■ ROTATING MACHINERY AND CONTROLS LABORATORIES ■

ROMAC

FALL, 1993

Message from the Director

Ron Williams

This first year of my term as ROMAC Director has been one of change. The organizational evolution that often accompanies major administrative change is certainly one of the benefits of regular rotation through the helm. While change need not always be for the better, it is generally necessary to keep pace with the world.

This year we have begun to sharpen the focus of ROMAC work to ensure that our industrial members receive good value return for their membership fees. We have started to review the research history and directions of our faculty and students, and we have carefully reconsidered our administrative support structure.

Two of our colleagues, Houston Wood and Bob Ribando, have decided that their efforts and interests no longer coincide sufficiently with the directions of ROMAC to justify their continued participation as ROMAC faculty members. They are both continuing as members of the University of Virginia faculty, and we wish them the best for success in the directions for their future work. ROMAC will continue to perform focused fluids research under the direction of Ron Flack and Hossein Haj-Hariri.

Our review of the administrative support structure revealed that the work of our executive secretary had declined over recent years as more typing and other similar tasks have been assumed by the researchers. This is a trend that has been seen elsewhere as personal computers have assumed much of the support role that was previously handled by clerical staff. Similarly, the work of our conference coordinator has declined as we have become more experienced and organized in this area. Therefore, we have combined these two separate areas of responsibility into a single office manager position that is filled by Sandy Maslen.

We have been working to improve the working environment in our laboratory. Joe Keith started an effort that has been continued by Klaus Brun to reorganize our laboratory space. This reorganization has included disposal of some obsolete equipment, transfer of less frequently used equipment to a long-term storage space, and general sorting and organization of our supplies. Partitions have been acquired to replace the makeshift dividers used previously in our graduate student office space. We are now purchasing several new and powerful personal computers that will be available for use by our graduate research assistants. We believe that the improved facilities will help our graduate students to be more productive, and we hope to foster a professional attitude about our lab.

The changes that have been made this year have all been directed to make better use of our available resources. We continue to seek new members for the ROMAC consortium, but we are not asking any more from our current members. The membership fees for 1994 will remain at the same level ($12,000) as they were in 1993.

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

ROMAC Annual Meeting `94

Charlottesville, VA. - June 5-9

The 1994 annual meeting is scheduled to begin with registration on Sunday, June 5, and end on Thursday, June 9. The 1994 meeting has been scheduled much earlier in the month than has been typical in recent years, but this scheduling was necessitated by the availability of conference facilities and because of conflicts with other significant meetings.

The annual meeting will be held at the Sheraton Inn in Charlottesville, VA. This hotel was selected because of both its attractive room rates and meeting room/catering facilities.

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While the hotel is definitely not within walking distance of the University, it is a short and convenient drive for those who choose to have automobiles. The hotel will provide an airport shuttle, and we will provide transportation for the ROMAC events that are held at the University.

We are planning two significant special events to be held on the grounds of the University. The first of these will be the banquet which will be held on Monday night, June 6, in the Dome Room of Thomas Jefferson's Rotunda. This is a truly inspiring setting for a pleasant meal and conversation with colleagues.

The second special event will be a tour of the ROMAC laboratory facilities. We like to return the annual meeting home to Charlottesville at least every other year so that our members can have the convenient opportunity to visit our laboratory and see first hand the work that we are doing. If you have never visited ROMAC, this will be a good opportunity. If you have previously visited, you may be surprised at some of the changes that we have made.

The ROMAC annual meetings have consistently attracted a loyal core of members, but we would like to encourage increased attendance and participation by all of our members. We believe that this year's meeting will offer certain special enticements for better attendance.

First, we have worked hard to find pleasant accommodations at a very attractive price ($60 per night for a single or double room). We are also holding the registration fee at the same level ($500) where it has been for several years. We understand that the greatest cost of attendance for our member companies is the absence of you, their critical employees. We also understand that travel budgets can be tight.

Second, we will be providing you with information about the many activities and points of interest that are available in the Charlottesville area. There is a wide variety of interesting things to do for those of you who may be accompanied by family.

Registration materials will be sent to our members in March, 1994. Mark your calendars and plan to join us in June.

ROMAC Short Course

Basics of Rotor Dynamics

This introductory course will be back by popular demand sometime in April, 1994. Many of you have expressed interest in attending this course, so enrollment may be limited. More information will be provided after the Christmas holidays.

ROMAC Industrial Liaison

Ted Brockett is the ROMAC Laboratory Engineer responsible for liaison with the industrial members on technical issues with our computer programs. He works directly with other 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 Computer News

W. Tobias Korn

We are continuing our efforts to make ROMAC codes more user-friendly and more easily maintained.

The Scripted Editor and Shell

Development continues on the ROMAC scripted editor and shell program which we demonstrated at the ROMAC annual meeting in June. The Scripted Editor will allow data files to be interactively edited and also allow for automatic transfer of data from one ROMAC program to another. This will eliminate the painstaking task of lining up data in the proper rows and columns manually and also of retyping data created by one program into the file format of another program.

We have released the first Beta version of the Shell and Scripted Editor. We appreciate the suggestions that we have received thus far, and we welcome your continued input. If you do not yet have a copy of the Shell and Scripted Editor, please let us know.

Further development on the Shell will include preprocessors, post processors, and incorporating your suggestions. More discussion on the shell is provided in an article starting on page 11 of this newsletter.

ROMAC Shell & Scripted Editor (Version Beta2.0) (July 12, 1993)
The first Beta version of the program was released.

ROMAC Shell & Scripted Editor (Version Beta2.1) (July 21, 1993)
(update by Eric H. Maslen)

Due to a minor bug in Windows, pressing the "Other Input...", "Other Output...", or "Code Switches" buttons appeared to lock the program up under some conditions. Actually, the code was not locked up, but the dialog windows invoked by pressing these buttons were off of the visible screen. Pressing <esc> immediately restored proper operation of the code.

The Beta 2.1 release corrects this problem by implementing a work around to avoid the faulty Windows operation. The work around is negligible and does not slow the code or add to its complexity in any substantial way.

For those with a technical interest in this problem, Windows sends a message to any window when it is resized, telling it that it is about to be resized. Along with the message is a structure (WINDPOS) parameter which is supposed to tell the window what size it will be. The Shell originally used this message and parameter to update a set of global variables indicating the corner coordinates of the main window. These coordinates were then used in launching the three dialogs mentioned above to determine their locations. Unfortunately, under some circumstances, Windows sends the WM_WINDOWPOSCHANGED message with an invalid WINDPOS structure containing all zeros. If the last message sent by windows prior to a press of one of the three buttons affected came with an invalid WINDPOS structure then the dialog would think that the upper RIGHT corner of the parent window was at the upper LEFT corner of the screen. The dialog would then place itself to the left of this point - off of the visible screen.

The fix was to supply a handle to the parent window to each dialog at initialization. In this manner, the dialog is able to directly query the parent window as to its size and location. The global window coordinate variables are no longer used. This solution is actually more elegant than the original approach and is, of course, not affected by the Windows bug.

New Features Added to Codes

We will continue to add the capability for ROMAC codes to accept command line arguments in the DOS environment. We have used command line arguments to input data file names and parameters to redirect output. This will allow batch processing and is a necessary modification to enable programs to work under the ROMAC shell/scripted editor environment. In addition to command line arguments we are adding a feature to our codes to enable file names and other options to be listed in a file and specified by placing @filename as the first input to the program. This is done on the command line or interactively. Since this feature is implemented in standard FORTRAN, those compiling the code on systems which do not provide a command line option capability, may enter the name of a file at the first interactive prompt, thus enabling near batch-mode operation.

We are continuing to use standard FORTRAN conventions in our codes, while also taking advantage of the DOS and Windows operating environments. The DOS and Windows versions of our codes will necessarily have some non-standard FORTRAN code in order to take advantage of the DOS command line. In programs where we use any non-standard options, these sections will be commented and are not necessary for the operation of the code. These sections are simply commented out to port the code to a non-DOS system.

Instant Access to ROMAC Codes and Technical Support

In order to make access to ROMAC programs easier for our members, we have made programs available via FTP (Internet File Transfer Protocol), Internet electronic mail and MODEM dial-in line. Electronic mail is an especially useful tool for providing Technical support. If you have difficulty running a program, you may e-mail the input file to us. We then extract the data file from the e-mail message and run it here to see first hand the difficulty. Please be sure to let us know if you have an INTERNET connection, subscription to Compuserve, America On-Line, MCI Mail, Delphi, BIX, a subscription to some other service that provides electronic mail services, or a MODEM, at your disposal.

If you use a MODEM to dial-in to the ROMAC server, you then have access to ROMAC codes, as well as to electronic mail. You may use the electronic mail service on our server to send mail to ROMAC faculty, staff, other ROMAC member companies, as well as any one who has access to electronic mail worldwide (including those services mentioned above).

Updated ROMAC Programs

The following ROMAC programs have been recently upgraded:

CRTSP2 Version 2.13 (June 17, 1993) (update by W. Tobias Korn) STATUS='NEW' removed from FRESP2 mode shape file to allow overwrite of existing file.

CRTSP2 Version 2.2 (July 15, 1993) (update by W. Tobias Korn) Formal arguments which were never used in subroutines CRITMAP and MODPLT were removed. Variables declared but not used were removed throughout the program. File name variable sizes were made consistent and increased to 80 characters for full path names. Calls to subroutine WHERE with too many formal arguments were corrected. Potential divide by zero errors were removed from the plotting routines. Type mismatches in calls to GEOGRAF subroutines were corrected. The length at the final station must be zero. This is now forced by the program. Call to MS FORTRAN specific DOS command line options, TIME and DATE subroutines placed in separate subroutines.

CRTSP2 Version 2.21 (July 22, 1993) (update by W. Tobias Korn) Added STANDARD FORTRAN capability of accepting a list file for the "command line options." To use a list file, put @filename in place of the input file name. The file names and options will be read from the file "filename". To create a list file, create a standard text file with the command line options, one per line.

Example: CRTSP2 @CRTDAT.LST
Example CRTDAT.LST (NOTE: Start at Column 1 when entering options):
CRTDAT CRTDAT.OUT 0 NONE

CRTSP2 Version 2.3 (Sept. 8, 1993) (update by W. Tobias Korn) The maximum number of stations was increased to 100. This size was parameterized to facilitate future modifications of the program. The rotor model is now displayed in the graphing routine even when a "dummy rotor" is used to analyze a single rotor system.

CRTSP2 Version 2.31 (Sept. 13, 1993) (update by W. Tobias Korn) Minor correction made to CRITMAP subroutine. The correction was necessary due to an undetected error when the maximum number of stations was increased from 50 to 100 stations in Version 2.3.

FSTB3 Version 1.34 (June 11, 1993) (update by W. Tobias Korn) Corrected use of default value for CHOICE in SUBROUTINE WHEREOUT and corrected version numbers which were incorrect in the output.

RESP2V3 VERSION 2.2 (Sept. 13, 1993) (update by W. Tobias Korn) Added STANDARD FORTRAN capability of accepting a list file for the "command line options." To use a list file, put @filename in place of the input file name. The file names and options will be read from the file "filename." To create a list file, create a standard text file with the command line options described above, one per line. The size of the file name variables was increased to 80 to allow for full path names.

ROTSTB Version 5.01 (August 3, 1993) (update by W. Tobias Korn and Theodore S. Brockett) A minor modification was made to the rotor plotting subroutine ROTORPL. The modification affected the drawing of the dotted vertical line for bearings. The condition where the number of speed cases is accidentally set to zero is trapped and the program halts with a descriptive error message. The PARAMETER LR (the maximum number of elements along the rotor where Young's modulus is allowed to vary from the value specified on card 4 of the input file) was increased from 80 to 151 (to match the PARAMETER LS). According to the input description, the last element of the rotor model must have length zero. This is now enforced by ROTSTB. That is, the length of the last element in the rotor model is automatically set to zero. The version number and date were placed in variables to facilitate future updates. A new subroutine FF was used to produce page breaks in the output (CHAR (12)) rather than using printer control code 1. Also added is the STANDARD FORTRAN capability of accepting a list file for the "command line options". To use a list file, put @filename in place of the input file name. The file names will be read from the file "filename." To create a list file, create a standard text file with the command line options, one per line.

Example: ROTSTB @ROTDAT.LST
Example ROTDAT.LST (NOTE: Start at Column 1 when entering options): ROTDAT.DAT ROTDAT.OUT

ROTSTB Version 5.02 (Aug. 6, 1993) (update by W. Tobias Korn) Two minor corrections were made. In FUNCTION GETLIST, the size of the formal argument for the file name was changed from 80 characters to 79 characters. In the main program, CON was used as a file name and opened to have the program send output to the screen (standard out). Since the use of the file CON is DOS specific, this usage was removed, and if the output file name is `CON', the output unit is changed to unit 6 (standard out) rather than opening the file CON.

ROTSTB Version 5.03 (Oct. 1, 1993) (update by W. Tobias Korn) Version 5.02 accepted a list file if given as the first argument on the command line, but not when entered interactively as the input file name. Version 5.03 corrects this so that if no command line options are used, a list file may still be used by entering the list file specification when prompted for the input file name.

THBRG Version 2.01 (June 17, 1993) (update by W. Tobias Korn) Modified DOS command line argument structure to accept input file and output file. If no output file is given, output is directed to standard output (screen). Made file name variables CHARACTER*80 to handle full paths. PARAMETERized version number and VERSION date to facilitate updates. Removed variable TRANG which was declared but not used.

THBRG Version 2.21 (July 22, 1993) (update by W. Tobias Korn) Added STANDARD FORTRAN capability of accepting a list file for the "command line options". To use a list file, put @filename in place of the input file name. The file names and options will be read from the file "filename." To create a list file, create a standard text file with the command line options, one per line.

Example: THBRG @THBRG.LST
Example THBRG.LST (NOTE: Start at Column 1 when entering options): THDAT THDAT.OUT

THPAD Version 2.24 (July 23, 1993) (update by W. Tobias Korn) Added STANDARD FORTRAN capability of accepting a list file for the "command line options." To use a list file, put @filename in place of the input file name. The file names and options will be read from the file "filename." To create a list file, create a standard text file with the command line options, one per line. Formal arguments which were not used were removed from subroutines TEMP (TBCK), BALANCE (GROOVE), and REDUCE (FLAG). Variables declared but not used were removed from READIN and THPAD.

THPAD Version 2.24a (Sept. 8, 1993) (update by Lyle A. Branagan of PG&E) The following modifications were made to THPAD: * Continue development of response (mils/lb) calculation * Add ellipse and phase angle calculation * Convert sign of rotating response force to CCW * Modify thermal deformation calcs; Add `y' input option * Terminate for starting guess outside of bearing * Add (wC/K) calculations to the output * Correct error in carryover output.

TWIST2 Version 3.00 (Nov. 1, 1993) (update by Theodore S. Brockett) Revised from Version 2.10 to include several new features: * Use of degree rule for calculating the stiffness of an element. * Included a global stiffness multiplying factor and element stiffness multiplying factors. * Ability to model disks using dimensions and material properties and have disk information automatically included in the global mass and stiffness matrices. * Rotor model plotting capability added (for single speed non- branched systems). * Changed forced response calculations to be more efficient: replaced matrix inverse routine with an L-U decomposition routine. This allowed program memory requirements to be reduced by removing variables. * Program now calculates the nominal stress in each element during the forced response calculations. In addition, plots of the stress and stress phase as a function of excitation frequency are possible. * Program now writes to a direct access scratch file the data necessary to perform the plots. This eliminated variables that were previously used to store the data. * The maximum length of the input and output file names was changed from 60 to 80 characters. * The format of the modal file was changed in order to include shaft element properties and shaft global nodes. * Addition of command-line options. The format is: TWIST2 [input.fil] [output.fil] [modal.fil]. Any number of the files may or may not be specified. The modal file, modal.fil, is only used if NTRAN=1. * Corrected error in the scaling of the applied torques when the torque was applied to a node not running at the reference shaft speed. * Added STANDARD FORTRAN capability of accepting a list file for the "command line options". To use a list file, put @filename in place of the input file name. The file names and options will be read from the file "filename." To create a list file, create a standard text file with the command line options described above, one per line.

Current Research Projects

Fluid Film Bearings and Seals

Fixed And Tilting Pad Bearings

Karl Wygant, Carmen Müller-Karger, Lloyd Barrett, and Ron Flack

The large rigid rotor bearing test rig (70 mm dia bearings) is being used for tests on a three lobe fixed pad bearing (preload = 0.50). Dynamic as well as static characteristics are being documented. Next, another three lobe fixed pad bearing (preload = 0.25) will be installed. Data is being compared to predictions. In response to the members suggestions to tilting pad geometries, Turbo Components & Engineering will make us such bearings for testing. We have just received the second draft set of design drawings from TC&E that we are currently inspecting for compatability with our rig.

Flexible Rotor/Bearing Rig

José-Antonio Vázquez, Ron Flack and Lloyd Barrett

The small (25 mm dia bearings) flexible rotor rig is being modified to incorporate pedestal flexibility. Preliminary studies were presented at last summers annual meeting. The pedestals will be flexible so that the forced response and stability will be modified from the rigid support results. Results will be used for code verification. Fixed and tilting pad bearings will be tested.

Assessment of Non - Linear Effects in the ROMAC Bearing Test Rig

Carmen Müller-Karger, Lloyd Barrett, and Ronald Flack

Carmen Müller-Karger is developing a non - linear bearing transient program to simulate the bearing test rig. The purpose is to assess the influence of non - linearities in the bearing fluid film on the measured stiffness and damping coefficients. The transient program represents a "perfect" for which the linearized stiffness and damping coefficients are known. The program will be run under the same conditions of dynamic forces as the test rig, and the transient data will then be processed the same as the data obtained from test rig, and the resulting "measured" stiffness and damping coefficients will be compared to the known linear values.

Preliminary results indicate that the measured data may differ substantially from the linearized coefficients depending on bearing type, load, residual unbalance, and magnitude and phase of the dynamic excitation forces. It is anticipated that this project will further increase our knowledge of the accuracy of the measurements obtained from the test rig and give additional guidance on testing procedures.

Thrust Bearing Program

Ted Brockett, Lloyd Barrett, Paul Allaire

Ted Brockett is currently developing a sophisticated thrust bearing analysis program. He has completed an exhaustive literature search and discussed potential features of the code with many of the industrial members.

The program will be capable of modeling numerous commonly used fixed and tilting pad thrust bearing geometries, including several that appear to have never been analyzed previously. The program will include sophisticated thermal and mechanical deformation models as well as deformation in the thrust runner. The deformation models will include pad cut outs and a more detailed description of the pivot geometry in tilting pad bearings.

Flow Simulation and Calculation of Hydrodynamic Rotordynamic Coefficients for Labyrinth Seals

Avichal Mehra and Hossein Haj-Hariri

The major contribution of this effort is the development of a Fortran code for modeling the flow in labyrinth seals. In modeling the dynamic behavior of turbopumps it is important to consider the fluid forces developed in the seals. Using this code we can address various configurations including inclined teeth, as well as grooves on both rotor and stator. Furthermore the effect of rotor whirl can be studied. Fluid forces due to the movements of the shaft in small orbits around the center position are used in the evaluation of hydrodynamic stiffness and damping coefficients.

Initially an incompressible and a compressible version of the code were developed. They are now in the process of being merged together through using a common formulation capable of treating both cases. Our immediate efforts are concentrated on modeling the flow in a single groove and developing a formalism for extracting leakage and pressure-drop information for the whole seal by replicating the single-groove calculations.

The flow in the seals is described using Navier-Stokes equations with a k-e turbulent model. A finite-volume formulation is used to solve the equations governing the basic-state (concentric) and the perturbed (whirling) flows. Some preliminary results for the velocity of an incompressible flow through a single groove of the labyrinth have been obtained for the zeroth order equations. They agree well with the earlier published results for similar geometries. More complete results, as well as some for compressible flows, will be shown at the annual meeting.

Fluids

Plexiglas Pump

Daniel Baun, Len Whitehead, Ron Flack, and Steve Miner

Tests were completed last year for the double volute Plexiglas pump. Velocities (from LV data) and pressures were collected. Impeller loads were found for both the single and double volute geometries. As expected, the double volute resulted in much lower loads at off-design conditions. Also from the LV data volute losses and slip were calculated for the double volute case. The efforts are continuing and load and other characteristic predictions are being made for both double and single volutes and are being compared to measurements.

The pump is now being modified and magnetic load cells are being installed which will directly measure the impeller loads. Thus, different volute shapes, impeller geometries, tongue shapes, etc., can easily be changed and the total forces can quickly be measured. Once interesting geometries are identified, LV and pressure data can be measured to complement the force information.

Torque Converter

Steve Ainley, Klaus Brun, and Ron Flack

This is an industrially sponsored problem but has been used to expand our experimental capabilities and understanding of a complex mixed flow turbomachine. Data that was collected at a fixed point in space was correlated to provide an understanding of the complex unsteady flow because of component interactions. "Movies" have been presented at the annual meeting showing the complex jet-wake interaction from the exit plane of one component on the inlet plane of the downstream component. Also, strong secondary flows and slip factors were measured in the pump. Work is continuing for different pump and turbine geometries.

Three Directional Laser Velocimeter

Ron Flack

A year ago a three directional laser velocimeter was obtained under a separate contract. This was purchased for some very low velocity measurements (approximately 1 ft/min) for fire propensity studies, including free convection. The system is motor driven and fiber optics so the system is quite versatile and adaptive. It is capable of velocities in the supersonic regime. Although the ustem is not currently on a ROMAC project and the free convection studies will last another year, it is under the jurisdiction of Ron Flack so that when the current fire propensity project ends it may be used for turbomachinery flows.

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 July 1, 1993 through June 30, 1994 is $108,000. This brings the total CIT funding for the Center to over $1,300,000 since July 1989. The Center is one of ten Technology Development Centers funded by the CIT. This funding has supported much of the magnetic bearing development in ROMAC.

Load Cells for Pump Test Rig

Roger Fittro, Ron Flack, Eric Maslen, and Paul Allaire

Magnetic bearings designed to both support the shaft and measure the forces on the Plexiglas centrifugal pump test rig have now been constructed. Extensive testing is now underway to characterize the relation between the actual force, as measured independently, and the coil current. This relation is not simple, as both eddy currents and hysteresis effects are present. The tests are in the process of quantifying these relations. An uncertainty analysis of the system is also in progress.

A New Digital Controller for Magnetic Bearings

Jeff Ebert, Paul Wayner, Ron Williams

With applications requiring high-speed control and sophisticated signal processing entering the industrial workplace, digital signal processing (DSP) technology is no longer reserved for audio, video, and data acquisition systems. In some of these applications, very high processing speeds are necessary, and this need may be met by multiprocessing platforms. Others require that the controller have high reliability and fault tolerance over a long time period, and this need may be met by a redundant, modular system. The control of magnetic bearings in rotating machinery is one of the most demanding of these new industrial applications. I/O bandwidth and processing speed must be sufficient to support fast, flexible rotors, and available DSPs have the capacity to meet these demands. However, innovations in adaptive and open-loop control are demanding more processing power in embedded controllers.

Furthermore, magnetic bearings applications cannot tolerate a controller failure. Therefore, simplex digital controllers are not sufficient to meet advanced needs in magnetic bearing control or, more generally, industrial control.

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. Currently, the operating frequency of the `C40 is 40 MHz, but the design is may be upgraded to 50 MHz with a peak performance of 275 MOPS and a data throughput of 320 Mbytes/sec. The `C40 is a widely accepted DSP for both control and signal processing, and many tools are available to support this device. 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. The system has 32 14-bit D/A channels and 24 14-bit A/D channels.

Multiprocessing Configuration

The `C40 has six byte-wide asynchronous communication channels which may be used to interconnect these chips for multiprocessing. When configured for multiprocessing, the system's four `C40s 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). A functional diagram of this system is shown in figure 1. Software may determine how the DSPs actually interact; pipeline or array architectures are possible. Further, each TIM-40 will have its own system and user software. The system software is ROMAC's own real-time multi-tasking operating system which is currently running on the Integrated Controller for Magnetic Bearings. The flexibility and ease of use of this system will allow designers to experiment with the power of multiprocessing.

Fault-Tolerant Configuration

To provide fault tolerance for the processing section, we use the redundant TIM-40s to provide TMR (Triple Modular Redundancy) with spare and repair. When the system is running in this mode it will be configured as shown in figure 2, and only three of the boards will be powered during normal operation (shown in black). The PIOL provides a synchronizing clock signal to all the TIM-40s 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 initially reset the questionable board, and later, replace it with the spare (active). Thus, the system can tolerate the failure of two TIM-40s before it is 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

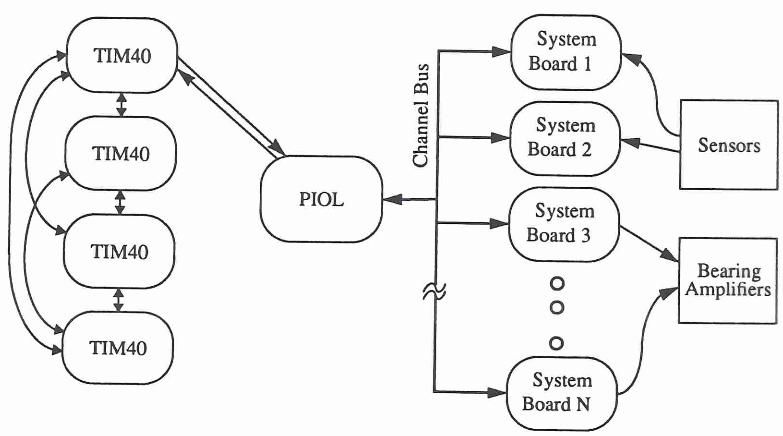

Figure 1: Multiprocessing Functional Viewpoint of the Next-Generation Digital Controller

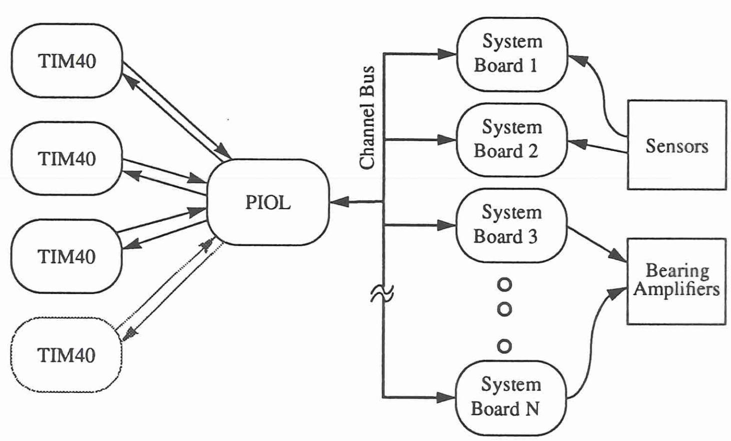

Figure 2: Fault-Tolerant Functional Viewpoint of the Next-Generation Digital Controller

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 detect faults that occur in the bearings. The sensors include current detectors to determine if a coil has current. If a coil has no current then the controller will try to determine whether the coil is faulty or if the amplifier is faulty. The amplifiers have status lines that are read by the controller to facilitate fault detection.

Using this digital controller, configured for fault tolerance, as the heart of a magnetic bearing application, a very robust and reliability 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.

Real-Time Operating System

Steve Fedigan and Ron Williams

Digital control of magnetic bearings requires software that meets the demands of a real-time computing environment. System performance not only depends on the results of a computation, but also on the time that the results are delivered. Sensor data must be collected and actuator data delivered at regular intervals. Open-loop controllers or diagnostic programs must not cause the program stabilizing the rotor to miss a deadline.

The real-time operating system (RTOS) is designed to help users meet the demands of this environment. Multitasking capabilities allow users to prioritize programs. This permits low priority programs to run without compromising ones which have critical deadlines. Timing functions ensure that code that needs to run periodically does.

The hardware details of sensor input and actuator output are handled by the operating system. The ability to inject rotor-synchronous forces and observe responses supports advanced control schemes. By insulating the user from the hardware and timing details in the new controller, the operating system allows users to concentrate on the development and testing of control algorithms. Also, since the operating system has been designed by ROMAC faculty and staff, as user needs change, the operating system can be modified to support those needs.

The first version of this real-time operating system was completed last year. This summer, the controller's operating system was revised to boost performance and enhance flexibility. To minimize overhead, all time-critical elements of the operating system were written in assembly language to execute from the TMS320C30's fast internal RAM. The relative timing of events in a control loop is now completely under user control, and can tuned to a specific application, freeing up more CPU cycles for control computations. Under the latest version of the operating system, the version 3 controller hardware can now execute a third order digital filter across four channels at a rate of 10 kHz/channel. To enhance flexibility further, the RTOS now supports multiple independent control loops. This means that several control loops, each having distinct or even varying periods, can be executed simultaneously. The operating system will be retuned to support a parallel processing environment when the forth generation controller comes on line in February, 1994.

Open Loop Unbalance Control

Winston Hope, Carl Knospe

Much has been accomplished in the past year with the control of unbalance vibrations using open loop control methods. The advent of the third generation digital controller with a real-time, multi-tasking operating environment has allowed many new techniques to be explored. As was presented at the 1993 ROMAC Conference, the basic method involves measurement of rotor/bearing influence coefficients and the calculation and application of synchronous vibration canceling forces.

Initially, influence coefficients were measured by injecting a series of synchronous test forces while the rotor

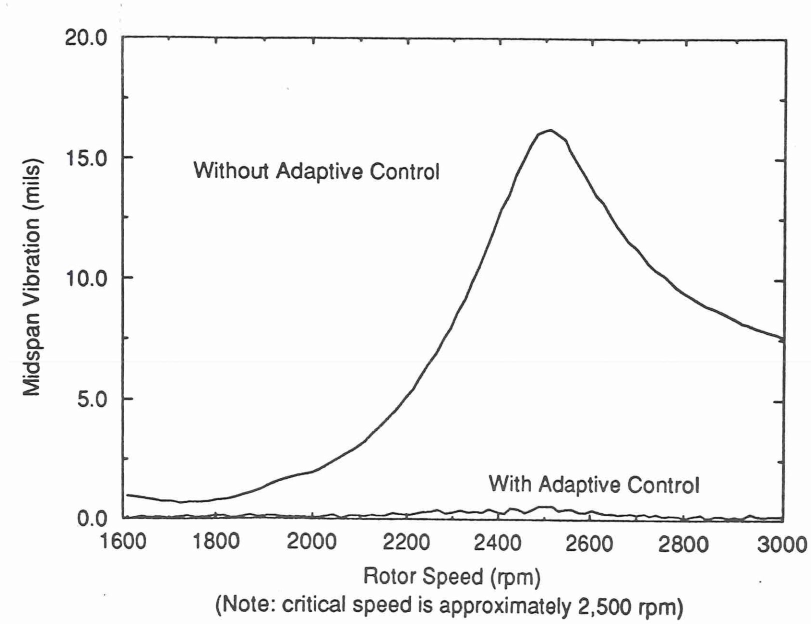

Figure 3: Midspan Vibration of the Rotor With and Without Adaptive Control During a 30 Second Run-up from 1,600 rpm to 3,000 rpm

was running at a speed of interest. A series of measurements were made at a range of speeds and stored in the digital controller's memory. Linear interpolations of these coefficients were then applied to balance the rotor throughout the speed range. (Please see Figure 3 on the previous page.)

A new method of measuring the influence coefficients by injecting noise into the bearing coils has now been incorporated into the balancing software. With this new feature, the digital controller learns the rotordynamics by itself. This reduces the time required to train the system and does not require the rotor to be spun without vibration cancellation. The next topic of investigation is reducing rotor vibration at locations were the response cannot be measured with position probes. This will involve the incorporation of a rotor model to estimate the unbalance response.

Thrust Bearing Hysteresis Study

Daniel Noh and Eric Maslen

A very detailed study of a dead zone in the force vs displacement characteristics of a permanent magnet biased magnetic thrust bearing has revealed far more about the interaction between lossy magnetic loads and their associated power amplifiers than was anticipated. Daniel Noh has completed a series of experiments and a parallel series of simulation studies which clearly demonstrate the deterioration of conventional switching power amplifier performance when driving a lossy (hysteresis and eddy currents) magnetic load. The study illustrates that conventional amplifier schemes such as PWM and Sample and Hold, as well as our original MPW amplifier will all demonstrate varying degrees of crossover distortion when driving lossy loads. The practical consequence of this crossover distortion is a dead zone in the magnetic bearing because of the null amplifier gain in the immediate vicinity of the zero control current point.

The simulation studies, based on nonlinear magnetic hysteresis models, indicated that, by increasing the delay threshold ratio in the MPW switching control scheme, the crossover distortion can be eliminated. The required extent of the increase in the threshold ratio depends on the degree of loss in the stator core iron. Later experiments with an increased threshold ratio confirm the prediction nearly exactly.

By eliminating the bearing dead zone without adding an additional "clean" inductor in series with the bearing coil, the high slew capacity of the bearing is retained without increasing the power supply voltage.

Sensorless Bearings

Daniel Noh and Eric Maslen

Work continues on a signal processing scheme for extracting shaft position from the switching waveform of the bearing power amplifier. As described in last year's newsletter, the objective of this work is to be able to measure the position of a magnetic bearing journal by simply studying the correlation between the switching noise waveform induced by high efficiency switching power amplifiers and the switching logic itself. This permits the magnetic bearing to be operated without any explicit sensor -- the bearing stator itself serves as the sensor. The real advantages to this arrangement are the reduction in wire count between the controller and rotating machine (through elimination of the sensor wires) and the reduction in required bearing axial length (through elimination of sensing surfaces and sensor rings or probes). It is expected that the achievable bearing performance with the sensorless scheme will be somewhat inferior to that which can be attained with conventional sensors, but in applications where the rotordynamics are not extremely demanding the small loss in performance may be more than offset by the reduction in failure prone components and wiring.

A preliminary signal processor has been constructed and demonstrated with some limited success. While the performance of the processor is not yet adequate, the initial tests do support the underlying theory and clearly point out the required direction for improvement. Refinements to the processing circuit are underway and a better test fixture which uses an actual magnetic bearing is presently being constructed.

High Force to Weight, Low Power Consumption Magnetic Bearings

Mary Kasarda, Paul Allaire, Carl Knospe, Eric Maslen, and Bob Humphris

A magnetic bearing test rig to measure power consumption is being constructed at this time. The rig will have two radial magnetic bearings and use the rundown technique to measure power losses. It will operate in a vacuum to allow for operation with windage and without windage. It will have a high speed motor allowing operation of magnetic bearings up to 5 million DN (50,000 rpm). Both planar radial and homopolar bearings will be tested.

High force/coil current bearing relations are being tested using the radial and thrust bearings from the Plexiglas pump test rig as mentioned earlier.

Fault Tolerant Coil Control for Magnetic Bearings

David Meeker and Eric Maslen

Although it is not immediately apparent, most magnetic bearing stators have at least one structurally redundant coil. This means that, if a coil failure can be detected, then it is possible to "work around" the bad coil and still operate the bearing. The only performance loss is some reduction in load capacity. In fact, for an eight legged magnetic bearing stator, if the coils on each of the eight legs are operated independently, up to four of the coils can fail without substantially impairing the bearing operation.

The basis for these observations is a newly developed bias linearization theory for a broad class of quadratic devices which includes magnetic actuators. This theory permits optimization of a linearizing distribution of bias and control currents for the coils of a generalized n-pole magnetic bearing. The poles need not be regularly spaced or equal in cross sectional area, nor do the coils all have to have the same number of turns. These symmetries are normally imposed on magnetic bearing stator designs and permit an ad-hoc bias linearization. However, when the symmetries are destroyed as when a coil fails, the ad-hoc methods will no longer suffice.

The theory permits computation of a family of control-to-coil current maps in the form of linear matrices which can be used in a digital controller to accomplish coil (and amplifier) fault tolerance. When a coil failure is detected, the current map for that particular coil failure configuration is loaded from memory and used in generating subsequent coil current requests. Since the maps can be computed off-line, they impose no significant computational burden on the digital controller yet provide a new level of fault tolerance.

We are presently in the process of refining computational tools for computing these matrices. Although the coil map matrices can be defined with a few (deceptively) simple equations, the needed solutions have proved somewhat difficult to obtain. At present, a method has been implemented which is clumsy but sufficient to demonstrate the existence of solutions. Further work is required to reliably obtain fully optimized solutions.

Boiler Pump Magnetic Bearings

Patrick Depret-Guillaume, David Lewis, and Robert Humphris

This project is funded by Mobil Research and Development of Princeton, NJ to develop a feedpump with three radial magnetic bearings and a double acting thrust bearing. This research project will involve the design, construction, and operation of a test rig (which simulates certain characteristics of the feedpump) to demonstrate the digital controllability of the three radial bearings. In addition, certain types of redundancies are being incorporated into the test rig for several different modes of component failures. The structural aspects of the project have been completed. Robert Humphris and David Lewis are co-directors of the project which will likely become the foundation of a Ph.D. dissertation by Patrick Depret-Guillaume. As the project moves forward, additional details will be reported to the ROMAC membership. Robert Aimone of MOBIL is the moving force behind the project and will likely present further details of the project at the next annual meeting.

Rotor Dynamics

Rotor and Support System Identification using Time Domain Methods

Ping Zhong, Lloyd Barrett, Carl Knospe

Ping Zhong is continuing his Ph.D. dissertation research in the area of identification of rotordynamic system parameters applying time domain signal processing techniques to vibration data obtained in the field or on the test stand. He has developed one computer program that is nearly ready to release to the industrial membership.

MODID 1.0 is a Microsoft Windows program for modal parameters identification. It employs the Backward ARMA model method and uses a Singular Value Decomposition or Minimum Norm solution to automatically choose system orders and cancel the noise effects. Program features include:

- Automatic order selection

- Identification of modal parameters, such as
  - Natural Frequencies
  - Modal damping
  - Mode shapes can be identified (depending on how many measurement locations are used).

- Identification of well damped modes which are difficult to detect using FFT and other frequency domain techniques.

- Identification of closely spaced vibration modes which are also difficult to detect using frequency domain techniques. Time domain techniques like the ARMA model method have much higher frequency resolution. This is especially valuable for closely spaced structural resonances.

So far, the program has been used to identify rotor system data using simulated transient data. The results have been quite promising. It has been used on actual steam turbine start up data supplied by one of the member companies. Since the start up time was quite long and the data very "smooth", or not very frequency rich, it was difficult to identify parameters. This has prompted some additional study to develop ways to overcome this problem.

Additional areas which are being developed include:

- Recursive identification and monitoring methods.
- Pattern recognition using monitoring data
- Combinition of rotordynamics and bearing analysis with parameter

ROTSTB-Continued Modifications

Substructure Flexibility

Karl Wygant and Lloyd Barrett

Karl Wygant has completed his Masters thesis where he developed techniques for including multi-frequency models of bearing pedestal into ROTSTB. He utilized a modal representation of the support structure in combination with a dynamic reduction scheme.

Models include both simple pedestals and casing structures (Figure 4). He is currently developing a manual for the program before it is released to the industrial membership.

Magnetic Bearing Models

Ted Brockett and Lloyd Barrett

Ted Brockett has completed the inclusion of magnetic bearing and controls models into the stability program, ROTSTB, Version 5.xx. The controls are represented by polynomial transfer functions, and non-collocated actuator and sensor locations are included. Effects of flexibly mounted magnetic bearings are also included.

The program manual has been written and the program has been released to the industrial membership.

Bearing Design and Optimization

Work continues on a series of projects underway to develop methods for designing bearings using rotor dynamic criteria. The goal is to decrease the amount of time spent designing bearings while examining many more possible bearing designs. Currently, stability criteria are used to select acceptable designs.

Design and Optimization of Magnetic Bearing Controls

Deb Dhar, Lloyd Barrett, Carl Knospe

Deb Dhar (PhD) has nearly completed his dissertation and computer program implementing an algorithm 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.

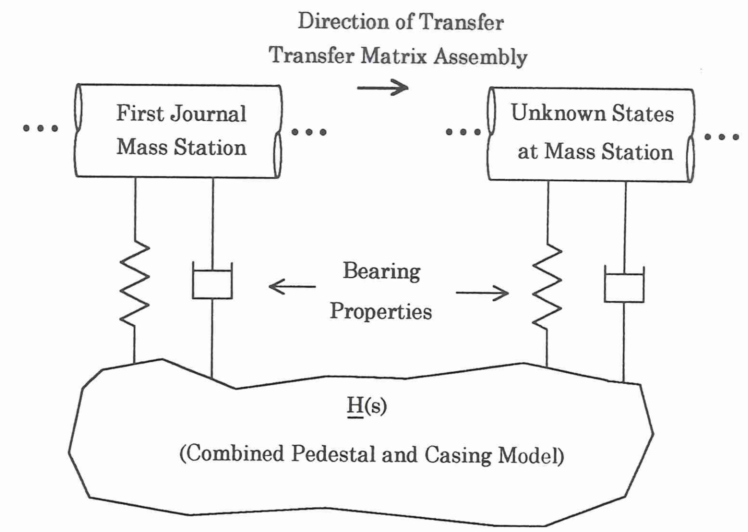

Figure 4: Iterative Solution Technique (Dependence on Unreached Bearing)

The program 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 coefficients of magnetic bearing controller transfer functions.

Design and Optimization of Fixed Geometry Journal Bearings

Jeannette Smith, Lloyd Barrett, and Carl Knospe

Jeannette Smith recently completed her Master of Science thesis. In this work she developed a fixed geometry bearing design program based on Deb Dhar's program. For a particular fixed geometry bearing type, bearing stiffness and damping coefficients are calculated over a range of Sommerfeld numbers using THBRG or TEMBRG. These are input to the design program which then searches over user defined ranges of bearing clearance, viscosity, or other design parameters. For each set of values of these parameters, the program uses the appropriate values of stiffness and damping coefficients for the Sommerfeld number defined by the set of parameters.

Extensions to tilting pad bearings, including a complete description of the pad dynamics, and a wider range of design parameters are planned for future development.

Jeannette's program is currently undergoing additional testing, and a program manual is being written.

Optimization of Bearing Location

Sriram Srinivasan, Lloyd Barrett, and Eric Maslen

Sriram Srinivasan has recently completed his Ph.D. dissertation, and has developed a computer program to determine the "best" locations for bearings on a rotor. The bearing design process for the stability of rotating machinery can be sensitive to the bearing locations. In many cases, it turns out that if the stability specifications are not being met by designing bearings from a particular set of bearing locations, a change in bearing locations can improve the bearing design. Designing the bearings from all the candidate bearing locations and then choosing the best location and design can be a computationally intensive procedure.

Program PLACEBRG is intended for use by rotating machinery designers to select the ``best" bearing locations prior to the bearing design process. The purpose of the program is to improve the overall design process by separating the problem of determining the ``best" bearing locations from that of determining the actual bearing design. Typically, bearings designed from the ``best" locations determined by PLACEBRG are more likely to satisfy the stability specifications and have better properties.

The method implemented in PLACEBRG is independent of the type of bearing employed. It is only dependent upon the rotor without the bearings and the stability specifications being considered. Within certain limits, the stability specifications are defined by the designer and involve moving the damped eigenvalues of the rotor-bearing system into an acceptable region of the left half of the complex plane.

PLACEBRG computes a scalar measure of the relative ability of bearings to meet the stability specifications from the candidate bearing locations. The program uses these scalar measures to rank the candidate bearing locations and presents this ranking in the output thereby selecting the best locations.

PLACEBRG uses methods from control theory and is non-iterative and very computationally efficient. PLACEBRG would ideally be used as a preprocessor to the bearing design programs described above. Presently, the program can only handle a single level rotor.

A manual is being written and the program will be released soon to the industrial membership.

The ROMAC Shell

For those who missed the demonstration at the last annual meeting, interactive computer analysis has arrived at ROMAC! The ROMAC Shell, which has been released in a beta version for operation under Microsoft Windows, integrates all of the ROMAC analysis codes under a single simple interactive shell. Analyses can be selected from a convenient menu system which groups the various analysis codes according to the type of analysis that they perform. Online help is available for any of the codes at the click of a help button. The Shell maintains an inventory of the analysis codes on even the most complex file servers, permitting any user with appropriate access privileges to find and execute the codes without any need to browse directories. Further, because the shell knows the structure of each analysis code's command line, it sets the command line up automatically while providing full and well organized editing of each piece of information needed to complete the command line: data file name, output file name, resource file names, and option switches.

The real power of this system is that it provides a fully interactive analysis environment without sacrificing any of the computational tools in which you have made such substantial investments. The Shell is not a collection of separate interactive analysis codes. Instead, it wraps an interactive environment around the same batch analysis codes that you are already using. This means that you do not have to rewrite the data files which you have already developed, nor do you have to validate new computational tools. Further, the flexible binding employed by the Shell permits you to add ANY batch analysis tools under the interactive umbrella -- whether they were developed by ROMAC or not. All of the codes then present the same uniform front end to the analyst and can make use of the same pre- and post processing tools. This translates to a faster learning curve on new codes and simpler organization of analysis jobs.

Scripted Editing

Data file editing, preprocessing, and postprocessing are supported by auxiliary tools including an interactive scripted editor, a fast file viewer, and graphical data file validation codes. While most analysts eventually become intimately familiar with the peculiar structure and formatting required of the input data files for their favorite batch analysis code, few would claim that these files are easy to understand or painless to construct. The Scripted Editor is a new kind of editor which uses a script to interpret the data file appropriate to a given batch analysis code and then constructs a fully interactive editor with pull down menus, online context sensitive help, and extensive error checking. The script is a detailed description of the structure of the data file: each batch analysis code has its own special script. While the specific structure of the editor is different for each analysis code, the look, feel, and logic of the editor is always the same. Further, confusing configuration flags common in most batch analysis data files are represented by easy to understand menus in the editor. For instance, the gyroscopics parameter in CRTSP2 is represented by a menu of options including "forward synchronous whirl" and "rotor 1 at fixed speed".

Units Conversion

By using a simple linear transformation defined in the script, the scripted editor can easily support specialized units so that the user can develop data files using the most familiar or appropriate units for a particular job and the editor will translate to "code native" units when the file is written to disk. This permits data files to be written in arbitrary units systems without the need to recompile the analysis software. Postprocessing is presently under development which will support the same units conversion for output files.

Data Exchange

Another powerful feature of the Scripted Editor is the ability to extract pieces of a model from data files written for other analysis codes. For instance, suppose that you have completed a critical speed analysis for a single level rotor using CRTSP2. You now wish to carry out a stability analysis of the same rotor using

RESP2V3. Rather than reentering the rotor model into the data file for RESP2V3, you start up the scripted editor for RESP2V3, select the rotor model from the main menu, click the import icon, enter the CRTSP2 data file name, and the necessary data is automatically located and imported. The data appears instantly in the editing fields for the rotor model, ready for modification if you wish. That's all there is to it! No need to retype the data with the attendant likelihood of entry errors and subsequent need for model debugging.

We believe that first time users of any of the analysis codes will be truly relieved to find out how simple it is to create, edit, and execute data files using the combined resources of the Scripted Editor and the Shell. Even the most diehard adherents of line editors will eventually succumb to the charms of the powerful scripted editor. (Our own Ted Brockett has openly admitted that he would rather use the Scripted Editor than his cherished KEDIT!)

Preprocessing

The capabilities of the other pre- and post-processor tools which are planned for this system are illustrated by the first tool we've provided: the rotor validation tool. If you select a rotor analysis code (eg.: CRTSP2, ROTSTB, RESP2V3, FRESP2, etc.) while running the Shell, a button will appear in the main shell screen labeled "CHECK". Click this button to invoke the rotor model validator which will instantly draw a scale diagram of the rotor described by your model. Click on any feature of the diagram with the mouse and an inset window will appear with any relevant numerical data for that feature (such as bearing coefficients or shaft diameter and material properties). The diagram can be printed or imported into another document as a bitmap. If the rotor validator detects any inconsistencies in the data file, it lists them in an error window as an aid to correcting the data file.

Future Plans

Several separate projects are presently underway to develop tools to round out the complement of pre- and post-processing capabilities for the interactive system. A very powerful general report generator is being written which will permit the output format of any analysis code to be tailored to whatever format the analyst desires. While one objective of this project is to provide data conversion for output files, the completed tool will also support translation of the data in the output file to analyst-customized report formats. This, in conjunction with the unit conversion capabilities of the Scripted Editor, should eliminate ninety percent of the software rewrites currently carried out by member companies.

Additional tools planned include a bearing geometry and property pre-viewer, mode shape and critical speed map plotters, and a general purpose utility for extracting output data for commercial plotting packages. Finally, an effort is underway to port the Scripted Editor, originally developed as a DOS application, to Windows.

We hope that you will share in our enthusiasm for the underlying objectives of this project as well as the actual software realization of it. Please feel free to offer suggestions for useful auxiliary tools or for refinements of any of the tools already developed.

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

For More Information

We want to hear from you

Write to ROMAC at the address given below. 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 suggestions will be appreciated. Updates to keep our Industrial Contact List current are always welcome.

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