for his position. Tana Herndon is our conference coordinator and office manager; she is my savior when it comes to paperwork, of which there is plenty. Toby Korn plays a similar role where computers are concerned: the software and hardware upkeep, installation and networking problems are all handled by him.

Fees. We continue to seek new members for the ROMAC consortium, but we are not asking any more from our current members. The membership fee for 1996 remains at the same level ($12,000) as it has been for years.

Job placement. We have a number of highly qualified students in a number of areas and they are about to graduate in the coming year. I have identified the ones who have expressed an interest in industrial positions with an asterisk in their research writeups. If you have job openings in strength areas of ROMAC, then I hope that you will give our students serious consideration. I will be glad to provide you with resumes and letters of recommendations for any of our students. As always you are more than welcome to cut out the middleman (me) and contact the adviser directly. The adviser will usually be the faculty-member coauthor on the research narratives which follow later.

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In closing, we appreciate your continuing support of the ROMAC program and welcome any comments or suggestions that you may have to improve our program further. Please contact myself or any of the ROMAC faculty members if you have any questions, comments, or suggestions regarding our program.

ROMAC Annual Meeting `96

Charlottesville, VA - June 16-20

The 1996 annual meeting is scheduled to begin with registration on Sunday, June 16 and end on Thursday, June 20. This was the week most preferred by the members. The meeting will be held at the OMNI hotel in downtown Charlottesville. Some of you who attended the 1992 meeting are familiar with the location; however, the downtown area has been drastically transformed and revitalized since then. There are many cafes, restaurants, movie theaters, and performance-arts centers in the area, as well as an ice rink! The hotel itself offers excellent rooms, comfortable conference facilities, as well as a swimming pool and exercise room. Of course most of you are familiar with the natural beauty and the historic offerings of Charlottesville and Albemarle County.

We had many positive comments about the 1995 meeting in Williamsburg. While Charlottesville is not a resort location, it still provides many attractions. Most importantly, it provides a chance for you to visit our labs and meet most of the students. We had a good turnout for the 1995 meeting and we hope to have an even better one for 1996. We understand that the research areas of ROMAC are quite diverse, and we recognize that few of our members are truly interested in all facets of our research program. We therefore consistently schedule our core work of rotor dynamics at the center of the conference with the specialized topics of magnetic bearings and fluids placed at either end of the conference. 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. The many cafes and restaurants in the downtown area will probably encourage such interactions among groups of any size in an informal setting. The accommodations we have selected should be very pleasant, and they are reasonably priced ($84 per night/single and $99 per night/double). The registration fee will be $550, as it was last year. We understand that the greatest cost of attendance for our member companies is the absence of you, their critical employees. However, we also understand that travel budgets can be tight, so we have done our best to keep these latter costs as low as possible.

Registration materials will be sent to our members in March, 1996. At that time we will also be providing you with information about the many activities and points of interest that are available in the Charlottesville/Albemarle area. Mark your calendars and plan to join us in June. Hope to see you all in Charlottesville.

ROMAC Industrial Liaison

Ted Brockett, now a Research Assistant Professor in the ROMAC Laboratories, is still currently responsible for liaison with the industrial members on technical issues with our computer programs. He works directly with graduate students and the faculty in trying to find answers to your questions. These interactions have resulted in updates and corrections to several of our programs. If you have questions, please call Ted at (804) 982-3049. Computer questions and questions about receiving programs should be sent to our Programmer/Analyst, Toby Korn at (804) 924-6234.

ROMAC Short Courses

Bearings & Seals

Basics of Rotor Dynamics

During 1996, we are planning to offer a short course on *Bearings & Seals* in the Spring and one on the *Basics of Rotor Dynamics* in the Fall. Both courses 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 for these courses. Meeting space will limit the number of attendees. More information on the Spring short course will be provided around the first of the year. Please contact us with your requests or suggestions for short courses.

ROMAC Computer News

W. Tobias Korn

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

ROMAC On-Line

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

ROMAC is now on the World Wide Web. Members have access to information about ROMAC, ROMAC Programs, faculty, staff, and students, and much more. The pages have been under development for some time now, and are being improved on a regular basis. If you've browsed our home page before, take another look. The address is "http://kelvin.seas.virginia.edu/~romac".

ROMAC User Interface Suite

The ROMAC User Interface Suite is a collection of programs designed to facilitate the use of the ROMAC codes. These programs provide the user with an integrated environment from which to perform the analysis, provide validation of input files, menu-driven entry of data files, post-processing capabilities which include graphing and customized reports. Currently, the ROMAC User Interface Suite includes the ROMAC Shell, ROMAC Scripted Editor (SED), ROMAC Output Scripted Editor (OSED), ROTORVAL, and SPLOT.

ROMAC Shell

The ROMAC Shell is a novel environment intended to simplify your use of ROMAC analysis codes. Running under Microsoft® Windows®, the shell and its support tools streamline the analysis process and provide extended pre-processing and post-processing capabilities. The ROMAC Shell may also be used to run non-ROMAC programs. The ROMAC Shell has been very well received by the ROMAC member companies and is widely used.

Future development of the ROMAC Shell will include:

- the port to Multiple Document Interface, where multiple processes may be run simultaneously.
- Development of 32 bit versions for use under Windows® 95 and Windows® NT.

ROMAC Scripted Editor

The ROMAC Scripted Editor (SED) is a program which facilitates the creation of text files, specifically input data files. This menu-driven data entry program provides on-line help, data validation, units conversion, and other features. Using the SED also eliminates the tedious task of lining up columns in a fixed format data file.

Future development of the ROMAC Scripted Editor will include:

- Port to Microsoft® Windows®. Currently, the Scripted Editor is a DOS-based code which uses DPMI memory management to make use of memory above 640K on a PC. Porting the Scripted Editor to Windows will allow for more streamlined interaction with the ROMAC Shell, as well as providing better support for Windows 95 and Windows NT.
- The ability to have the SED use external programs to perform calculations and return results to be saved in variables in the SED data file. This will greatly increase the capabilities of the SED. This capability will be able to be implemented after the SED is ported to Windows.
- Various features will be enhanced or added.

ROMAC Output Scripted Editor

The ROMAC Output Scripted Editor (OSED) is a program that reads a ROMAC output file and rewrites it in a user-defined format. The ROMAC output file is read using a script that describes its format. A second script is used to describe the final report format desired by the user.

Updates to the ROMAC User Interface Suite (since June 1995)

ROMAC Shell

Version 1.0 (06/15/95; update by W. Tobias Korn): This is the first full release of the ROMAC Shell. Incorporated into this release is the ROMAC OSED as demonstrated at the ROMAC Annual Meeting in Williamsburg, Virginia.

Version 1.1 (07/07/95; update by W. Tobias Korn): Each process now saves a data directory, so that once a file name is entered in any of the fields, the other fields will default to that directory. Improvements were made in the way that the Shell obtains the location of the ROMAC Scripted Editor. The way in which the Shell runs the Scripted Editor was modified to be compatible with the new Version 2.xxß of the Scripted Editor. This modification does not affect the operation of Version 1.xxß of the Scripted Editor.

Version 1.11 (07/13/95; update by W. Tobias Korn): The validate button was being enabled after editing for codes for which there was no validator. This is corrected in this version. A menu option was added for selection of the OSED, and the selection is now saved in the ROMACW.INI file. The OSED now uses a response file to allow for longer path names.

Version 1.12 (07/13/95; update by W. Tobias Korn): The switch window now resizes so that the entire prompt will appear in the window.

Version 1.13 (07/18/95; update by W. Tobias Korn): The use of optional files which have a prefix was modified to correct an unfortunate feature in the construction of the command line used to run programs.

Version 1.14 (07/25/95; update by W. Tobias Korn): A bug was corrected which caused the input and output file names not to be used if they were tagged as optional in the ROMAC.ORG file.

Version 1.15 (08/17/95; update by W. Tobias Korn): The Report File button would, under some circumstances, become disabled when it should have been enabled. This has been corrected. The routines which validate the file names were improved.

ROMAC Shell Updates continued

Version 1.16 (08/21/95; update by W. Tobias Korn): If a process had no data file associated with it, there was the potential to cause an error when reading the CMD file. This situation was resolved.

Version 1.17 (08/22/95; update by W. Tobias Korn): The file date checking routine was made to compare seconds, where the previous routine only compared minutes.

Version 1.18 (08/23/95; update by W. Tobias Korn): This version checks for the existence of the driver WINDPMI.386 in the user's Windows system.ini and installs it if necessary.

Version 1.19 (08/24/95; update by W. Tobias Korn): The select script function was improved to account for a missing file name. The selection of the SED was modified so that if a PIF file exists, the Shell will always make use of the PIF file, rather than the EXE. This is necessary since the DOS 32 bit SED will not run without using a PIF.

Version 1.20 (09/15/95; update by W. Tobias Korn): The installation of the WINDPMI.386 driver was improved to account for the user not deleting the SYSTEM.BKF file which is required to complete the installation of the driver.

Version 1.21 (09/20/95; update by W. Tobias Korn): The installation of WINDPMI.386 was modified to only occur on Windows versions less than Windows 95. If WINDPMI is installed, Windows will now restart automatically.

Version 1.22 (09/21/95; update by W. Tobias Korn): Added the ability for the Shell to report the version of the SED file for the data file.

Version 1.23 (10/02/95; update by W. Tobias Korn): The reading of the Ini file was modified (just slightly).

ROMAC SED File Releases (Script Files)

RESP2V3.SED Version 2.0 by Theodore S. Brockett and Peter Allan with modifications by Thomas Johnson.
PADFEM.SED by Theodore S. Brockett
PDAM2D.SED by Theodore S. Brockett with modifications by W. Tobias Korn.
TWIST2.SED by Theodore S. Brockett and Peter Allan, with modifications by Thomas Johnson.
TURSEAL.SED by Theodore S. Brockett.

ROMAC SED File Updates (Script Files)

CRTSP2.SED Version 2.01 (07/25/95; update by W. Tobias Korn): CRTSP2 has a maximum number of modes which is set to 8. The SED now checks to make certain that the number of modes is between -8 and 8 and not zero. CRTSP2 would halt with an error if this variable were set too large, too small, or zero.

FINBRG.SED Version 1.1 (07/06/95; update by W. Tobias Korn): The Fluid Density (ROO) is now modified by the script. Due to a misunderstanding of the wording in the input description, the ability to modify this variable was omitted.

FINBRG.SED Version 1.11 (07/07/95; update by W. Tobias Korn): Version 1.1 allowed the modification of the variable ROO; however, due to an oversight, the variable was always written out with the default value. All users of FINBRG should update to this new version of FINBRG.SED.

RESP2V3.SED Version 2.02 (10/10/95; update by W. Tobias Korn): If any one of the stations was selected to be plotted, the plot option on the main menu should be selected. Not having this selected would cause the data for the plot information to not be written. This version of RESP2V3.SED fixes that problem.

THRUST.SED Version 1.01 (10/04/95; update by Theodore S. Brockett): Minor corrections regarding value validation, enabling datums for pad rotations when analyzing fixed pad bearing (not needed).

Updated ROMAC Programs

LABY3 Version 1.11 (06/28/95; update by Theodore S. Brockett): Changed the tolerance level at which the program would not calculate dynamic coefficients due to a singular matrix. Recent numerical tests indicated that the tolerance limit (condition number) could be lowered. The following line was modified from:

if (rcond .LE. 1/1.0e7) then
to: *if (rcond .LE. 1/3.0e7) then*

in the file PERT.FOR. User is still strongly encouraged to perform a trend analysis to verify the coefficients when the following message appears:

Warning: Matrix Condition Number is High
Matrix Condition Number is (value)
See Manual for Details

In addition, the open statement in SETUP.FOR was changed so that the output file would be overwritten if it already exists.

PADFEM Version 1.2 (09/08/95; update by Theodore S. Brockett):

- Indented source code for better readability.
- Added some basic comments showing flow of code.
- Rearranged header for better readability.
- Added variables KV(2,2) and CV(2,2) for storing the calculated dynamic coefficients. Program now prints out the calculated dynamic coefficients at each load condition. These coefficients are non-dimensional.
- Removed a repeated line.
- Added the program name, version number, version date, and input data file to the program printed output.

- Added error checking on the data in the input file. Subroutine ERRWARN added to code for this purpose.
- Added information output to screen while code runs.
- General code cleanup.

RESP2V3 Version 2.31 (07/05/95; update by W. Tobias Korn): In versions 2.3 and previous versions, the PLOT file was required to be a new file. In this update, this is no longer a requirement. The plot file may be overwritten.

ROTSTB Version 5.10 (08/24/95; update by W. Tobias Korn): Versions 5.08 and previous versions required unique bearing files for each of the bearings input. Version 5.10 allows for the same bearing file to be used for any number of the required bearing files.

THBRG Version 2.34 (06/09/95; update by T. S. Brockett): Commented-out the following line in the main file:

*IF (FLOWS.GT.0.0) NUQ=NU** (FLOWD/FLOWS)*

The value of NUQ is not used anywhere, but for certain conditions this expression caused a numerical overflow problem. Removed NUQ from list of variables.

TORTRAN2 Version 1.1 (07/18/95; update by R. Scott Orsey): Common block variables in euler2.for changed to the correct form. In OUTPUT.FOR, STRPLT.FOR, RUNPLT.FOR, and TORPLT.FOR, the variable EIGVEC was redimensioned to correct the dimensions (N,NNN). The stress concentration factor (SCF) computation in OUTPUT.FOR was corrected. FUNCTION GETMAX was rewritten to cut down on computation. The need for the L-U Decomposition routines was eliminated. COMMON block "PLACE" was added to allow for initialization of variable "IPLACE" in FUNCTION CALTOR. COMMON block "PLACE" appears only in the main routine and in FUNCTION CALTOR. The variable SWITCH in SUBROUTINE LIFE is initialized by setting it equal to zero at the beginning of the routine. Variable AVEL in SUBROUTINE PRNDATA is redimensioned so that it is no longer an array. Variable VELT in SUBROUTINE RUNUP is changed to VEL in the first two calls to FUNCTION CALTOR. Lines in main routine that reference variables NEIGEN,NTHPR, and PNTH are moved into an "IF" block so that they are not referenced when NANALY = 1. Variable AVEL in SUBROUTINE RUNUP is multiplied by PI/30.0D0 to convert it to RAD/SEC. This is done in the "IF" statement that appears on line 92. The graphics routines were rewritten to support the MS FORTRAN Powerstation compiler. The formal arguments were changed in the process. The SUBROUTINE TRANS2.FOR was modified to indicate the elapsed simulation time on the screen. The SUBROUTINE OUTPUT.FOR was modified to check for IO errors on every "WRITE" statement.

TURSEAL Version 2.11 (07/28/95; update by W. Tobias Korn and Theodore S. Brockett): The variable ECHOICE was declared and used as a DOUBLE PRECISION; however, it was meant to be an INTEGER. The comments in the header were made clearer. The output of the stiffness and damping coefficient file was modified to ensure that the numbers were separated by a space.

TWIST2 Version 3.01 (06/27/95; update by W. Tobias Korn): If, when prompted for the modal output file, the user did not specify the name, and just pressed enter, the input file would be overwritten with the modal output. This behavior was seen when compiled both with MS FORTRAN 5.1, as well as when compiled using MS FORTRAN Powerstation. This undefined behavior may or may not appear when other compilers are used. This version makes certain that some character is input for the modal output file name.

New Computer Programs

ROMAC Shell Version 1.23

W. Tobias Korn

The ROMAC Shell has been released as a full version and is no longer in its Beta release stage. For more information, see the section titled *ROMAC User Interface Suite* on page 3.

ROMAC Scripted Editor Version 2.20β

Thomas Johnson

This new version of the ROMAC Scripted Editor (SED) incorporates the functionality necessary to expand our supported programs to include codes such as RESP2V3, PADFEM, PDAM2D, RESP2V3, TWIST2, and TURSEAL. The most obvious of these new features is the conditional editing of fields. Based on the values of variables in the file, certain options may be "grayed-out" to indicate that they do not pertain to the given problem. This helps the user to be more efficient and eliminates questions about which data items must be entered for individual cases. Other enhancements include the ability to define and use variables when editing and to save the file using a "hot-key". Script developers will benefit from the enhanced debugging capability, which now provides the script writer with a line number and description of the problem. For more information, see the section titled *ROMAC User Interface Suite*.

ACCDES Version 3.01

Deb Dhar

ACCDES is a program for determining magnetic bearing controller transfer functions or hydrodynamic bearing stiffness and damping coefficients that satisfy a user-specified stability acceptability function. This function specifies the desired minimum logarithmic decrement for modes within a user-determined range of frequencies, and thus "optimizes" the stability of many modes simultaneously. The method uses an optimization search strategy to find acceptable designs within constraints on the design parameters which consist primarily of ranges of values for the stiffness and damping coefficients and the coefficients of magnetic bearing controller transfer functions.

PREDES Version 3.01

Deb Dhar

PREDES is a pre-processor for the program ACCDES and is distributed with ACCDES.

SPLOT Version 1.0β

W. Tobias Korn

SPLOT is a mode shape plotting program which produces 2-D as well as 3-D plots. The input file for SPLOT is generated by the ROMAC OSED (Output Scripted Editor) which obtains the data from the output files of ROTSTB and CRTSP2. The program is designed to be run under the ROMAC Shell, which automates the process of running the OSED to extract the data from the output file of either ROTSTB or CRTSP2, then running SPLOT to display the plots. This program is in the early development stages and your feedback is appreciated.

Program Development

THRUST

Ted Brockett, Lloyd Barrett, and Paul Allaire

ROMAC's hydrodynamic thrust bearing program THRUST has been available to the industrial membership for almost a year. The code is capable of analyzing tilting pad bearings with various pivot geometries and several fixed pad styles including parallel surface bearing, tapered-land bearing, parallel-tapered land bearing, and complex-tapered bearings. Several ROMAC companies have been using the code regularly and this has led to some recent updates.

Thermal deformation of the thrust runner has recently been incorporated into the code along with automatic renumbering of nodes to minimize system bandwidths. The latter modification allows the program to use less memory.

Future development of THRUST will include calculations for stiffness and damping coefficients and the addition of circular pads to the tilting pad styles available for analysis. Other pad styles will also be added into the code. Ways to decrease the required run times are also being investigated.

Due to the interest in reduced run times, a less extensive thrust bearing code is being developed. It will include the same pad styles but will make some approximations on the thermal models in the film. This is where the majority of computational time is spent. This will lead to much reduced computational times while still remaining a valid design code.

THPAD

Ted Brockett, Lloyd Barrett, and Paul Allaire

The ROMAC computer program THPAD, used to obtain the operating characteristics of tilting-pad journal bearings, is widely used by the ROMAC membership. It recently came to our attention that several of the industrial members have encountered convergence problems with the code at one time or another since its release. This problem is currently being addressed.

Other improvements to be made to THPAD include the addition of bearing and flow calculations, improved groove mixing models, and the addition of plotting capabilities for multiple-run cases.

In an attempt to fix the convergence problems in THPAD, we strongly encourage you to send to ROMAC all your data files that fail to converge. Without your input in this matter we cannot hope to solve the problem.

Thermal Effects in Tilting Pad Bearings - THPAD

Ted Brockett, Paul Allaire, Lloyd Barrett, and Mary Kasarda

Work is progressing on improved modeling of thermal effects in tilting pad bearings using industrial measurements. This effort is aimed at correlating existing industrial tilting pad bearing experience with THPAD with a view to improving the program through modifications or assistance to industrial users.

Program SEAL3

Lucy Zhao and Paul Allaire

Work is progressing on the new incompressible seal program for leakage and rotordynamic properties. It uses a perturbation analysis of bulk-flow fluid equations of motion for nearly centered seals. Initial work is on plain annular seals but that will be extended to grooved seals of various geometries. Collaborative work has been arranged with Prof. Dave Brown of Heriot Watt University and his seal test-rig experimental results.

Program FEMAG

Robert Rockwell and Paul Allaire*

A computer program to model the magnetic field and eddy currents in magnetic bearings with finite elements is under development. It will be a two-dimensional code using isoparametric elements to solve for the magnetic vector potential in a radial magnetic bearing. The magnetic field, force and eddy current effects will be calculated by the program for various bearing geometries.

Current Research Projects

Fluid Film Bearings and Seals

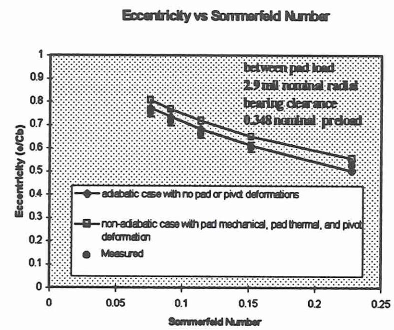
Tilting Pad Journal Bearings

Karl Wygant, Ron Flack and Lloyd Barrett*

The large rigid rotor bearing test rig (70-mm dia. bearings) is testing a 5 shoe tilting pad journal bearing. The bearing has an L/D ratio of 0.75, offset ratio of 0.5, an assembled bearing clearance of 2.90 mils (radial), and a preload of 0.348. The tilt pad shoes are bronze backed and tilt on a ball and socket assembly. The bearing was made by Turbo Components and Engineering (TCE).

Various assembled bearing clearances and preloads are to be examined. Testing for each tilting pad bearing assembly will include studies of thermal, static, and dynamic characteristics. The current research areas under investigation are listed below.

A technique for determining eccentricity, attitude angle, bearing clearance, pad clearance for each tilt pad shoe, and the pad tilt angles for each shoe is being developed. This technique uses proximity probes embedded in the shaft to sweep a profile of the film thickness as the shaft rotates. The measured film thickness profile is compared to a predictive model of the film thickness. An error minimization technique determines values for the parameters of the predictive model. This new technique will allow comparison to the existing method of measuring eccentricity and attitude angle. In addition, bearing clearance, pad clearance, and pad tilt angle can be examined as operating conditions are varied.



Dynamic data composed of the sinusoidally varying forcing functions and the resulting vibration orbit are collected by a high speed data acquisition system. The data acquisition system allows for simultaneous collection from multiple channels. An FFT transforms the raw data into its frequency components. These collected frequency components are then used to calculate stiffness and damping coefficients. Testing over a range of static loads, running speeds, and various excitation frequencies is in progress.

An extensive comparison of measured and predicted static, dynamic, and thermal characteristics is underway. The program THPAD is used to predict bearing performance. This research will provide an important benchmark for THPAD and help indicate when certain modeling features of the program should be used.

Evaluation of Leakage and Rotordynamic Coefficients for Incompressible Flow Seals

Lucy Zhao and Paul Allaire

Work on this project is continuing. For more information on SEAL3, see the entry under *Program Development*.

Hydrodynamic Force Coefficients for Labyrinth and Honeycomb Gas Seals

Hossein Haj-Hariri and Avichal Mehra

Fluid forces developed in the seals are important in modeling the dynamic behavior of turbopumps accurately. The two major contributions of this effort are the development of codes for modeling the flow in labyrinth and honeycomb seals and evaluation of the relevant dynamic coefficients. Fluid forces due to the movements of the shaft in small orbits around the eccentric position are used in the evaluation of stiffness, damping and inertial coefficients. The flow in the seals is described using the Navier-Stokes equations with an algebraic turbulent model. These equations are expanded by using the eccentricity as the perturbation parameter (e.g. eccentricity). The resulting zeroth and first harmonic equations are solved using a finite-volume formulation. Mathematically, the only force contribution comes from the first harmonic of the shaft precession, and hence our truncated perturbation expansion does quite well in predicting the forces.

The zeroth order equations are assumed to be steady and axisymmetric. The velocities near the wall are represented by the logarithmic law of the wall. The temporal and azimuthal dependence of first order equations is removed by assuming periodic solutions and a circular shaft precession orbit. The forces and dynamic coefficients are obtained by integrating pressures and shear stresses on the rotating surfaces. An iterative algorithm which can be applied both to zeroth order and first order equations is adopted, which uses

Roe linearization for upwinding and an explicit procedure for discretization. The algorithm can address various configurations including teeth-on-stator, teeth-on-rotor, interlocking seals and rotor whirl.

The treatment of the honeycomb seal is quite novel and the results which have been compared with experiments have provided remarkable agreement. The main idea is to consider the honeycomb as being generated by the periodic replication of a "unit" cell. Then, the pressure-driven and the boundary-driven flows through these cells are studied and compared with similar flows if the honeycomb were replaced by a flat wall. The ratio of the shear stresses between the two cases is a measure of the enhancement of the wall friction as a result of the presence of the honeycombs. Then the flow through the honeycomb seal is studied using the code developed for the labyrinth seal, and the only difference is the modification of the wall friction factors which appear in our turbulence models. Two journal articles now in preparation describe these results.

Some initial results were presented during the annual meeting. The run times, even though very short on CFD scale, are still too long, and we are considering ways to modify the formulation and generate faster codes, or to provide look-up tables for our members.

Fluids

Plexiglas Pump
Daniel Baun and Ron Flack

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

The pump has now been modified and magnetic bearings/load cells have been installed which can directly measure the reaction loads at the bearing locations. Both average (static) and instantaneous force measurements can be made. All the bearings have been calibrated to establish the force versus air gap and coil current functions. In addition, the uncertainties due to hystersis and the frequency limitation of the bearings have been determined. The complete control and instrumentation system including calibrated differential proximity probes (for shaft position sensing), high output Power Amplifiers (to drive the bearings), PID controller, and data acquisition system has been installed and the functions verified. The first force-measurement verification test was run for the single volute pump geometry for which LV and pressure data have already been taken. The direct radial force measurement results compared well with previous measurements and also with force predictions from standard thrust models. Verification tests for the double volute configuration are also planned. A testing program is being designed for the measurement of dynamic impeller forces. The objective is to measure casing/impeller dynamic influence coefficients; stiffness and damping. A parallel computational effort is also planned. This effort will employ a commercially available fluid code to model the impeller and flow field with the goal of calculating linear direct and cross-coupled stiffnesses and damping coefficients resulting from a small impeller perturbation within the volute.

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

Torque Converter
Klaus Brun, Warren Claudel, Alexander Yermakov, and Ron Flack

This is an independent industrially sponsored project, but has been used to expand ROMAC's experimental capabilities and understanding of the mixed flow in a complex multi-element turbomachine. Laser velocimetry is used to map the internal flow field of seven different torque converter geometries in detail. Thirteen measurement planes throughout the pump, turbine, and stator of the torque converter at three significantly different torque converter operating conditions are studied. A method to correlate/translate discrete laser velocimeter measurements taken in the stationary frame to the unsteady rotating-element frame, which was developed in an earlier phase of this project, is employed to determine the transient velocities throughout the torque converter. Results show highly unsteady element interface flows, large separation regions, and circulatory secondary flows in all elements. Also, from the experimental data, slip factors, mass flow rates, input/output torque, and element interface angles are determined. The data collected with this apparatus provides a benchmark for torque converter and other mixed flow computational flows codes.

Magnetic Bearings

THE CENTER FOR MAGNETIC BEARINGS

The Center for Magnetic Bearings, part of the ROMAC Laboratories, has again received continuation funding from Virginia's Center for Innovative Technology (CIT). The funding for the period July 1, 1995 through June 30, 1996 is $75,000. This brings the total

CIT funding for the Center to nearly $1,500,000 since July 1989. The Center is one of eleven Technology Development Centers funded by the CIT. This funding has supported much of the magnetic bearing development in ROMAC.

A Digital Controller for Magnetic Bearings

Steve Fedigan, Feng Shen, and Ron Williams*

The control of magnetic bearings in rotating machinery can be a very demanding industrial application. Processing speed and bandwidth must be sufficient to support fast, flexible rotors. Additional innovations in adaptive and open-loop control are demanding more processing power, and magnetic bearing applications typically cannot tolerate a controller failure.

ROMAC's next-generation digital controller provides a powerful, flexible platform which can be configured for multiprocessing or redundancy, in order to satisfy the different demands of magnetic bearing applications. The base processor for the digital controller is the Texas Instruments TMS320C40 digital signal processor. The CPU boards are TIM-40 compatible. (TIM-40 is an open-standard, designed and supported by Texas Instruments and an industrial consortium.) Each TIM-40 board measures 2.5" by 4.2" and has a local memory of 128 kbytes of EPROM and 256 kbytes of SRAM. The CPU boards plug into a motherboard which may be configured for multiprocessing or fault tolerance. The motherboard, in turn, connects to a backplane into which the I/O cards are inserted.

Multiprocessing Configuration. Each computer has multiple communication channels that are used to interconnect the multiple computer chips for multiprocessing. When configured for multiprocessing, the system's four computers form a fully interconnected network. Only one of the devices communicates with the input and output boards, and this is done via the Processor-I/O Link (PIOL).

Fault-Tolerant Configuration. To provide fault tolerance for the processing section, the multiple computers are configured to provide TMR (Triple Modular Redundancy) with spare and repair. The PIOL provides a synchronizing clock signal to all of the computers to ensure that they perform I/O operations at the same time. The PIOL implements both the active and passive aspects of the fault tolerance scheme. An output error from a single module will be masked by voting (passive), and repeated errors will cause the PIOL to replace the faulty computer with the spare (active). Thus, the system can tolerate the failure of two TIM-40s before it becomes vulnerable to catastrophic failure.

Fault tolerance is achieved in the PIOL and Channel Bus by traditional encoding methods. The ADC and DAC boards do not need to be fault-tolerant if the sensors and bearings of the application are redundant. So, losing a particular ADC or DAC channel should not cause a breakdown. The system can also be configured to detect faults that occur in the bearings. The sensors can include current detectors to determine if a coil has current.

Using this digital controller, configured for fault tolerance, as the heart of a magnetic bearing application, a very robust and reliable system can be developed, even to meet the long-life demands of typical industrial machines.

Many magnetic bearing applications demand sophisticated digital signal processing technology. Some even require multiprocessing, while others require higher reliability than that provided by a single processor system. ROMAC's new digital controller strives to meet both of these needs in one powerful, flexible platform.

Status. A single computer version of this digital controller was constructed and tested early in 1995. The complete reconfigurable multiple computer version of this digital controller is scheduled for completion late in 1995. Several copies will be constructed, and several projects are ready to make use of their capabilities.

Investigation of Magnetic Bearing Inductances

Daniel Noh, Chris Sortore, David Meeker*, Eric Maslen, and Paul Allaire*

Work was completed this year on an extensive study of the nonidealities which cause magnetic bearing stator inductances to differ from those predicted by simple circuit models, particularly at high frequencies. The resulting model is a combination of static correction for leakage effects and a dynamic correction for eddy currents. The leakage correction requires a finite element calculation but is reasonably economical. The eddy current correction describes the stator iron permeability as frequency dependent, leading to an extremely economical model which is valid out through the switching frequency of commercial power amplifiers. An alternative formulation allows a finite dimensional state space description of the stator electrical impedance for use in stability analysis of transconductance schemes.

The models are easily derived from manufacturing drawings and manufacturer's data for the material including initial permeability, electrical conductivity, and lamination thickness. Validation of the models was accomplished through fairly extensive comparison to experimental data obtained from three substantially different bearing stators. It exhibited excellent agreement: errors in inductance prediction are reduced from 10-20 percent to 2-3 percent, typically.

Ultimately, the value of the findings of this effort lies in two areas. First, the performance of bearing stators as sensors or in self-sensing applications can be predicted more accurately than previously. Second, this work demonstrates a very simple and direct measurement technique for determining actuator electro-mechanical bandwidth and power loss.

Compressor Magnetic Bearings Audit

Chris Sortore, Robert Rockwell, Eric Maslen, Lloyd Barrett, Carl Knospe, Paul Allaire, and Ted Brockett*

A very extensive audit was carried out for the magnetic bearing performance in four gas pipeline compressors operated by NOVA Gas Transmission, Ltd. (NGTL) of Calgary, Alberta. NGTL is probably the largest single user of magnetic bearings and so the unsatisfactory operating reliability experienced with these compressors posed a significant threat to the continued application of magnetic bearings in this market. The audit, which was conducted jointly by the University of Virginia, Cooper Compressors, Magnetic Bearings Inc., and S2M of France, was meant to clearly pinpoint the key design or operating flaws leading to these problems.

The audit did not uncover any gross design or application errors, but did reveal a broad range of small problems, all of which added up to produce significantly reduced reliability. The findings are too extensive to present here in any detail, but the audit report is now available either through ROMAC or directly from Paul Alves at NGTL. NGTL has started an extensive program of equipment upgrades as suggested by the audit report and is reporting substantial gains in operating reliability. Further, the critical units which were operating at reduced capacity due to bearing capacity limitations are now operating well at full capacity. Confidence within NGTL in this technology appears to have been substantially restored and there is some hope that they will begin ordering equipment with magnetic bearings in the near future.

Of particular interest to researchers at ROMAC was the excellent access to real machine operating data provided by this exercise. Open- and closed-loop transfer functions were obtained for the bearing systems in all of the compressors examined. These transfer functions were compared to models assembled and analyzed using ROMAC magnetic bearing/rotordynamic software. The match between model and experiment was excellent, providing added confidence in the analyses and embodying software.

Self Sensing Magnetic Bearings

Daniel Noh and Eric Maslen*

An ongoing study of self-sensing magnetic bearings is nearing completion with extremely promising results. Daniel Noh will complete his doctoral studies this fall, documenting a novel and highly successful signal processing technique for obtaining an accurate measure of shaft motion from the combined current and voltage signals for a conventional radial magnetic bearing. This approach does away with the usual eddy current or variable reluctance probes, moving the sensing function into a relatively compact and inexpensive filtering board which resides in the power amplifier itself - the only external connections to the rotating equipment are the power leads for the bearing coils.

Based on a nonlinear parameter estimation technique, the signal processing circuitry embeds a model of the bearing inductance parameterized by the air gap. This simulation is subjected to the same switching voltage as the actual magnetic bearing coils. A feedback loop compares the output current waveform from the simulation to that measured for the actual bearing and adjusts the gap length parameter until the two waveforms match. The achievable linearity and bandwidth are excellent (less than 2 percent deviation from linearity of a stroke of half the air gap, bandwidth of at least 1 kHz) and feed through of bearing force, the primary drawback of previous techniques, is acceptably low.

A big advantage to the parameter estimation technique over competing approaches is that the embedded inductance model can easily incorporate nonidealities like saturation and eddy current effects without affecting the estimation bandwidth or performance. This will be extremely useful in application to highly loaded magnetic bearings in high performance applications.

Magnetic Bearings for Textile Spindles

Randy Hammond, Roger Fittro*, Michael Baloh, Curt Reynolds*, Paul Allaire, Eric Maslen, and George Gillies*

The magnetic-bearing supported, heated textile spindle developed for Dienes Apparatus has been successfully designed, installed and levitated in the first prototype. It has been demonstrated for the textile industry at the International Textile Manufacturers Association in Milan, Italy in October 1995. The prototype will return to Charlottesville later in the fall for characterization and fine tuning.

High Speed Magnetic Bearing Loss Test Rig

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

The NASA high speed loss test rig has been levitated and rotated up to 30,000 rpm in one set of magnetic bearings. Run down tests have been very successful and various bearing tests conducted. The vacuum chamber is currently being constructed. Several other bearing configurations have been ordered and will be tested over the next year.

Mobil Test Rig

David Lewis

Work on the test rig will resume shortly as the sponsor is providing additional funding. Eric Maslen will be directing additional work on the rig with the direct assistance of Chris Sortore and George Gillies and input from Dave Lewis and Lloyd Barrett.

The rig will be moved from the test cell to the basement as much space pressure exists on the use of the test cells. The Mobil rig is very well contained structurally and will not be running at high speeds. Further, the flooding of the container, simulating the wet motor, will likely cause less concern in the basement if there are initial leaks in the system.

Eric Maslen has outlined the series of tests that will be done on the rig to bring it to a state of final completion. It will be operated under analog controls initially before switching to the digital controls for testing of the fault tolerant aspects.

Flexible Quadrant Control

Eric Green and Carl Knospe

Introduction. Traditionally, magnetic bearings have been designed to operate with four quadrants which are fixed by the coil winding used. Each of these quadrants is operated independently of each other, often with the currents in opposite quadrants operating as perturbations about a bias current. This method greatly simplifies the coil control problem. Desired forces are broken down into components along two orthogonal axes. Each component is then controlled independently by the currents supplied to two opposing quadrants.

If the coils on each pole are controlled independently, a significant increase in load capacity can be obtained without any other change to the stator. This increased capacity occurs because more poles are dedicated to producing the force. In a stator with 8 poles, for example, a 30% increase in load capacity is obtainable when an individual coil control method is used.

The individual coil control (ICC) concept is simple. A feedback controller commands a desired force to the ICC system. This computes the proper currents to command to the transconductance amplifiers. The amplifiers respond by providing the requested currents to the coils thus producing a force upon the journal. If the ICC system functions properly, then the bearing force is equal to the desired force. Thus, the ICC system can be thought of as an inverse of the mapping from currents to forces. Note that the ICC system must account for the nonlinearities of the actuator introduced by both the squared relationship between flux and force and the variable permeability of the magnet iron. The ICC algorithm would be executed on a DSP-based digital controller.

A Solution: Flexible Quadrant Control. We have recently devised an algorithm known as **flexible quadrant control** which performs very well. We recently studied an example problem, an eight pole silicon iron bearing. The desired forces were picked evenly distributed over an angle of 22.5° and a range of magnitudes up to the load capacity. For each desired force, the ICC algorithm was used to calculate the currents to apply to the coils. The force generated with these currents was then calculated using the magnetic bearing model. The desired and generated forces were very close over the entire range of both angle and magnitude. The maximum error, in fact, is less than 2%. It should be noted that the flexible quadrant algorithm is very simple. The calculations involved consist only of linear interpolation between elements of a special look-up table that is generated from off-line testing. The algorithm has been coded in C on a TMS320C40 DSP and executes at a rate greater than 10 kHz.

Synthesis of Robust Gain Matrices for Adaptive Rotor Vibration Control

Samir Tamer and Carl Knospe*

The active control of unbalance vibration in rotating machinery using magnetic bearings has generated a great deal of interest in the last decade. As has been demonstrated at the University of Virginia, the synchronous vibration in many machines can be greatly reduced with active control. Much of our recent research has focused on the application of adaptive open loop (or feedforward) strategies. This type of control has the advantage of not placing any constraint on the bearing stiffness or damping. Thus, the stability and transient performance of the machine can be optimized without considering its unbalance response.

An important issue in the application of the adaptive open loop control (AOLC) to industrial machines is the stability and performance robustness of the unbalance control algorithm employed. Recently, we have demonstrated that the stability and performance robustness of an AOLC algorithm can be analyzed using structured singular value methods. We have also shown that these methods may be extended to provide a synthesis procedure for the design of the AOLC gain matrix. The design procedure involves an iterative two-stage minimization of the singular value of a matrix.

This may be used to determine the gain matrix so that the worst case performance is guaranteed to be close to the optimal performance. For the example problems to which we have applied the new technique, the design procedure works very well. We are now conducting experiments to demonstrate the effectiveness of this new robust control method.

Heart Pump with Magnetic Bearings

Michael Baloh, Daniel Noh, Paul Allaire, Eric Maslen, Ron Flack, George Gillies*

The magnetic bearing supported centrifugal artificial heart pump research is getting started. One prototype is in operation and two others are currently under development.

Finite Element Analysis of Magnetic and Electric Fields in Magnetic Bearings

Robert Rockwell and Paul Allaire*

Research is underway to develop the proper governing differential equations for the magnetic vector potential formulation of Maxwell's equations. These equations are being formulated into finite element matrices and coded up as a magnetic bearing analysis code. The magnetic fields, forces, and eddy currents will be calculated, including nonlinear magnetic properties of the materials.

Controls Test Rig

Katsuya Yamashita, Paul Allaire, and Carl Knospe

A magnetic bearing controls test rig is being developed for controls research on a vertical flexible rotor. Gyroscopic effects, overhung disk, imposed external forces and other interesting topics can be studied with this rig. The rig is being constructed in cooperation with Mitsubishi Heavy Industries, Kaman Instrumentation, and Rotating Machinery Technology.

Rotor Dynamics

Analysis of Torsional Vibration Including Nonlinear Flexible Couplings and Gear Interaction

Scott Orsey, Lloyd Barrett, and Ted Brockett*

Based on the interest shown at the last ROMAC Annual Meeting, work is underway to develop a new torsional transient program to include the effects of flexible couplings utilizing elastomeric elements. These couplings have nonlinear torque - deflection relationships, and a method of modeling them to include the nonlinear effects is under development. Additionally, elastomers have frequency dependent stiffness and damping properties, and the modeling technique attempts to include these effects. One approach being investigated is to create models utilizing multidegree of freedom subsystems that, when dynamically condensed to a single degree of freedom system, have the appropriate frequency dependent properties. The stiffness and damping elements of the multidegree of freedom system include the amplitude nonlinearities. Catalog data available from coupling manufacturers is being used to develop the models. The intent is to make the user input as simple as possible using data normally supplied by the coupling manufacturers. Processing of the data to create the appropriate model will be accomplished internal to the computer program.

Work is also in progress to formulate the equations of motion in a form suitable for including flexibility of gear teeth for gear-coupled shafts. A number of issues arise regarding suitable numerical integration techniques to solve the equations in as efficient a manner as possible while retaining numerical stability. Some studies are presently underway to evaluate some of these methods.

Design and Optimization of Bearings

Deb Dhar, Hari Kandadai, Lloyd Barrett, and Carl Knospe*

The computer programs being developed to implement an algorithm for determining magnetic bearing controller transfer functions or hydrodynamic bearing stiffness and damping coefficients that satisfy a user-specified stability acceptability function are currently being tested as part of a funded research project within the laboratory. The acceptability functions specify the desired minimum logarithmic decrement for modes within a user-determined range of frequencies, and thus "optimize" the stability of many modes simultaneously. The method is well suited for designing squeeze film bearings. These programs, PREDES and ACCDES, are described in the section *New Computer Programs*.

The testing underway involves bearing optimization for a flexible rotor test rig utilizing both magnetic bearings and squeeze film bearings. A number of bearing sets will be designed to test the design methodology in predicting dynamic performance by developing both "good" and "bad" designs that will be tested for comparison to predicted dynamic behavior.

Rotor and Support System Identification using Time Domain Methods

Ping Zhong, Lloyd Barrett, and Carl Knospe*

The initial phase of the work on system and parameter identification is in the final stage. This project has been aimed at examining techniques that permit these identifications from time history signals obtained from probes placed on machinery. Two types of identification are being considered. System identification involves the determination of the rotor - bearing system eigenvalues (damped natural frequencies and logarithmic decrements) from the test data. These can be compared to those calculated using a computer model of the system. Other system properties that can be identified include transfer functions and mode shapes, if data from a sufficient number of locations on the rotor are obtained. Parameter identification includes the identification of specific parameters, such as bearing or seal coefficients, which will permit a model of the system to more closely mimic the dynamics of the actual system. Some of the methods being studied are the inverse eigenvalue techniques where the measured system eigenvalues determined by the system identification methods are used to determine, if possible, the specific parameters of interest. Those of interest may include parameters that have a great deal of uncertainty or those that may change with time and be an indication of deterioration in the system.

Testing of Flexibly Mounted Bearings Supporting a Flexible Rotor

José-Antonio Vázquez, Ron Flack, and Lloyd Barrett

Work continues on the flexible rotor test rig to experimentally test the effect of flexible bearing supports on the effective stiffness and damping capability of bearings. This rig has been modified for use with flexible bearing supports that have been designed, built, and incorporated. Preliminary testing is underway, including single and multiplane balancing. Software has been written to extract the unbalance influence coefficients from digitized response signals obtained from tests over a frequency range, and involves curve fitting the data from each unbalance run so that the signals may be subtracted on a frequency-by-frequency basis. This provides a much better basis for comparison to predictions using unbalance response programs since the effects of unknown residual unbalance or other synchronous excitations are removed from the measured test responses. The data obtained from the tests will be used to further verify ROMAC forced response and stability computer programs such as ROTSTB and FRESP2.

As part of this project, an assessment of alternative formulations for stability calculations now include the effects of tilting pad bearings supported by flexible supports, which may have several resonances in the operating speed range of the rotor. As noted at the last Annual Meeting, this formulation is intended to combine these effects, which are now resident in different versions of ROTSTB, into a single version.

Effects of Bearing Pivot Flexibility on Rotor Stability and Forced Response

*Lloyd Barrett, Ted Brockett, and Karl Wygant**

A number of the member companies have expressed interest in further understanding the effect of pad pivot-flexibility in tilting pad bearings on rotor dynamic stability and response. Pivot flexibility effects on dynamically reduced tilting pad bearing stiffness and damping coefficients were included in the original release of THPAD. However, systematic studies on this effect have not yet been performed, nor have the pivot degrees of freedom been included in ROTSTB along with the pad degrees of freedom in the dynamic reduction of the tilting pad bearing coefficients in that program. A small project has been initiated to examine these effects. The inclusion of the pad degrees of freedom in ROTSTB could easily be accomplished using the new formulation of tilting pad bearing/ flexible support equations being performed as part of the project on **Testing of Flexibly Mounted Bearings Supporting a Flexible Rotor** described above. As part of other work he has performed elsewhere, Karl Wygant has worked on the development of equations for calculating pivot stiffness for a variety of pivot geometries, which will be useful in this project.

Definition of Instability Mechanisms for Rotor Dynamic Analysis

Lloyd Barrett and Ted Brockett

Several member companies have asked that ROMAC assist in defining instability mechanisms, such as "aerodynamic cross coupling", for use in performing rotor dynamic stability calculations. A difficulty noted by both machine users and manufacturers is that there is presently no accepted standard or specification for assessing the stability of machines similar to those for assessing unbalance response and amplification factor. As a consequence, ROMAC is surveying its membership to determine what various users and manufacturers do to deal with this issue. The information will form the basis of a round table discussion at the next ROMAC Annual Meeting to discuss this topic and determine areas of research that ROMAC can perform that may lead to the establishment of reasonable, generally accepted specifications for performing stability design audits.

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 as FFTs, oscilloscopes (DSO or analog), DVF-2 or DVF-3, 386 PCs, and any type of transducers (position, pressure, accelera-tion, etc.) would be greatly welcomed and appreciated, especially since our equipment budget is always quite small. In return, you may get an immediate capital write-off on taxes from the gift donation.

For More Information

We want to hear from you

Write to ROMAC at the address given on the next page. The telephone number to reach our Office Manager is (804) 924-3292. Our FAX number is (804) 982-2246. We can receive Internet electronic mail at romac@virginia.edu.

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

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