ROTATING MACHINERY AND CONTROLS LABORATORIES

# ROMAC

FALL, 1992

## Message from the Director

*Ron Williams*

Since its creation, ROMAC has endeavored to lead in research, experimentation, and program development in the dynamics of rotating machinery. The ROMAC laboratories have grown significantly, and we continually reflect on our current status and the directions that we will take in the future. The decisions that we make are fundamental to the future support of our members. The comments received from our members help significantly in this planning.

The many programs based upon ROMAC research are available to support the needs of our members, and we recognize that these programs are the foundation of the benefits enjoyed by our members. We are reviewing our library of programs with an objective of identifying and removing those programs that may be obsolete. In this process, we will also identify areas in our library that may need additional attention. New programs are always in development, and these continue to be added to our library as they are completed.

The ROMAC programs perform the computations that are necessary to assist in the design and analysis of various components of rotating machinery. While we have worked to ensure that these programs produce accurate results, we have not always been quite as diligent in providing a simple and friendly user interface. We are beginning to place greater emphasis on the user interface to simplify the use of our programs.

Another major member benefit is the direct access to the results of our research through our library of reports. New reports are added to this library regularly and are provided to our members. The projects summarized in this newsletter will eventually yield new information that may be useful to you. We are continuing to emphasize the importance of these reports as a valuable resource for our members.

Our programs help in design and analysis of rotating machinery. Our reports provide details of our cutting-edge research. These benefits are supplemented by our short courses for our members only. These short courses are designed to provide reviews for experienced engineers, offer introductions to new areas, and detail advanced concepts.

Of course, our principle "product" remains education. We are pleased that our students have been prepared to make valuable contributions to the companies that they join after graduation. Since some of our members have expressed interest in where our students go in the "real world," we have included some of this information in this newsletter.

I sincerely hope that you will let me know your thoughts regarding the range of benefits that we provide. Please share any suggestions that you may have to improve our current benefits. Also, I would like to hear any suggestions for new services that would be of value to you. We want to ensure that your membership in ROMAC continues to be a good value to you and your organization.

## ROMAC Annual Meeting '93

*Sponsored by Duke Power*

The ROMAC meetings have traditionally alternated between Charlottesville and some other location. The other location has typically been either a resort area or an area near one of our members. The surveys collected at our 1992 annual meeting indicated a tie between the member company option and the resort option.

We believe we have reached an agreeable compromise with our 1993 annual meeting in Charlotte, North Carolina. This is the home of Duke Power, one of our member companies. It is also a very pleasant area with many attractions beyond our meeting. It should be easy to reach by air; many of you probably made connections there en route to Charlottesville. Also, the costs of accommodations are very competitive.

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SCHOOL OF ENGINEERING AND APPLIED SCIENCE
UNIVERSITY OF VIRGINIA
CHARLOTTESVILLE, VIRGINIA 22903-2442

The annual meeting is scheduled for June 21-24, 1993. It will be held at the Mariott Hotel in downtown Charlotte, NC. We hope to encourage more member presentations next year. Registration materials will be sent to our members in March, 1993. Mark your calendars, and plan to join us there.

## ROMAC Computer News

*Toby Korn*

We are endeavoring to make your life easier. ROMAC is striving to make our codes more user-friendly, and more easily maintained. We are also making an effort to provide better service by offering instant access to our codes.

### *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. The first version of this scripted editor is available to our members now.

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.

At the Annual Meeting, Members expressed their concerns about using non-standard FORTRAN in ROMAC codes. 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 will not be 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*

In order to make access to ROMAC programs easier for ROMAC members, we have made programs available via electronic mail and MODEM dial-in line. Please be sure to let us know if you have an INTERNET connection, subscription to Compuserve, America On-Line, MCI Mail, 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 Codes*

The following ROMAC programs have been recently upgraded:

**CRTSP2** Version 2.12 (7/8/92)
Type mismatches in calls to **GEOGRAF™** routines were corrected.

**RESP2V3** Version 2.1
Command Line Options have been added. **RESP2V3** now allows command line options to be used for specifying input, output, plot file names and plot options. This is illustrated below.

**RESP2V3** VERSION 2.12 (9/24/92)
Modified **RGRAPH7.FOR** to correct type mismatches and subroutine calls with too many parameters which caused extraneous characters to appear in **GEOGRAF™** plots.

**SEAL2** Version 2.21
Changed from single precision to double precision

**THPAD** V2.23 (9/8/92)
Changed TITLE lines from REAL to CHARACTER type to correct problem with output to tilting pad bearing file.

**THPAD** Version 2.23a
Changes involve increasing the number of pads to 20, improving the output, adding a heat flow calculation, and improving the thermal deformation calculations. Lyle Branagan (PG&E)

## ROMAC Industrial Liaison

Ted Brockett is the ROMAC Laboratory Engineer responsible for liaison with the industrial members on technical issues with our computer programs. Ted has been quite busy working with a number of you in understanding the theory, output, sign conventions, and data input requirements. He works directly with other graduate students and the faculty in

```
RESP2V3 infile plotfile choice outfile
```

where `infile` is the name of the input file
`plotfile` is the name to five the GEOGRAPH™ plot file
`choice` is the plot option choice with:
*1* → Calculate Responses Only, to Plot Later
*2* → Plot From a Previous Run
(Requires a Plot File From a Previous Run)
*3* → Calculate and Plot
`outfile` is the name of the output file to produce

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. Computer questions and questions about receiving programs should sent to our programmer/analyst, Toby Korn.

## Rotor Dynamics

*Rotor and Support System Identification using Time Domain Methods (Ping Zhong, Lloyd Barrett, and Carl Knospe)*

System identification is a subject which has been studied extensively in many different fields including controls and dynamics. The motivation for system identification is quite straightforward: numerical and analytical solutions to many problems, such as finite element methods, are often not satisfactory because of insufficient knowledge of either the real parameters, such as clearance or elastic modulus, or because the governing relationships between different characteristics of the system are not well known. System identification has developed greatly during recent years, from the previous frequency domain methods to newly developed time domain methods. The trend is to improve identification accuracy, reduce the computational cost, and to adapt the method to specific problems, such as rotor and support identification, open loop control, and general adaptive control. Ping Zhong (Ph.D.) has been developing identification techniques for rotor and support system identification.

Time domain methods have developed rapidly in recent years, partially due to the availability of the low-cost high-speed digital computers. Time domain has advantages over frequency domain methods. Most noticeable are the elimination of data truncation error in the time history introduced by the discrete fourier transform, relatively greater accuracy, and elimination of FFT hardware. In time domain identification methods, determining the order of the system has been a major subject. Even with the low pass filters, system order is difficult to determine. Over-specification has been widely used to overcome the effect of signal noise by shifting the noise effect to computational modal parameters.

A recently developed time domain method, the Backward ARMA model method, has been successfully implemented on some test rigs. The method has its own disadvantages, such as high computational cost and sensitivity to noise. Miss-identification and false identification have been reported. Our recent work has been to develop further the method to identify more accurately the system poles and especially the system zeros.

The Generalized Backward ARMA model method has been successfully applied to identify the system zeroes. The almost singular least square method has also proved to be satisfactory with much lower computational cost. This method is especially useful for rotor and support system identification because usually the data collected in the field is frequency rich and the identification problem is usually non-singular. The choice of different components of the identification scheme, such as low pass filters, cutoff frequencies, and sampling intervals, have been shown to be crucial to the success of identification methods, and their satisfactory ranges are being studied.

Recent computer simulations have been carried by ROMAC using the Rouge Kutar fifth order method to simulate the rotor and support time domain data. Identifications carried out using the simulated data are found to be quite satisfactory with the noise range at 5% of the real time domain data and with moderate over-specifications of the system order. For example, a real 4th order system is over-specified as 10th order. High over-specification was observed to accommodate a noise level of 10%, still with satisfactory results. Further studies are being carried out. Implementation of these methods on real rotor and support systems are in progress and application of system identification to open loop control is being considered. Comments are extremely welcome.

*Continued Modifications to* **ROTSTB** *Substructure Flexibility (Karl Wygant and Lloyd Barrett)*

Karl Wygant (M.S.) has been developing techniques for including models of bearing pedestal that have several resonant frequencies, rather than the single resonance model that is currently included in **ROTSTB**. He is utilizing a modal representation similar to that used in the **FRESP** series of forced response programs together with a dynamic reduction scheme similar to that developed for the stability program **FSTB3** by Jim Bielk and for complete tilting pad bearing models developed for **ROTSTB** by Ted Brockett.

It is well known that bearing pedestal flexibility can have strong effects on the "effective" bearing stiffness and damping forces acting on rotors. In general, the effect of pedestal flexibility is to reduce the effective damping provided by the bearings. In tuning bearing designs for particular rotors, it is often necessary to know the effect of the pedestal flexibility in order to maximize the stability of the rotor in response to seal and process flow destabilizing forces.

A formulation based on modal representations permits the use of experimentally obtained transfer functions for the pedestals, as well as analytic models. This will make it easier to "fine tune" entire system models for analyzing and modifying existing rotor-bearing designs.

*Magnetic Bearing Models (Ted Brockett and Lloyd Barrett)*

Ted Brockett (Ph.D.) has been working on the inclusion of magnetic bearing and controls models into **ROTSTB**. To date, complete models for collocated bearings and feedback sensors have been included. The controls are modeled using transfer functions. This approach fits in well with the dynamic reduction scheme utilized in **ROTSTB** by Ted for including complete tilting pad bearing models. Planning is underway for including the effects of non-collocated bearings and feedback sensors. A method has been formulated that eliminates the need for an additional level of iteration in the solution of the damped eigenvalues. However, implementation of this method requires some further modifications to the program.

*Optimization of Bearing Location (Sriram Srinivasan, Lloyd Barrett, and Eric Maslen)*

Sriram Srinivasan (Ph.D.) has developed a method for determining a measure of the effect of changing bearing locations on the stability of rotors. The method is independent of the bearing type, and is based on a stability acceptability function similar to that used by Deb Dhar. This project was motivated by the observation when performing stability analyses that sometimes even a small change in bearing location could have a large effect on the stability. This is particularly true for overhung rotor configurations.

Sriram has been running a large number of verification cases with different bearing types to show that the relative measure of merit is indeed valid for a wide range of bearing types.

*Design and Optimization of Magnetic Bearing Controls (Deb Dhar, Lloyd Barrett, and Carl Knospe)*

Deb Dhar (Ph.D.) has developed an algorithm for determining a magnetic bearing controller transfer function or squeeze film bearing stiffness and damping coefficients that satisfy a user specified stability acceptability function. This function defines acceptable logarithmic decrements over a range of frequencies. The user also specifies constraints on the bearing. For magnetic bearing controller transfer functions, the constraints consist of the order of the polynomials defining the transfer functions and ranges on the values of the polynomial coefficients. For squeeze film bearings, the constraints consist of ranges on the values of stiffness and damping coefficients.

The program then attempts to find a design that will satisfy the acceptability function within the constraints. The user can also specify ranges of frequency in which a damped critical speed should not occur. The program being developed models multi-shaft rotors with various combinations of bearing locations.

If an acceptable solution exists at all, there are usually several, so that additional constraints must be used to select the actual final design. These will usually be based on hardware considerations.

A major advantage of this approach is that the stability of many modes can be considered simultaneously. Most previous optimization methods have focused on a single mode. Although this is often acceptable, it is limiting for designing bearings that must operate over a frequency range spanned by a number of modes of vibration.

*Design and Optimization of Fixed Geometry Journal Bearings (Jeannette Smith, Lloyd Barrett, and Carl Knospe)*

This project is based on the program developed by Deb Dhar. However, instead of independently determining stiffness and damping coefficients to satisfy the acceptability function, Jeannette Smith (M.S.) is modifying the program to search over bearing parameters such as clearance or lubricant viscosity.

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.

## Magnetic Bearings

*The Center For Magnetic Bearings*

The Center for Magnetic Bearings, part of the ROMAC Laboratories, has received continuation funding from Virginia's Center for Innovative Technology (CIT). The funding for July 1, 1992 through June 30, 1993 is $213,000. This brings the total CIT funding for the Center to over $1,200,000 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 (William Wakefield, Hideaki Egashira, Ron Flack, Eric Maslen, and Paul Allaire)*

A feasibility study and design evaluation is nearing completion on adapting the existing Plexiglas pump test rig for support in magnetic bearings. By suspending the impeller shaft in magnetic load cells, measuring the impeller loads accurately is possible at any operating condition as well as to impose arbitrary impeller orbits not attainable with conventional bearings. This modification will create an unique opportunity to correlate actual force measurements with the detailed flow and pressure measurements already afforded by the pump test rig.

The modifications will involve removing the existing ball bearings and replacing them with a pair of radial magnetic bearings at the impeller end of the shaft, a single radial magnetic bearing at the drive end of the shaft, and a double acting magnetic thrust bearing, also at the drive end of the shaft. The bearings will be equipped with flux sensing tip coils to improve the estimate of the magnetic forces exerted on the shaft. By using two bearings at the impeller end of the shaft it will be relatively simple to change the load capacity of the bearings and thereby improve the accuracy of the measured bearing forces when running at low loads while retaining adequate reserve capacity to run under high load conditions as would be encountered in extreme part flow.

The estimated cost of the modifications is $17,000: substantial reduction in cost was obtained through an agreement with Thomson Laminations, Inc. who will be supplying the magnetic components for free. Construction of the bearing parts began in October of 1992. (Additional information on this project can be found on page 8).

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*Interactive Code for Thrust Bearings (Beng-Jit Lim and Carl Knospe)*

An interactive code for designing thrust bearings with a graphical user interface is currently being developed. The code will feature design optimization and will allow the user to select different types of thrust bearings. The code will allow the user to select thrust bearings that are either single acting or double acting. The automatic design feature will allow the user to analyze many designs easily and efficiently.

A good leakage/fringing model is crucial in obtaining accurate results for magnetic bearing analysis. A theoretical model for the leakage factor will first be developed. The theoretical model will be compared to a leakage model derived from finite element analysis. A thermal model may also be developed from finite element analysis.

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*Thrust Bearing Hysteresis Study (Daniel Noh and Eric Maslen)*

In the course of experimental evaluation of the performance of the thrust bearing on the Sundstrand high speed rotor, it was noted that the bearing displayed a significant dead-zone or hysteretic behavior which tended to lead to small limit cycle behavior. An investigation of this phenomenon was initiated in the Fall of 1991 when an undergraduate, Patrick O'Neill undertook a senior thesis project involving the design and construction of a load cell/ jacking mechanism for very precise measurement of the force characteristics of this bearing.

Actual experimental evaluation was carried out in the Summer of 1992. Ph.D. student Daniel Noh measured the relationship between bearing force and current, displacement, and requested control effort. (The bearing is controlled by a PD feedback controller.) He found that the source of the force anomaly lies in the inability of the power amplifier to track the requested current properly when the current is in the immediate neighborhood of 0. This result was quite interesting as previous work by Joe Keith and Eric Maslen on the amplifier design itself was addressed in part at minimizing crossover distortion. The previous work had been quite successful for the range of load impedances tested.

To check the influence of amplifier control algorithm, Noh also studied the bearing behavior when controlled by a linear power amplifier and found that the anomaly disappeared with this amplifier. Additional tests were performed with a different switching amplifier control algorithm (sample-and-hold instead of minimum-pulse-width). The alternate control algorithm displayed a qualitatively similar force anomaly, suggesting that the problem could be associated with the switching noise itself rather than a specific switching control algorithm.

An investigation of the impedance of the thrust bearing revealed that it was extremely hysteretic. The switching noise when the amplifier minimum state period was approximately 23 microseconds was on the order of one amp peak. This amplitude is nearly enough to nominally saturate the magnet iron. A simple test was performed where a "clean" inductor was inserted in series with the thrust bearing coil in an effort to mask the iron hysteresis. This removed the force anomaly to the resolution of the experimental setup.

Further research of this problem is under way at present. To pin- point the primary mechanism responsible for the crossover distortion in the power amplifier, a detailed numerical simulation is being assembled by Daniel Noh to permit evaluation of the relative effects of hysteresis cycle depth, magnetic saturation on switching noise, and the amplifier control algorithm itself.

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*Study of Leakage Factors for Radial Magnetic Bearings using Finite Elements (Beng-Jit Lim, Eric Maslen, and Paul Allaire)*

A study is currently in progress to model the leakage effects in radial magnetic bearings using finite elements. The magnetics capabilities of ANSYS are used to analyze the forces in magnetic radial bearings of varying geometry. A 2-D, linear parametric finite element model has already been created in ANSYS. The magnetic forces are calculated for bearings of different shaft radius, pole tip ratios, leg length, and number of legs. The ratio of the FEM force to the theoretical force gives the leakage/fringing factor.

Preliminary results seem to indicate that the pole tip ratio is not the dominant effect. This is contrary to what we expected. It is suspected that there is inadequate mesh refinement in the region between pole tips. The submodeling and adaptive meshing capability in ANSYS will next be used in the finite element analysis. We hope to see a better trend in results.

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*Sensorless Bearings (Daniel Noh and Eric Maslen)*

When switching amplifiers are employed to control the current in magnetic bearings, a triangular switching noise waveform is superimposed on the primary (desired) current waveform. The amplitude of this high frequency triangle wave depends upon the amplifier duty cycle, the power supply voltage, and the bearing impedance. Since the duty cycle and the power supply voltage are easily measured, it is in principle possible to determine the bearing impedance from this switching waveform. Since the impedance is primarily dependant upon the air gap, this measure can be translated into a useful measure of shaft position which can then be used for feedback control of the bearing, thereby eliminating the need for an independent position sensor.

A variety of previous researchers have investigated this idea, including Vischer [1988, Swiss Federal Technical Institute] and Okada [1992, Ibaraki University]. We propose a somewhat novel scheme for demodulating the switching waveform which we believe will be much more robust and accurate than the methods investigated by previous researchers. The method is based on a nonlinear estimator and the output would be a voltage which varies in direct proportion to gap variation.

### *High Temperature Sensors (Chris Doane and Eric Maslen)*

In continuation of earlier work completed in Summer 1992 by Daniel Maurer on variable reluctance position sensors, Chris Doane is investigating the thermal behavior of inductive sensors. Relatively low temperature sensors operating up to a possible limit of 500 F and based on commercially available Ferrite transformer cores will be examined to explore offset and gain drift with temperature as well as irreversible effects.

Sensors for use in higher temperature environments, as high as 1000 F, will also be studied. The magnetic material for these sensors is yet to be determined but may have to be a laminated vanadium based alloy or perhaps a nickel based alloy. Primary concerns are low hysteresis and eddy currents, high thermal stability both for magnetic properties and for mechanical properties, and acceptably high magnetic permeability at the elevated temperature.

In support of this work, an undergraduate student, Mike Dunevant, will be designing, constructing, and testing an apparatus for evaluating null and gain drift as a function of temperature for his senior thesis research.

### *Open Loop Unbalance Control (Subra Sundaram and Carl Knospe)*

In the last year, we have continued our investigation of the control of synchronous vibrations using open loop methods. As was presented at the 1992 ROMAC Annual Meeting, this method of unbalance response control uses synchronous control currents, in addition to the stabilizing feedback control, to cancel rotor vibration. The amplitudes and phases of the open loop control currents may be adjusted on-line so that the balancing forces may be changed while the machine is operating.

While we have been demonstrating these methods for nearly two years, electronic hardware had prevented us from fully exploiting this technology through on-line, adaptive balancing. In the last year we have been examining adaptive balancing through simulation and, recently, experiments. The simulation work, which was part of Subra Sundaram's Masters thesis, clearly indicated the benefits of adaptive balancing using magnetic bearings. Results demonstrated reductions in synchronous vibration over all running speeds with large decreases near the critical speed. This work examined several different control and estimation algorithms.

One of the adaptive controllers derived for the simulation research has recently been coded in C by electrical engineering graduate student Steve Fedigan. This code has been run on the multi-tasking third generation magnetic bearing digital controller. Several tests have been done, and adaptive balancing is working very well. When this task is executing, the rotor system is identified and then the proper open loop control is computed and employed. Then identification and control are done continuously. With the algorithm employed currently, approximately three seconds lapse between the time the program starts executing and when the vibration is nearly completely cancelled.

In the next year, we plan to continue to improve our adaptive control algorithms and increase the speed of the open loop controller's implementation.

### *Microgravity Vibration Isolation (David Hampton, Bibhuti Banerjee, and Carl Knospe)*

We continued our research effort with NASA Lewis Research Center on active isolation of microgravity vibration. NASA needs this technology to improve the quality of materials processing such as crystal growth and science experiments such as free convection studies in space. Graduate student David Hampton has been investigating the use of modern control theory for the controller design for active isolation systems. In the last year, he has uncovered many important implementation issues of the latest design methods. We have recently completed an isolation control system design that has excellent performance in spite of a large number of possible uncertainties or variations in our model. David will be finishing his doctorate in January.

Our research in this area has also included construction of an active isolation test rig by Bibhuti Banerjee. This experiment was designed to demonstrate the isolation of a magnetically suspended mass attached to a vibration source through an umbilical. Our experiment achieves isolation through acceleration feedback which, in effect, makes the suspended mass much more massive. So far we have achieved a ten-fold reduction in the mass's vibration at 2 Hz. In the next year, we plan to increase the controller's gain and achieve much higher levels of isolation.

We are currently talking with NASA about continuing our research to build an isolation experiment which will fly aboard the Space Shuttle in 1997.

### *Implicit Flux Control (Joe Keith and Ron Williams)*

As reported at the 1992 Annual Meeting, work continues on the implicit flux control project for magnetic bearings. The primary goal of the research is to develop magnetic bearings in which the bearing forces can be accurately inferred from non-intrusive flux measurements. Additionally, bearings employing flux feedback will be insensitive to eddy current and hysteresis effects, will operate properly above magnetic saturation, and will be invariant to changes in the bearing air gap length. The ability to operate a magnetic bearing above saturation permits proper handling of transient bearing overloads without excessive bearing over-sizing; the resulting weight reduction should be significant for aerospace applications.

Construction of an experimental apparatus for testing flux feedback schemes is nearing completion, and a substantial amount of testing, data gathering and analysis should be complete by the end of the Fall semester, 1992.

*Boiler Pump Magnetic Bearings (Patrick Depret-Guillaume, David Lewis, and Robert Humphris)*

A project has been funded by MOBIL Research & 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 Ingersoll Dresser Pump Company and Kingbury, Inc. Pleuger Worthington GmbH of Hamburg, Germany, will be supplying the electric motor to drive the multistage pump. Robert Humphris and David Lewis are co-directors of the project which will likely become the foundation of a Ph.D. thesis 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 he will likely present further details of the project at the next annual meeting.

*High Force to Weight, Low Power Consumption (Paul Allaire, Carl Knospe, Eric Maslen, et.al.)*

Our NASA sponsored research project "High Performance Magnetic Bearings for Aero Applications" continues to conduct research on high force to weight, low power consumption magnetic bearings. We have made measurements on power losses due to eddy currents in magnetic bearings and gotten good agreement with theory. Also, we have started work on flux/force feedback for magnetic bearings. Work on high DN operation characteristics with homopolar bearings is in progress.

*Digital Controller Software (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 is now complete and running on ROMAC's digital controller. A rotor has been brought into support by magnetic bearings controlled by this controller. The operating system has then been used to permit the implementation of electronic balancing of the rotor while in operation. Refinement of the operating system continues, but it has now reached the stage where it can be used to support experimentation with various control techniques.

*Digital Controller Hardware (Paul Wayner, Jeff Ebert, Ron Williams)*

While we now have a powerful digital controller for magnetic bearings, we are already working to improve our capabilities in this area. Our current controller includes numerous features that make it useful for laboratory experimentation. These features are really necessary and appropriate as we experiment with new control algorithms and techniques. When the magnetic bearings are installed in the field, a slightly different set of controller features will be needed.

We are currently developing new controller hardware that will give us the best of both worlds. This new controller is designed for the industrial environment, but it will retain software compatibility with our current controller. This will permit control software to be developed in the friendly environment of the laboratory. The code can then be executed in the more harsh environment of the real world.

The new controller will continue to use a digital signal processing computer as its principal component. However, the new machine will be designed for the kind of extended uninterrupted operation that is needed on the factory floor. The modular design of this new controller will permit different component arrangements to support a range of magnetic bearing configurations and reliability requirements. The target for completion is the second quarter of next year.

## Fixed & Tilting Pad Bearings

*(Karl Wygant, Carmen Müller-Karger, Jose Antonio Vazquez, Lloyd Barrett, and Ron Flack)*

Tests were completed for the three lobe fixed pad bearing (preload = 0.75). Dynamic as well as static characteristics were shown. These were reported at the meeting and presented in reports. Next, a three lobe fixed pad bearing (preload = 0.50) has been installed and tests will initiate shortly. In response to the members suggestions to tilting pad geometries, we have agreed to having Turbo Components & Engineering make us such bearings for testing. We are in the initial design phase currently. Also, Glacier has offered to manufacture such geometries and we also may test these.

We have three new students working on the experimental bearing work. Karl Wygant (Ph.D.) will be the primary rigid rotor bearing student. Carmen Müller-Karger will also be working on this apparatus and will also be involved with detailed comparisons of theory and experiment. Jose Antonio Vazquez will be modifying the small (1 inch diameter bearings) flexible rotor to incorporate pedestal flexibility. Fixed and tilting pad bearings will be tested. Holger Herbert is a continuing student (M.S.) and is working on the data acquisition system.

## Fluid Dynamics

*Seals (Brad Williams and Ron Flack)*

Brad Williams completed modifications to the laby seal program (now **LABY3**). Convergence problems were eliminated and other numerical problems were corrected from **LABY2**. Dynamic coefficients and flow rates are predicted. Comparisons were made to new experimental data from other institutions to verify the code. Both the theoretical background report and a users manual are available.

*Plexiglas Pump (Willy de Ojeda and Ron Flack)*

Tests were completed for the double volute Plexiglas pump. Velocities (from LV data) and pressures were collected. Impeller loads were found for both the single and double volute geometries. As expected the double volute resulted in much lower loads at off-design conditions. Pressure induced loads were much higher than the momentum induced loads. Also from the LV data volute losses and slip were calculated for the double volute case.

The pump is now being modified (by Bill Wakefield, MS and Hideaki Egashira, MS) so that magnetic load cells 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. (Additional information on this project can be found on page 4).

*Torque Converter (Kevin Gruver, Klaus Brun, Steve Ainley, and Ron Flack)*

This is a problem sponsored by a particular industry, but it 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 at the inlet plane of the turbine. A "movie" was presented at the annual meeting showing the complex jet-wake interaction from the exit plane of the pump. Also, strong circulatory secondary flows were measured in the pump. Work is continuing for different pump and turbine geometries.

*New Laser Velocimeter (Ron Flack)*

Over the past year a three directional laser velocimeter was obtained with support from outside of ROMAC. 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 includes fiber optics so the system is quite versatile and adaptive. It is capable of velocities in the supersonic regime. Although the system is not currently on a ROMAC project, it is under the jurisdiction of Ron Flack so that when the current fire propensity project ends it will be used for turbomachinery flows.

*Cross Coupling Stiffness in a Whirling Centrifugal Pump (Amish Thacker and Houston Wood)*

Amish Thaker completed his M.S. and defended his thesis entitled "Computation of Cross Coupling Stiffness in a Whirling Centrifugal Pump." The thesis will be distributed as a ROMAC report.

In this work, the steady state potential analysis code **POT2D** was extended to include whirling motion of the impeller and the resulting hydrodynamic stiffnesses were computed. Appropriate choice of impeller eccentricity radius and time interval for computing the resulting unsteady terms allows the use of the same mesh for all computations. Results were obtained for the ROMAC Plexiglas pump as a linear function of the whirl ratio. These predictions were validated with another geometry model corresponding to a pump at Cal Tech, and the results were found to be in good agreement with published data. The code is currently being made "user friendly," and a user's manual is being prepared.

It is hoped that another student can be assigned to extend this code to include the capability to model non-circular whirl orbits and to include three-dimensional pumps. This code can be further validated with the ROMAC Plexiglas pump once the magnetic bearings are installed in the pump.

*Computational Fluid Dynamics (Hossein Haj-Hariri)*

Work is under way on the development of a Computational Fluid Dynamics (CFD) code for modeling the flow in labyrinth seals. A uniform formulation, capable of addressing both compressible as well as incompressible flows, is adopted. There will be capability to address any of the following configurations and/or conditions: teeth on stator, teeth on rotor, interlocking seals, inclined teeth, and rotor whirl. The latter condition is used in the determination of the rotor dynamical coefficients. The accurate calculation of these coefficients, as well as the details of the turbulent flow inside each chamber of the seal, are the main goals of this effort.

Code development is done using standard Fortran. The graphical interfaces will be developed using the X platform in a UNIX environment. The solution formulation adopts a finite-volume approach with a flux-limited treatment of the convective terms. Turbulence is currently being modeled using an algebraic method (Baldwin-Lomax). More sophisticated methods will be incorporated later. An artificial compressibility factor is utilized to allow for the treatment of incompressible flows while retaining the compressible formulation.

As this project is still in its infancy stages, we are looking forward to feedback from the member companies regarding their particular needs, and will make every effort to address those needs.

Also, concurrently with the above effort, work is under way on the development of CFD capability for modeling flows in mixed-flow geometries. Both compressors as well as pumps are being considered. Given the higher priority of the seal work, there may or may not be results for this second effort by the time of the annual meeting.

*Viscous Flow Simulations In Rotating Channels Having Complex Geometries (Qingping Shi and R.J.Ribando)*

The major contribution of this work is the development of a new pressure-based numerical procedure for three-dimensional viscous flow simulations in rotating components having complex geometries. The basic ideas and calculation strategy of general parabolic numerical procedures were applied and extended to rotating flow computations with modifications to include the effect of the Coriolis force on the pressure corrections. The research features the following aspects:

1• To overcome the difficulty of geometrical complexity, the compressible form of the Navier-Stokes equations was written for rotating flows in a body-fitted curvilinear coordinate system.

2• A new pressure-based numerical procedure was developed and applied to rotating flows. The finite-volume method was employed to discretize the partial differential equations on a non-staggered grid arrangement.

3• The techniques of grid generation were utilized, and smooth, non-uniform computational meshes were generated.

4• Two-equation k-epsilon turbulence models, including Coriolis-modified forms, were dealt with to handle turbulent flows because turbulence is very important to turbomachinery flows.

Computer codes have been developed based on the above features and tested against experimental data for both compressible and incompressible flows in simple and complex geometries. Two-dimensional results have been published in the journal Computers and Fluids and as ROMAC Report No. 341, "Numerical Simulations of Viscous Rotating Flows Using a New Pressure-based Method". Three dimensional results have been submitted for publication to the International Journal for Numerical Methods in Fluids and have been published as ROMAC Report No. 349, "A Parabolic Numerical Procedure for 3-D Viscous Rotating Flows." Because of its length, the complete dissertation, which was defended August 26, will only be sent to those ROMAC companies requesting it.

*A Numerical Simulation of Flow Separation in Centrifugal Diffusers. (Gerry O'Leary and R.J. Ribando)*

Development is continuing on the numerical simulation of flow in vaned centrifugal diffusers. The simulation uses an interactive-boundary-layer algorithm to capture flow separation phenomena existent at near peak-performance conditions. The major portion of the flow field is modeled as potential flow using finite-element or finite-volume discretizations. The viscous regions near the vane surfaces are modeled with a finite-difference approximation of the boundary layer equations. Strong interactions of the viscous and inviscid flow fields (seen at separation or at the vane trailing-edge) are resolved using a new quasi-simultaneous scheme designed for these internal flow regimes. The wake region formed downstream of diffuser guide vane is simulated with the boundary-layer equations, using special numerical procedures to patch the regions derived from the vane pressure and suction surfaces. Numerical oscillations associated with reattachment of the viscous shear layer have resulted in convergence difficulties in the global algorithm. Several schemes are being examined to eliminate these oscillations without sacrificing overall accuracy.

## Departures

*Students Completing their Studies*

Several of our members have inquired regarding our students who have completed their studies and left the University. The table below lists the students who have recently left or will be leaving soon along with their destinations on the "outside."

## MAG '93

The MAG '93 Conference on Magnetic Bearings, Magnetic Drives and Dry Gas Seals will be held on July 29 and 30, 1993 at the Radisson Plaza Hotel in

**Students completing their work in ROMAC**

| *ROMAC Graduate* | *Degree & Date* | *Destination* |
|---|---|---|
| Vincenzo Lefante | M.S., January, 1992 | Aura Systems |
| Patrick Depret-Guillaume | M.S., May, 1992 | U.Va. Ph.D. |
| John D'Addio | M.S., May, 1992 | IBM |
| Daniel Maurer | M.S., August, 1992 | Xerox |
| Matthew Stewart | M.S., May, 1993[a] | Sundstrand |
| Brad Williams | M.S., August, 1992 | U.Va. Law School |
| Kevin Gruver | M.S., August, 1992 | Ford |
| Subra Sundaram | M.S., August, 1992 | MEPCO, INc. |
| Qingping Shi | Ph.D., January, 1993[a] | |
| Amish Thaker | M.S., August, 1992 | |
| Brian Pettinato | M.S., August, 1992 | Centrimarc |
| Debasish Dhar | Ph.D., January, 1993[a] | MBI |
| Manuel Grau | M.S., May, 1992 | LaGoven (Venezuela) |
| Sungwon Lee | Ph.D., May, 1992 | Hanla Heavy Industries |
| William De Ojeda | M.S., May, 1992 | IIT Ph.D. program |

a. Expected completion date

Alexandria Virginia, site of the previous Third International Symposium on Magnetic Bearings and MAG '92. An emphasis will be placed on industrial applications of magnetic bearings, magnetic drives and dry gas seals. The discussion groups have proven popular in the past conferences and will be expanded in MAG '93. Also, exhibitions will have increased emphasis. Plan to attend.

*Third International Conference On Magnetic Bearings/MAG '92*

Approximately 250 people attended the combined Third International Conference on Magnetic Bearings and MAG '92. 57 papers were presented at the Third International Conference and 21 papers in MAG '92. Four heavily attended discussion groups were held and received many positive comments. Exhibit space was filled by various industrial firms. We feel that this was a highly successful event to promote the targeted technologies.

## 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, 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.

Radian Corporation, for example, recently donated an HP5420B Digital Signal Analyzer, which is in excellent condition, to ROMAC. It is already in service as an integral part of Joe Keith's Ph.D. dissertation research on flux control for magnetic bearings. So, if you might have some equipment which may find a useful home in ROMAC, please call us.

## ROMAC Short Courses

*Magnetic Bearings*

We will be having a two day short course on magnetic bearings held on January 14 and 15 in the ROMAC laboratories. It will include discussions of magnetic circuit fundamentals, thrust and radial bearing design, magnetic bearing demonstrations, control circuit and power amplifier design, and applications. It is open only to employees of member companies of the ROMAC Industrial Research Program. Enrollment is limited so sign up early if you are interested.

*Advanced Rotor Dynamics*

ROMAC is planning a two day short course on advanced rotor dynamics. It will be held March 16 and 17, 1993. It will include discussions of modal analysis, frequency response functions, bearing design, and other topics pertaining to ROMAC advanced computer programs. This short course is also open only to employees of member companies of the ROMAC Industrial Research Program. Enrollment is limited so sign up early if you are interested.

## For More Information

*We want to hear from you...*

Write to ROMAC at the address given at the bottom of page 1. The telephone number to reach our secretary is (804) 924-3292. Please note that we now have a new FAX number: (804) 982-2246. We receive electronic mail through the internet at the address: romac@virginia.edu.

Your inquires, comments, and suggestions will be appreciated.

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