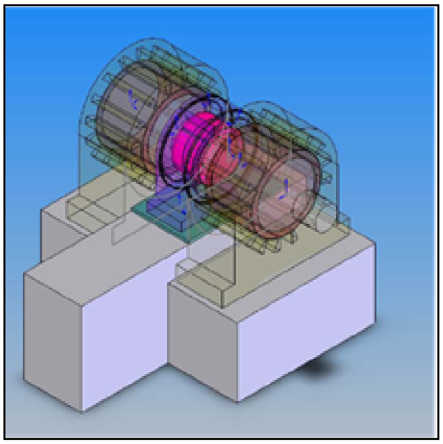
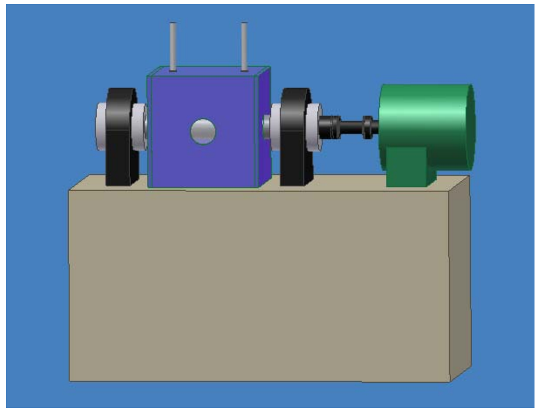
Rotating Machinery and Controls

2005-2006

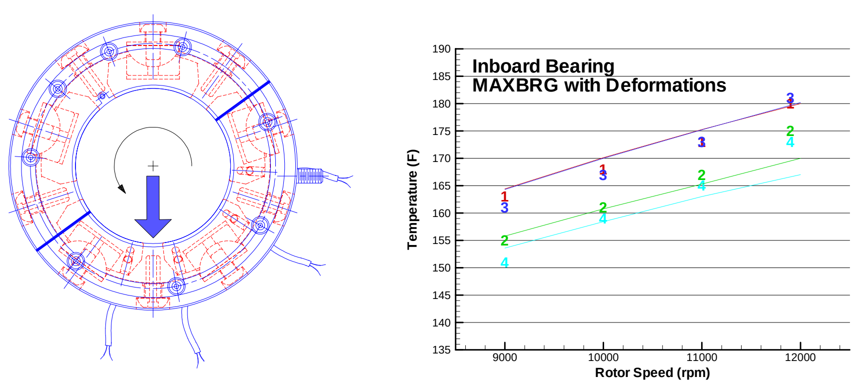
ROMAC Newsletter



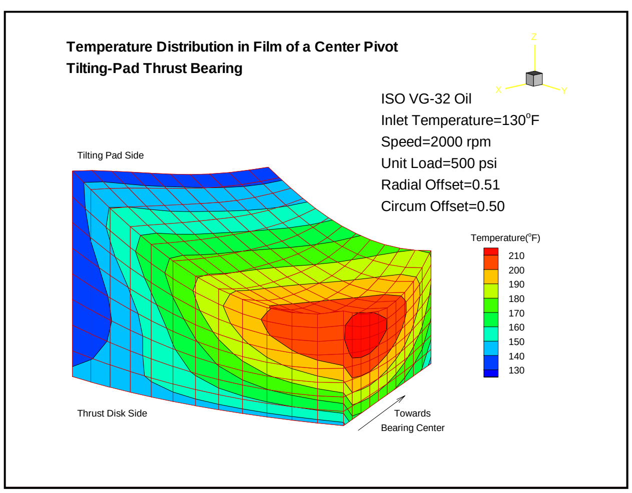
Current Bearing Test Rig Concept



Seal Test Rig Conceptual Design



MAXBRG Predictions versus Stability Test Rig Bearing Temperatures



Inside this issue:

Special points of interest:

- Significant improvements to MAXBRG
- New compressor seal experiment underway
- Four specific balancing methods being developed at ROMAC
- New faculty members join ROMAC
- 2006 Annual Meeting in Charlottesville

MESSAGE FROM DIRECTOR

ROMAC Updates

Paul Allaire, Wade Professor of Mechanical and Aerospace Engineering and Director of ROMAC

ROMAC Newsletter and Annual Meeting Summary

The 25th Annual ROMAC meeting was held June 12-15, 2005 in Charleston, South Carolina and was attended by 47 industrial members and ROMAC personnel. The meeting involved many reports of ongoing and finished research at the University of Virginia, industrial technical reports, much discussion about future research, and votes for new research projects. The companies that attended were: Curtiss-Wright, Boeing, Bechtel, Concepts, Cooper, Dow, Dupont, Dresser Rand, ExxonMobil, Framatome, Hamilton Sundstrand, Kingsbury, KAPL, Mechanical Solutions, Mitsubishi Heavy Industries, Petrobras, RMT, Rockwell Automation, Rolls Royce, Shell, Siemens, Solar, and Waukesha Bearings. A number of companies were unable to attend so we are sending out this newsletter to help inform them, and other companies, of the ROMAC activities.

"Some new faculty members have joined ROMAC to bring in new expertise and expand the research activities, as out-lined in this newsletter"

ROMAC Faculty Status and Changes

The ROMAC Director is Paul Allaire again. Some new faculty members have joined ROMAC to bring in new expertise and expand the research activities, as outlined in this newsletter.

Walter Pilkey, Chaired Professor of Mechanical and Aerospace Engineering, an internationally known expert on rotor dynamics for balancing and other research, has joined ROMAC for his expertise on rotor modeling and balancing. Zongli Lin, Professor of Electrical and Computer Engineering, has joined the ROMAC faculty with his interest and expertise on optimization for balancing and controls for our fluid film bearing and seal test rigs using magnetic bearings as actuators.

Chris Goyne, a Research Assistant Professor of Mechanical and Aerospace Engineering, has joined ROMAC to use his expertise on flow measurements with lasers for our new seal test rig. Also, James McDaniel, Professor of Mechanical and Aerospace Engineering and Director of the Aerospace Engineering Laboratory, has joined ROMAC to work with Chris Goyne on flow measurements in seals. Houston Wood, Professor of Mechanical and Aerospace Engineering, has joined ROMAC to work on CFD analysis in seals and other aspects of flow in rotating machines.

Annual Fee

Our annual membership fee is $17,500 for this year. This is a small increase over the last 3 years where the membership fee was fixed at $16,000 per year.

2006 Rotordynamics Short Course

A rotordynamics short course is planned for August 14-17, 2006. The course will cover rotordynamics, bearings and seals, flows and magnetic bearings. For more information on the short course, see page 23 of this newsletter.

Project Results and Future Research

An extensive discussion of the existing and new research topics are given in the rest of the newsletter.

Thrust Bearing Code Improvements (Computer Code THRUST)

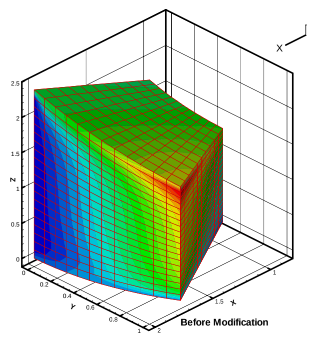
Consultants: Minhui He, Ted Brockett

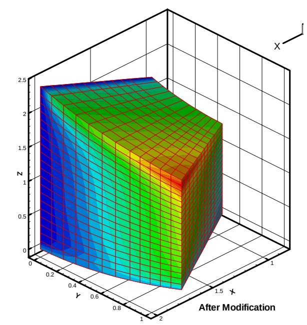
Faculty: Paul Allaire

Project Start Date: May 2005

Project Summary:

THRUST is a three-dimensional finite element code that performs TEHD analysis for thrust bearings. It was originally developed by Dr. Ted Brockett and is considered the most advanced and powerful code for thrust bearing analysis. Unfortunately, the program has experienced a serious convergence problem when the flow is turbulent *and* heat conduction is included. After six months of work, we are happy to report that the cause of this convergence problem has been successfully identified. By changing the formulation of the energy section of the code, the separate iterations between the film and pad temperatures are now integrated into a single formulation. The new formulation has been combined with the other solvers in the code and works very well for bearings with tilting pads. Other fixed pad geometries are currently under improvement using this single formulation approach. Potential future upgrades include dynamically allocatable arrays, improved search of the pad tilt angle, new pad geometries and modeling of the direct lubrication.





Fluid Film Bearing Test Rig

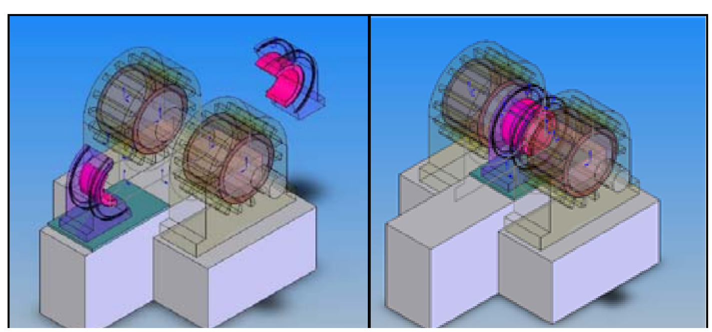
Student: Tim Dimond

Advisors: Prof. Paul Allaire, Prof. Pradip Sheth

Funding: ROMAC

Industrial fluid film bearings are now operating at surface speeds that clearly place them in the turbulent flow range for the lubricant film. Bearing computer modeling codes, such as MAXBRG, have the capability to model these properties. However, virtually no measured data on dynamic properties of industrial bearings in this range have been obtained.

The purpose of the ROMAC fluid film bearing test rig is to measure load capacity, thermal effects, stiffness and damping of oil-lubricated bearings under high speed industrial application conditions. The initial design specifies a 6 inch diameter tilting pad bearing with L/D = 0.5 operating at 16,000 rpm. Magnetic bearings will use exciters to support the shaft and to perturb it with small displacement and velocity motions. Strain gauges on the magnetic bearing poles and other methods will be used to measure the forces to determine the load capacity, stiffness and damping. A parameter optimization study is underway to finalize design values for the test rig. ROMAC will be working directly with bearing manufacturers to test the tilting pad bearings of primary interest.



Current Test Rig Concept

Left: Exploded View. Right: Assembled View.

Labyrinth Gas Seal Code/Program Development

Student: Jie Zhou

Advisor: Paul Allaire

Project Start Date: Sept. 2000

Funding: ROMAC

Laby4 is a new gas labyrinth seal analysis program under development. It will replace the current code LABY3. LABY3 gives out reasonably good results for cross coupled damping dynamic coefficients, but not so good for principal dynamic coefficients of stiffness and damping. The new key approach is to use three control volumes following a method by Prof. Nordmann from Germany, to better model the fluid stresses, forces and velocity of the fluid filed in the seals. Tascflow, a 3-D computational fluid flow code from AEA, is being used to determine the flow properties, such as the control volume velocity and pressures, as well as suitable boundary conditions to obtain a better flow description for the three control volumes in each industrial labyrinth seal configuration.

Progress in the past year:

To deal with converge problems, first the equation derivative process is reviewed, including the zeroth and first order governing equation and boundary conditions, both in dimensionless and perturbed form. Some errors have been corrected. At the same time, equation set for teeth-on-rotor configuration is added besides the already documented teeth-on-stator equation set.

Secondly, the data type of the first order equation set is changed from Double Precision to Double Complex, because it is a more compact and natural way to code 1st order equation. The convergence problem is still under investigation.

In addition, a new option is added so that users can specify a frequency at which LABY4 can run and give out dynamic coefficients at the frequency.

At the request of some members, the LABY4 will add the ability to handle labyrintrh seals with variable clearance. The equation sets are under construction. Programming will start once those equations are ready.

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TEHD Analysis of Fluid Film Journal Bearings(Computer Code MAXBRG 3.8)

Consultant: Minhui He

Faculty: Paul Allaire

Project Start Date: September 1996

Report Number: 458

Project Overview:

Widely used in turbomachinery, the fluid film journal bearing is critical to a machine's overall reliability level. The objective of this project is to develop a state of the art thermoelastohydrodynamic (TEHD) algorithm for industrial journal bearing analysis. The first version of the resulting computer code MAXBRG was completed and released in May 2003.

Many advanced models are employed in this finite element based algorithm. The pressure is calculated from the generalized Reynolds equation. The pad and film temperatures are obtained from a unique two-dimensional energy equation. Turbulence is automatically handled throughout the flow computations. Deformations of various components, such as pad and journal, can also be included. A coupled film-pad approach is utilized to achieve outstanding numerical stability.

This algorithm can be used to analyze directly lubricated bearings as well as conventional fixed geometry and tilting pad bear-

TEHD Analysis of Fluid Film Journal Bearings(Computer Code MAXBRG 3.8)

ings. Modeling of pressure dam bearings is extended to include adiabatic thermal effects. In addition to the flooded lubrication condition, it can be applied to several special conditions including starvation, high ambient pressure and axial flow. Moreover, the computer code is flexible, allowing the users to select and combine a variety of modeling options according to their specific needs and engineering judgment.

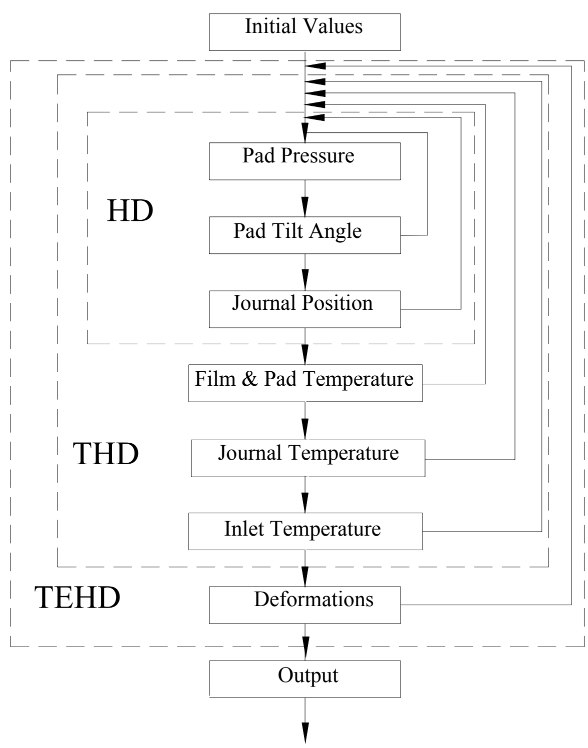
Progress in the past year:

Since the release of Version 2.0 in July 2004, several upgrades have been implemented in the current Version 3.8. First, all arrays in MAXBRG are redefined as dynamically allocatable. Thus, the only size limit of a model is the available memory of the computer. This modification also paves way for future upgrades involving large size arrays, for example, three-dimensional temperature calculation. Second, the drain temperature can be used as the ambient temperature at the back of a pad, which may be more appropriate for a flooded bearing. Third, a new model is added to determine the sump oil temperature for a ring lubricated bearing. A ring lubricated bearing requires a unique modeling in that there is no external oil supply or drain.

Future work

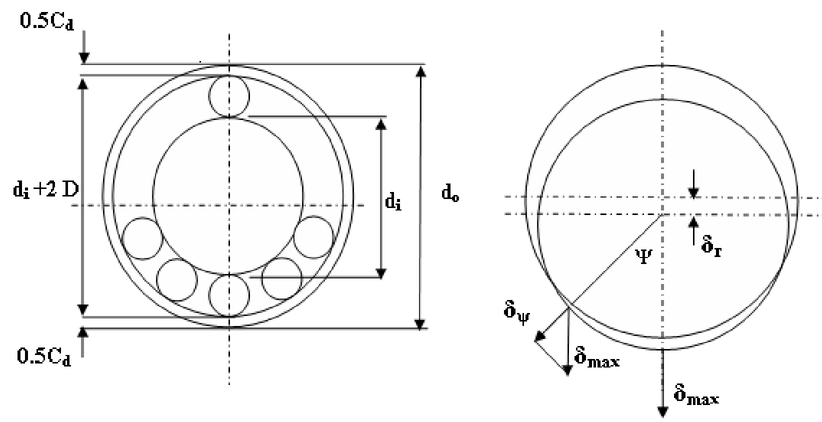
MAXBRG will continue to be maintained and upgraded in the future. One coming upgrade is to add fluid inertia effect to the pressure calculation. The inertia effect can be significant for water-lubricated bearings due to water's low viscosity. Other planned upgrades include addition of shear stress in the determination of pad tilt angles, addition of a correlation factor to improve the pad deformation predictions, and addition of a taper at pad trailing edge. As in the past, future upgrades will largely be based on feedback from ROMAC members. Your input is very important and will be highly appreciated.

"The computer code is flexible in that the users can select and combine a variety of modeling options according to their needs and engineering judgment."



Rolling Element Bearing Analysis and Code

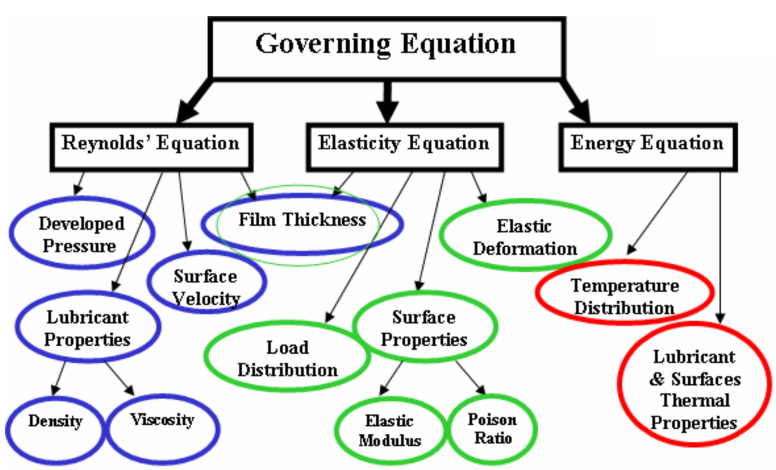
Student: Amir Younan
Advisor: Paul Allaire
Funding: ROMAC



Deflection distribution in Roller Bearing

Many rotating machines are supported in rolling element bearings, but computer models that predict the operating properties as well as stiffness and damping coefficients for rotor dynamic analysis are not widely available. A number of member companies have expressed an interest in having a modeling code for rolling element bearings similar to MAXBRG for fluid film bearings. The plan is to first develop a simplified solution using perturbation methods as outlined in the next paragraph. Then a full-scale finite element computer code will be developed. It will include the Reynolds equation for pressure, the elasticity equation for contact deformations, and the energy equation for thermal solutions.

The initial method employed by UVA consists of an isothermal elastohydrodynamic (EHD) numerical analysis for roller element bearing. The analysis will include the variation of the lubricant viscosity with pressure which affects the film thickness in the contact region. A steady state solution and dynamic solution of Reynolds equation is implemented using a linear perturbation approach. The film thickness is obtained from the geometry of the contact between the roller and the races modified by the elastic deformations of their surfaces. The elastic deformations are obtained from the analysis of force and deflection distributions over the loaded rollers which depend on the geometry aspects and the total applied load. Small perturbations produce the stiffness and damping properties using the dynamic pressures. These methods will be used to produce the first computer code for ball and roller bearings.



Compressor Seal Test Rig Now in Development

Student: Josh Keely

Advisors: Chris Goyne, Paul Allaire, Jim McDanial, Houston Wood

Funding: ROMAC

Start Date: September 2005

Of particular interest to the air compressor industry is the coupling between the fluid mechanics and rotor dynamics of high pressure aerodynamic seals. Unfortunately the coupling is often poorly understood and poorly modeled and this results in poor prediction of compressor performance and failure limits. There is thus a need for experimental investigation of the phenomenon. In order to fully understand the physics involved, not only are surface measurements needed, such as wall pressure and temperature, but also instream measurements of the flow properties. Of particular interest to fluid modelers are the velocity fields within the seal, both temporally averaged and instantaneous. With velocity databases in hand for various seal geometries at typical compressor operating conditions, seal modelers will be in a position to significantly improve the prediction accuracy of seal performance and fluid-rotor coupling.

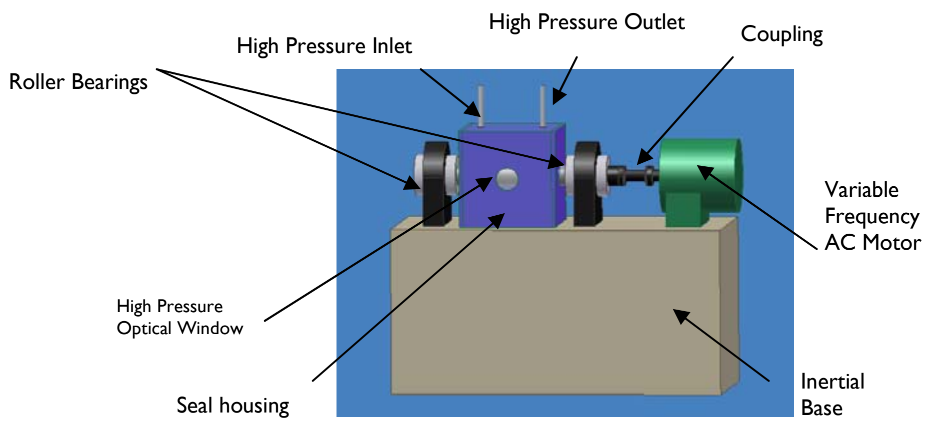
This project will involve the development of a test rig to perform these measurements on honeycomb, hole pattern, and labyrinth type seals. Current existing rigs of this type are limited to pressures of approximately 1000 psi, while industrial pressures are often found near 3000 psi. Of primary importance for this new rig is the ability to achieve actual seal pressures for better comparison to industrial conditions. Data will then be collected and used to validate and improve upon current seal CFD codes.

Professor Houston Wood of Mechanical and Aerospace Engineering will lead the fluid modeling and validation effort slated to begin in the summer of 2006. Professor Wood has experience in modeling and CFD analysis of fluids in rotating machinery, and he has most recently been responsible for designing the blood flow path in artificial heart pumps. He was a ROMAC faculty member and Director of ROMAC about 15 years ago.

Due to the aerodynamic diagnostics involved with the experiment, two faculty members with aerospace backgrounds have become involved. Prof. Chris Goyne and Prof. Jim McDaniel from the UVa Aerospace Research Laboratory will monitor the project, with Paul Allaire advising in the more conventional ROMAC areas. A M.S. student, Joshua Keely, began work on the project in 2005, and another student may be added in the coming year.

The conceptual design of the test rig is very similar to that of conventional fluid bearing rigs with roller bearings located on either end of a shaft that goes through the seal. The rig will be driven by a high speed electric motor with variable frequency drive. The rig is to be designed so that the bearings are interchangeable, with initial tests being done using roller bearings before it is fitted for magnetic bearings. The use of magnetic bearings will enable the rig to be used for measurement of fluid-rotor coupling. The aerodynamic seal itself will also be interchangeable, so that various geometries can be tested. A high pressure window will provide optical access to the seal geometry, and a Laser Doppler Velocimetry (LDV) system will be utilized to measure the flow velocities.

Current work on the project includes specification of the diagnostic requirements and conceptual design of the rig in order to begin the laboratory setup. By Summer 2006, it is planned to have the diagnostics online, and a conceptual design of the test rig finalized. Any companies with particular interest in this project are encouraged to contact ROMAC, or Joshua Keely directly at jmk4h@virginia.edu.



Seal Test Rig Conceptual Design: Roller bearings to be interchangeable with magnetic bearings so rig can be used for dynamic as well as fluid testing

Rotating Machinery Stability Test Rig

Student: C. Hunter Cloud

Advisors: Lloyd Barrett and Eric Maslen

Project Start Date: January 1999

Primary Funding: ExxonMobil, ROMAC

Project Objective:

The stability of turbomachinery is a major concern. This project is focused on avoiding these problems in the future by conducting research in the following two areas:

A. Determining test techniques which are suitable for accurately measuring the stability of a rotor/bearing system.

B. Examining how tilting pad bearing characteristics and common phenomena such as unbalance influence the actual stability levels and thresholds versus modeling predictions.

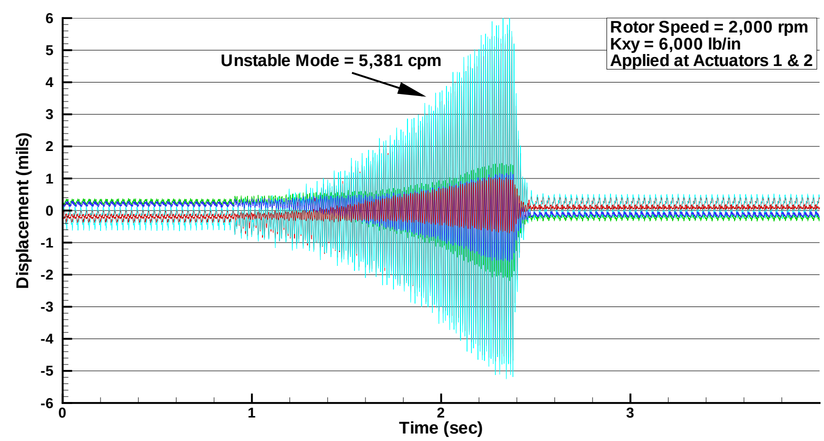
To investigate these issues, a test rig is being constructed which will simulate the dynamic behavior of many types of turbomachinery such as pumps, compressors, and steam turbines. Magnetic actuators will supply excitations in the form of destabilizing cross-coupled stiffness and non-synchronous forcing (sine sweep, impulse, etc). Several bearing designs will be tested with the base design being a 5 pad, load between pad bearing with L/D = 0.75, 0.3 preload, center offset rocker back pivots.

Progress in the Past Year:

Conversion of the magnetic actuator controls to a Linux based system has been completed. In order to develop a calibrated circuit model for the actuators, levitation testing was conducted. This provides an accurate circuit model for use in estimating the actuator applied forces through current and position measurements. With this model in place, current efforts are focused on the fine tuning for greater resolution of applied cross-coupled stiffness generated by the actuators. While this cross-coupling control tuning is in progress for high speeds, some tests at lower speeds have demonstrated its ability to dictate the stability level of the rig. This figure provides an interesting an example where the rotor is actually running below the first forward mode, but application of enough cross-coupling causes this mode to go unstable, supersynchronously.

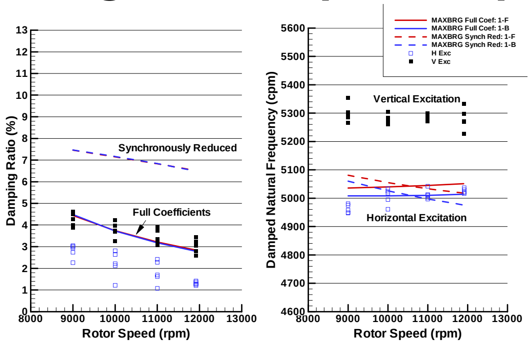
Initial stability tests have been conducted versus just rotor speed. Using a blocking type test, the free response decays (example shown in figure) are analyzed by the time domain technique for estimation of the modal damping ratios and natural frequencies. The last figure shows the measured parameters for the first two modes along with comparisons to those predicted using synchronously reduced coefficients and the full pad coefficients for the tilting pad bearings. The observed asymmetry of the measurements suggests pedestal effects need to be included, thus, these will be measured in detail for further model refinement.

Further enhancements to the time domain estimation technique (such as combining several data sets for one modal estimation) have been completed with some additional ones under evaluation. Once cross-coupling control tuning is complete, stability testing will proceed on the 5 pad, load between pad, 0.3 preload, 50% offset bearings currently installed.

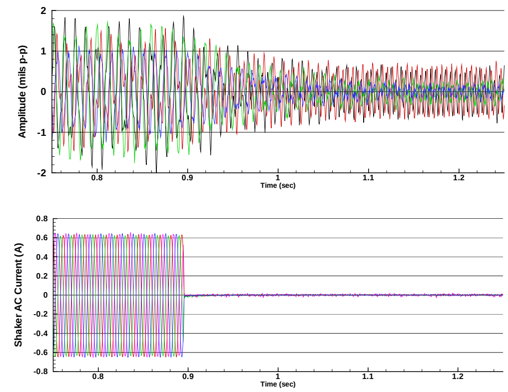


Demonstration of Actuator Cross-coupling Driving Rotor System Unstable

Rotating Machinery Stability Test Rig



Blocking Test Stability Measurements versus predictions (rigid supports)



Example Blocking Test Data used for Stability Measurements

Rotordynamics

Student: One Graduate Student, To be Determined

Advisor: Pradip Sheth, Paul Allaire

ROMAC has built a rich history of developments in rotor dynamics, going back to 1972 and the resulting technology has been embedded in the software available to the ROMAC members. This history includes the development of analytical and computational methods, software implementations, and perhaps most importantly experiences with the correlations between the field tests and the model analyses and the ongoing process of continuous improvements resulting from these experiences. At this stage, an interrelated set of activities is being defined as illustrated in the diagram on page 11.

Our ***highest priority*** efforts are directed towards ***upgrades of existing software and fixing any bugs or needs for improvements*** as reported by ROMAC members. Hunter Cloud and Minhui He have reported on this activity under "SOFTWARE HIGHLIGHTS. We invite comments and feedback from ROMAC members on their experiences in utilizing our Rotor Dynamics software so that a continuous improvement process can be carried out at ROMAC.

Associated with the upgrades of existing software and fixing any bugs, we are working on ***incremental developments of existing software***. For example, in the process of investigating TORTRAN3, Hunter and Minhui discovered that it is important to rationalize the full model versus the reduced model, and the selection of number of modes in the reduced model including the choice of master coordinates can have a significant influence on the accuracy of the results.

Clearly, all of these issues should remain as transparent to the User as possible to minimize the need for the User's involvement and decisions in these issues while keeping the focus of the User on the actual results of the analysis. We are, therefore, investigating the processes of model reduction and their applications to nonlinear, time-history solutions. The development of ROTORLAB as a unified platform for User Interactions with ROMAC software is another example of incremental developments for existing software. ROTORLAB developments are reported elsewhere in this newsletter.

The third activity is somewhat longer range, and can be classified ***as new developments and "research".*** This activity is being shaped by active feedback from ROMAC members

Rotordynamics (continued)

and their preferences for any new directions our Rotor Dynamics efforts should embark on. Development of new computational tools for Rotor Dynamics is an area which we are carefully investigating, because (i) Rotor Dynamics is mature field, and therefore (ii) we must avoid any activities and investment of resources which can lead to a "reinventing the wheel" situation. The following areas are presently being explored:

1. A common, robust suite of library routines for eigenvalues, SVD, numerical integration, matrix manipulations, etc. which can be utilized across all software packages of ROMAC.

2. While ROTORLAB provides a consistent platform for User Interactions, we are investigating the development and implementation of a consistent modeling platform as well. This platform will rely on the multibody dynamics methods, which will incorporate finite element or other models (e.g., from experimental data) in the overall model. Use of the multibody methodology will allow inherent capability to include geometrical nonlinearities, subsystem models such as couplings, variable speed transmissions such as a torque converter coupled with epicyclic trains, motor models, gear/pinion models, bearing models, and combined lateral/torsional/axial behaviors. Time history solutions for transients, large orbits and stability based on limit cycles, as well as frequency domain solutions can be obtained from a consistent modeling platform.

3. Signal processing applications for rotor dynamic fault analysis.

Associated with the consistent modeling platform of a multibody approach, tradeoffs between computational cost and accuracy are an important issue even with the capabilities of today's computers in terms of storage and speed. This becomes much more critical when optimization, real-time identification, and control processes are implemented using the same consistent modeling platform. Even the simplest rotor models can result in a relatively large numbers of degrees of freedom when the rotational and translational freedoms at each node are taken into account. The purpose of model reduction methods is to reduce the size of the model and thus save computational time while satisfying some criteria of accuracy, i.e. staying close to the original model.

The ability to model asymmetry in rotor dynamic systems, for modeling intentionally designed in features or unintended features such as cracks, requires a better understanding of the effects of model reduction schemes and their accuracies. A nonlinear normal modes method as an adaptation of the CMS method to asymmetric systems is recently reported with excellent results (Sinha, S.C. Redkar, S., and Butcher, E., "Order Reduction of Nonlinear Systems with Time Periodic Coefficients using Invariant Manifolds", Journal of Sound and Vibration, 284(2005), pp. 985-1002). Other reduction schemes have been put forth for both dynamic models and also for control applications. These include:

1. Static Condensation—one of the oldest methods

2. Dynamic Condensation

3. Improved Reduced System (IRS) and Dynamic Improved Reduced System(DIRS)

4. Iterated IRS

5. Modal Truncation with undamped modes or damped complex modes

6. Component Mode Synthesis (CMS) Hurty/Craig/Bampton used by MSC/NASTRAN

7. System Equivalent Reduction Expansion Tech-

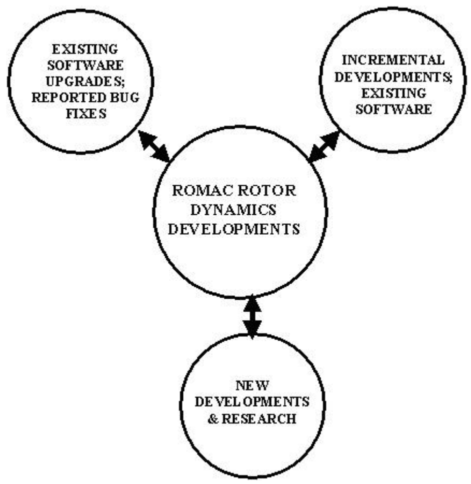
Rotordynamics (Continued)

nique, commonly refered to as SEREP.

8. Control oriented reduction techniques, such as Balanced Truncation, Krylov Subspace Methods, and Hankel Norm Approximation

Order reduction for nonlinear systems, particularly utilizing nonlinear normal modes (see for example: Apiwattanalunggarn, P., Shaw, S.W., and Pierre, C., " Component Mode Synthesis Using Nonlinear Normal Modes", Nonlinear Dynamics, Springer, 2005, Vol. 41, pp. 17-46).

Some very common reduction techniques used in rotordynamic and structural dynamic analysis are Guyan reduction, dynamic condensation, Improved Reduced Method (IRS), Dynamic IRS, and Iterated IRS. All of these rely on omitting physical degrees of freedom. The major problem with such methods is that they can only be reasonably accurate at a certain frequency and then only assuming that, that is a natural frequency, except for the iterative methods which converge to SEREP mentioned below. The other class of methods used on flexible structures includes modal reduction, system equivalent expansion reduction process (SEREP), and component mode synthesis. Reduction is based on the assumption that the contribution of modes with frequencies much higher than those contained in the excitation to the response of the system will be negligible. In these methods it is common to use normal or planar modes which are obtained from rotor mass and stiffness matrices. Bearing coefficients and gyroscopic moments are not included



in the eigenvalue problem since they are speed-dependent. As a result, the system is not completely represented in this way as the true modes of the system are complex. If damping and gyroscopic terms are included in the eigenvalue problem the resulting eigenfrequencies and mode shapes will be complex. However those modes would only be valid at a particular speed. Other methods such as balanced reduction and Hankel norm approximation have been traditionally used in the control community for time-invariant systems, though balanced reduction has more recently been applied to flexible structures as well. All the above methods are applicable to linear systems and nonlinearities should be modeled locally and dealt with on the right-hand side of the equations of motion.

We are investigating the efficacy of the various reduction schemes specifically for rotor dynamics applications. A numerical model has been developed for a stepped rotor using finite elements as a baseline model for comparing the various methods. The goal is to evolve a reliable model reduction scheme for the consistent modeling platform.

Advanced Balancing Research and ROMAC Code Enhancements

Students: Guoxin Li, Coston Untariou, Bin Huang

Advisors: Paul Allaire, Zongli Lin, Daili Fujimura, Pradip Sheth

Funding: ROMAC

Industrial members are interested in new, innovative balancing procedures. We have been working on new methods that have resulting in new balancing codes developed by Bin Huang and Guoxin Li. There are four specific balancing methods being developed. They are influence coefficient method optimization which employs 1) least squares balancing, 2) min-max balancing, 3) optimum stochastic balancing which takes into account a known distribution of uncertainty in the measured influence coefficient data, and 4) a balancing method to take into account uncertainty in measured influence coefficient data when the distribution of uncertainty is not known.

"The highlights of the new BALOPT are the two new balancing methods that take the system uncertainties into consideration and the advanced weight splitting function."

The optimum balancing code BALOPT, Release 1.1, has been released to member companies in November 2005. BALOPT, release version 1.2, is expected to be available to members in March 2006. The highlights of the new BALOPT are the two new balancing methods that take the system uncertainties into consideration and the advanced weight splitting function. The weight splitting function enables users to split the calculated weight solution at multiple holes with the total number of weight splitting holes pre-specified. This advanced weight splitting function is already available in a BALOPT beta version. Members are welcomed to request it from the developers.

Testing of BALOPT continues in the UVA ROMAC Labs on a three mass rotor. Additional balancing analysis on industrial rotors is also being carried out with Mitsubishi Heavy Industries with Mr. Daiki Fujimura, who was a Visiting Researcher in our lab for 2005. We are applying BALOPT to a large MHI turbine generator set with excellent results, better than conventional influence coefficient methods, using the different BALOPT balancing methods described in this article.

Finally, a different optimum minmax balancing method of splitting the balancing objectives into critical locations and other locations with less severe constrains has been carried out. Dr. Costin Untariou of UVA is conducting research into this method. This has been applied to a GE turbine generator set with excellent results compare to conventional least squares methods.

FLUID FLOWS: High Speed Centrifugal Compressor Test Rig

Advisors: Eric Maslen, Zongli Lin
Graduate Student: Dorsa Sanadgol

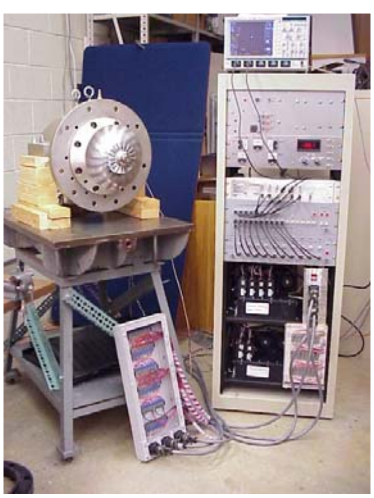
Undergraduate Students: James Chiu, Danielle Christensen
Project Start Date: 2000
Funding: ROMAC
Project Objectives:

One of the objectives of this test rig is to determine the bearing loads when the compressor is operated at flow/pressure combinations other than the "design point" and the examination of the forces arising from aerodynamic cross couplings. At the design point, the bearing loads due to aerodynamic flows are zero but at other operating points, they can be substantial. There are some design guidelines available for estimating off-design loading but they often produce very poor estimates. This is a problem because resizing bearings after the compressor design is complete is very difficult. Consequently, the evolution of compressor designs is slow and very conservative. One of the goals of the current research is to give accurate measures of off-design bearing loading and the aerodynamic cross couplings. The existing test rig provides a test bench to determine the bearing loads and the aerodynamic cross couplings using magnetic bearings as load cells. Such data could be used to calibrate existing models or to validate CFD based predictions. Better predictive tools would permit more aggressive design and would, hopefully, contribute to substantially better performance across the technology.

High Speed Centrifugal Compressor Test Rig

The other objective of this project is to use the sensitivity of the compressor characteristic to the tip clearance of the impeller to design a controller which is capable of actively suppressing the oscillations induced by compressor surge. This would be achieved, using a magnetic thrust bearing to modulate the tip clearance of the impeller. This way, the stable region of the compressor operation will be significantly increased and the compression system will not enter surge cycles for a wide variety of disturbances that might occur downstream of the compressor pipeline. The principal advantage of the proposed approach over conventional surge control methods lies in that, in machines already equipped with AMB thrust bearings, the method can potentially be implemented by simply modifying controller software. This dispenses with the need to introduce additional hardware, permitting adaptation of existing machinery at virtually no cost.

A theoretical model describing the sensitivity of the centrifugal compressor parameters to tip clearance variations induced by axial motion of the rotor was previously established; based on available measured effects of tip clearance on compressor efficiency. The well-known Greitzer compressor model was then modified to include the effects of tip clearance variation on the compressor characteristic. This provides a control mechanism: modulation of tip clearance in unshrouded compressor impellers - to affect and hopefully stabilize surge.



A backstepping controller is developed which is capable of substantially mitigating flow instabilities using a magnetic thrust bearing as the servo actuator to modulate the impeller tip clearance. The controller is designed with the objective that system trajectories remain on the steady state compressor characteristic curve. This ensures zero steady state offset of the impeller, which maintains the efficiency of the compressor. Effects of sudden changes downstream of the compressor are modeled as sudden changes in the throttle opening.

Results from simulation of the nonlinear model for a single stage high-speed centrifugal compressor show that using backstepping control, mass flow and pressure oscillations associated with compressor surge are quickly suppressed. Further, the stable operating range of the compressor can be increased significantly: minimum stable mass flow rate was reduced from 0.55 kg/sec to 0.3 kg/sec in a typical study. Actuator slew rate, peak force, and maximum tip clearance excursion requirements are well within the typical capacities of such systems: typically less than about 10 percent of available limit.

Having the promising simulation results in hand, the main focus of the project in the past year has been making the experimental test rig operational. The test facility has been assembled and fully levitated using magnetic bearings. Significant work has been done on developing the control system and on the identification of the system parameters. Danielle Christensen has developed a Lab View program for acquiring data. We are planning to move the test rig to its permanent site in the Aerospace Research Laboratory which allows for remote operation of the machine from a control room in January 2006.

Furthermore, considerable work has been done on designing a cooling system for the motor. The motor is a prototype induction motor produced by KaVo. Since the motor is a prototype, there is no manufacturer's data for the thermal output of the motor. A water jacket surrounding the motor is part of a closed loop system with a forced convection radiator to remove excess heat. James Chiu has been working on designing a cooling system for the motor. Using a CFD software he has analyzed the flow patterns and heat transfer through the motor which enabled him to determine the required air flow rate in the rotor and water flow rate in the water jacket. We are in the process of purchasing the equipment for the cooling system which will be in operation in January 2006.

Rotor Dynamics and Control of High Speed Rotors Supported in Magnetic Bearings

Student: Guoxin Li

Advisors: Paul Allaire, Zongli Lin

Funding: ROMAC

Project Objectives:

The control of a strongly gyroscopic rotor over a wide speed range using magnetic bearings is a challenging problem. Two dominant issues must be addressed in the control design. First, high bandwidth controllers are often required to stabilize the forward conical mode. This may compromise the high robustness requirements. Second, the dynamics of the rotor vary with the operating speed; a single linear time invariant controller often cannot stabilize the system over the entire operating range. Advanced multi-variable robust optimal controls, H_∞ and m-synthesis, provide systematic tools to achieve system robustness. To address the speed dependent dynamics, gain scheduled robust control including the switching control techniques are being investigated. Linear parameter varying (LPV) approach was employed to design gain scheduled H_∞ controllers. The gainscheduling problem was formulated in the context of convex semidefinite programming by linear matrix inequalities (LMIs). The LPV controller was obtained by solving the LMIs using interior point methods. A piecewise m-synthesis design was also adopted. Overall control was implemented by switching between controllers as speed varies from one region to another. A bumpless transfer scheme was implemented to guarantee smooth transition between controllers.

Progress in the Past year:

A test rig was constructed as a platform for investigating of different controllers. First, an accurate nominal model including the substructure modes was developed from physical laws and refined by experimental data. An uncertainty representation and a performance criterion were developed for the model AMB system. The influence of gyroscopic effects on the stability and performance of AMB system under a MIMO controller was analyzed.

SOFTWARE HIGHLIGHTS

RESP2V3

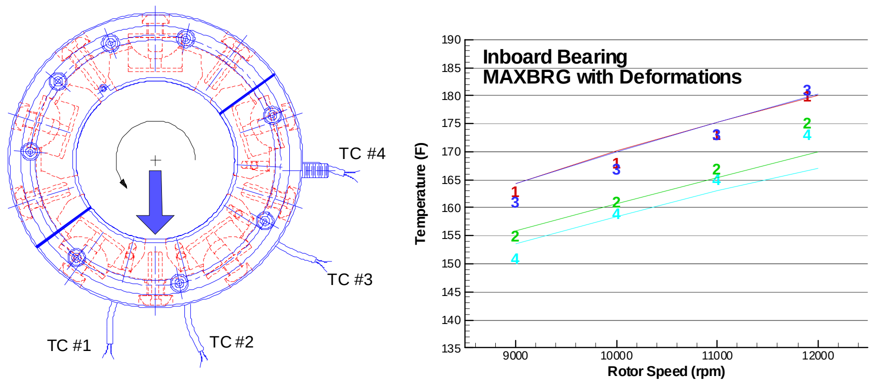
- Released version 3.02
- Increased maximum allowable unbalances

THPAD

- Scripted editor: released version 2.59
- Added case manager inputs for use with Rotorlab

MAXBRG

- Released versions 3.0 (6/05), 3.2 (7/05) and 3.8 (11/05)
- A number of model improvements for better predictions of exit and side leakage
- Converted to dynamic array allocation
- The ambient temperature at the back of a pad can be specified as the sump or drain temperature. This new boundary condition can be more appropriate in a flooded lubricating condition.
- An error of applying pressure force is corrected.
- An exception in the groove mixing model is addressed.
- A new model is added to determine the sump oil temperature for ring lubricated bearings.
- Scripted editor version 3.8
- MAXPLT version 3.0



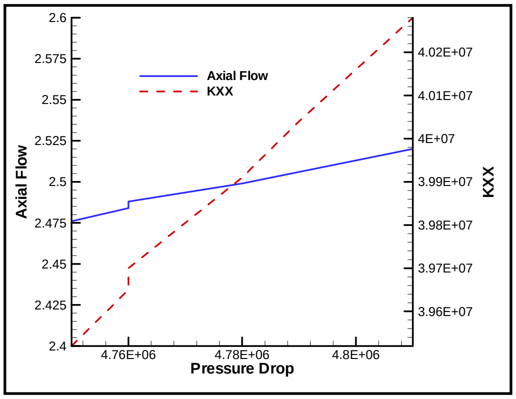
MAXBRG Predictions versus Stability Test Rig Bearing Temperatures

ROTORLAB

- Released version 7.7.3 (6/05) and 7.7.6 (11/05)
- Runs the following analyses:
  - -Undamped Critical (CRTSP2)
  - -Unbalance Response (RESP2V3)
  - -Stability (ROTSTB)
  - -Bearing (THBRG, THPAD, MAXBRG)
  - -Seal (SEAL3, LABY3)
- A number of interface/user friendliness changes
- Distribute mass and inertia option as well as squeeze film damper tool reinstituted
- Unbalance case manager for multiple bearing cases added
- Log file now generated
- Added function to shift portions of rotor model
- Frequency dependent flags now established on a part by part basis

SEAL3

- Released version 2.0
- Added capability to analyze multiple operating cases
- For each operating case, code now generates dynamic coefficient file for use with rotor analysis codes
- Corrected units for axial leakage (L/sec)
- Tecplot file for operating cases created (no macro, yet)
- Scripted Editor version 1.2

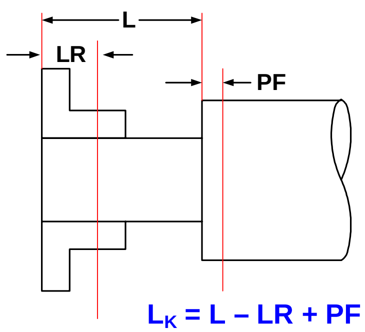


Example SEAL3 Output Results

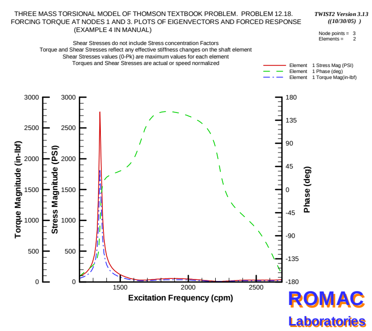
SEAL3—Version 2.0 released

TWIST2

- Released version 3.13
- Automatic calculation of shaft diameter penetration factors with effective stiffness length adjustment
- Additional length input for penetration effects due to shrink fits
- Element cyclic torque output
- Element stress and torque versus frequency plotting added
- PlotTwist2 version 3.11
- Scripted editor version 2.15
- Twist2_F macro version 1.11



Stiffness Length Correction Due to Various Penetration Factor Effects



Element Stress and Torque versus Frequency

TORTRAN3

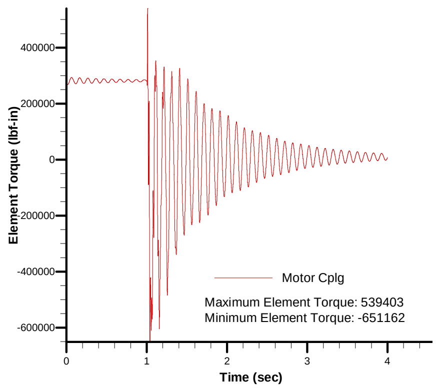
Conducted investigation of reported problems. The major conclusions were the following:

- Code does accurately handle gearbox speed ratios

- Depending on specific system, reduction method can lead to serious inaccuracies. Therefore, to insure accuracy until an improved reduction method can be implemented, it is recommended that no reduction be performed. Keep all modes in TWIST2 and specify all nodes as masters (# Nodes = # Modes = # Masters)

- Released version 2.0

- Added capabilities for performing electrical fault analysis or more general oscillatory time transients. These transients are assumed to take the following form:



Example Electrical Fault Transient

- Increased maximum number of masters from 15 to 150
- Floating precision variables converted to double
- TORPLOT3 version 4.6
- Torplot3 main data file scripted editor version 2.01
- Torplot3 element data file scripted editor version 1.01

BALOPT

- *First release*, version 1.1
- Multiple plane and multiple speed capabilities
- Provides two balance solution options: least squares and min-max
- Allows for balancing constraints such as weights and vibration
- Other features include simple weight splitting and runout compensation

WORK IN PROGRESS & FUTURE WORK

ROTORLAB

- Implement stability sensitivity curve case manager
- Add flexible support transfer function part as well as frequency dependent seals
- Add FORSTAB analysis capabilities

ROTSTB

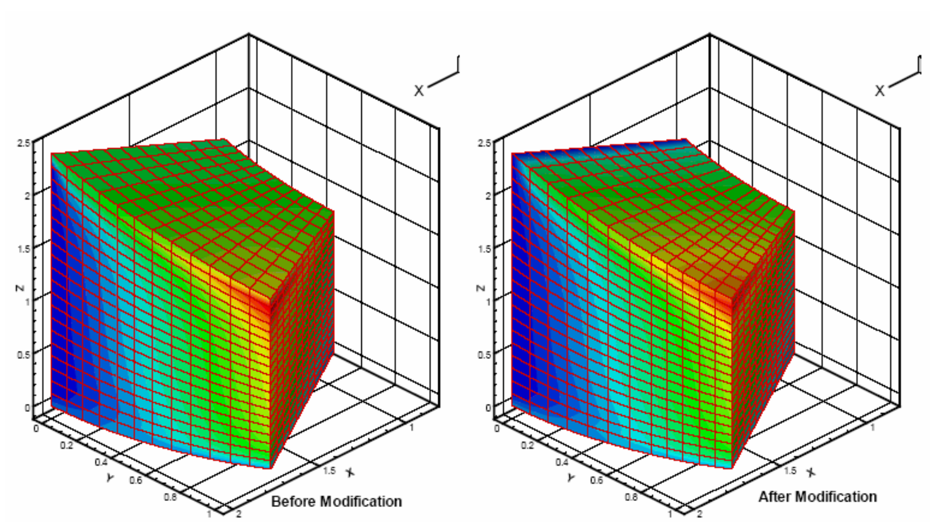
- Incorporate seal dynamics which are speed and frequency dependent
- Allow seal coefficients to be read from separate, formatted input file

TORTRAN3

- Identify and implement better reduction methods
- Improve data transfer from TWIST2 (element geometry and stiffness information)
- Provide coupling element cyclic torque output
- Improve generalized torsional stiffness model for elastomeric couplings (more general polynomial equation as well as possible interpolation for user input curve)
- Implement frequency dependent elastomeric coupling damping model

THRUST

- Resolve convergence problems for turbulent flow AND conduction situation
- Major effort requiring reformulation of runner, film and pad equations
- Additional mesh routines needed to fully couple components



THRUST Test Case Comparing Temperature Solutions Before and After Modifications

New Lab Engineer in ROMAC

ROMAC has a new Laboratory Engineer. Dr. Minhui He, of MAXBRG fame, takes over the duties as Lab Engineer for ROMAC from Hunter Cloud. Hunter is going to concentrate on finishing his Ph. D. thesis this year. Minhui will work with the ROMAC software, assist members with questions, work with ROMAC directions for the future and other tasks. To contact Minhui, email him at minhuihe@yahoo.com or call him at (434) 924-4547.

ARTIFICIAL HEART PUMP DEVELOPMENT

University of Virginia – NIH Funded Research Project .

Need for Circulatory Support

When a patient has long term congestive heart failure, the native heart pumps at a flow rate much below the normal rate of approximately 6 liters per minute. Over a long period of time with this disease, the human body is starved for blood flow and eventually we die. An estimate of the need for long term implantable blood pumps ranges from 17,000 to 240,000 patients annually in the U.S. that could benefit from such a system. At this time, the most promising approach is to use a ventricular assist device in the configuration shown in Fig. 1. Heart failure is diagnosed in nearly 500,000 new patients each year and is the primary diagnosis for over 900,000 hospitalizations a year in the U.S with an estimated total cost exceeding $10 billion/year. Initially the VADs were limited to bridge to cardiac transplantation (BTT). Recently, however, the FDA has approved the HEARTMATE I and the MicroMed-DeBakey VAD for long-term, i.e. destination, therapy.

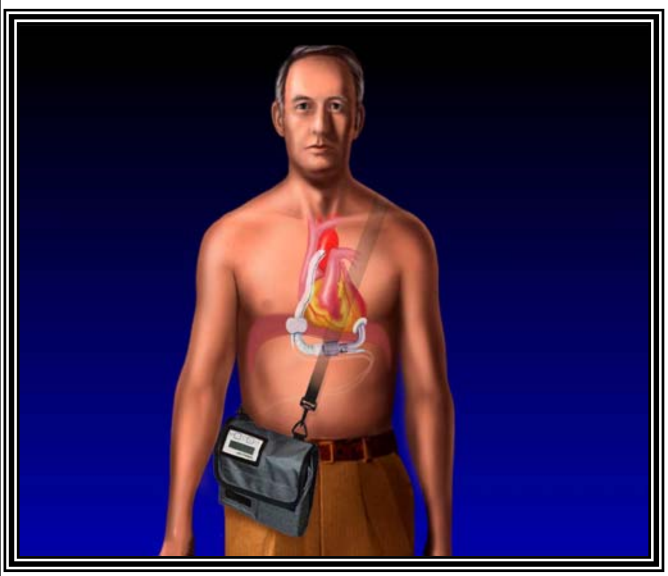


Figure 1 Schematic Drawing of Left Ventricular Assist Device for Support of Patients with Congestive Heart Failure

The left ventricular assist device (LVAD) is located just below the diseased heart and pumps in parallel with the native heart as illustrated in Fig. 1. A hole is placed in the left ventricle and an inlet cannula is brought to the axial flow LVAD which rotated continuously at a speed of approximately 8.000 rpm. It pumps additional blood (beyond that of the diseased native heart) through the discharge cannula up to the aorta and back into the bloodstream. It is powered by a battery and the speed controller contained in an external pack and connected to the LVAD pump by a wire placed through the skin.

"Heart failure is diagnosed in nearly 500,000 new patients each year and is the primary diagnosis for over 900,000 hospitalizations a year"

LEV-VAD2 Developed by Utah Artificial Heart Institute/University of Virginia/Flowserve/Kipp Engineering

A new magnetically suspended ventricular assist device is currently under development as funded by the National Institute of Health. The University of Virginia is responsible for the flow design and testing (Houston Wood of ROMAC), magnetic suspension and electronics (Paul

Allaire and Zongli Lin of ROMAC). Kipp Engineering is responsible for design drawings of the pump and Flowserve (ROMAC Industrial Member Company) is responsible for pump manufacture. Utah Artificial Heart Institute is responsible for animal testing, in cooperation with the University of Virginia Heart Surgery Team, and overall administration of the project. These systems are acknowledged by the blood pump development community as the ultimate in mechanical blood pumps. There are several 3rd generation pumps being developed to provide continuous flow with an impeller suspended with magnetic bearings. The previously developed CFVAD by the UAHI, UVA and MedQuest Products was the first to demonstrate feasibility of a totally suspended (no physical contact) impeller, and the only system incorporating a centrifugal pump to facilitate a simplified control mechanism.

The LEV-VAD nomenclature, components and structure are illustrated in **Figures 2 and 3. Figure 2** is a cutaway of the housing. **Figure 3** is cutaway of the Impeller structure, where numbers equate to the balloon callouts.

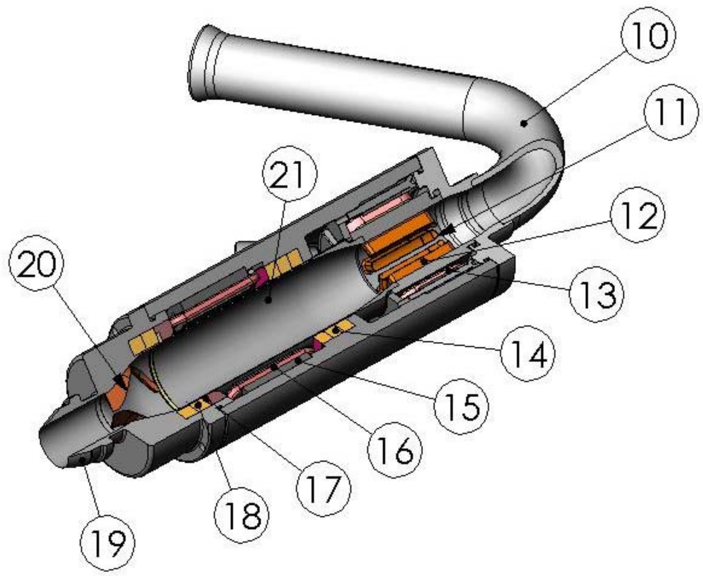


Figure 2. VAD Housing Assembly Cutaway

1. Inlet Cannula
2. AMB Stator / Inducer Region
3. AMB Stator Leg (1 of 6) which is covered by the Inducer "can"
4. AMB Coil (1 of 6)
5. Axial PMB Stator Assembly
6. Motor Stator
7. Motor Coil (1 of 6)
8. Housing Can to Diffuser Seal
9. Rear PMB Stator Radial Assembly
10. Dacron Vascular Graft Connector
11. Diffuser Region
12. Main Housing Can

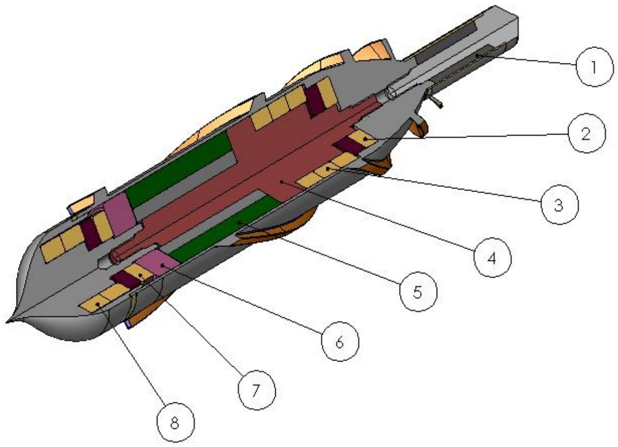


Figure 3. VAD Impeller Assembly Cutaway

1. Radial Active Magnetic Bearing (AMB) Rotor
2. Front Hall Effect (HE) Magnet
3. Axial Permanent Magnet Bearing (PMB) Rotor Assembly
4. Impeller Tie Bolt
5. Motor Rotor Magnet Assembly
6. Expendable material that will be used to High Speed Balance the Rotor
7. Rear HE Magnet

   Rear PMB Rotor Radial Assembly

Our new axial flow LEV-VAD employs a unique and innovative magnetic suspension system **(Figure4).** The proposed LEV-VAD will include a reduced size magnetic suspension as described in the following optimal magnetic design objectives: 1) a suspension that allows for a one pass blood flow path not obstructed by suspension or other pump components, 2) a very stable centering of the impeller when subjected to external disturbances, 3) compact, low energy consumption implementation. The attainment of these objectives with the magnetic suspension is the primary enabling feature of this axial pump design. It consists of one radial active magnetic bearing (AMB), one permanent magnet (PM) thrust bearing, and one radial PM bearing. The final sensors for detection of rotor radial position may be Hall or other sensors. The motor is a brushless DC motor.

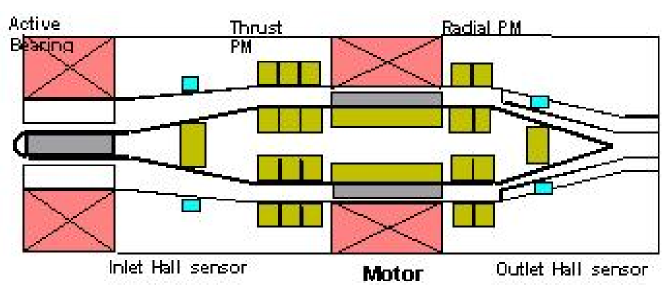


Figure 4 Schematic of Magnetic Suspenion and Motor System for LEV-VAD2

Computational Fluid Dynamics and Flow Testing

A detailed study using CFD enabled the estimation of performance for the LEV-VAD model. For rotational speeds of 5000 to 8000 RPM, the pressure rise across the LEV-VAD was determined for flow rates of 2 LPM to 10 LPM.

Also, a flow testrig was constructed for measuring the pump flow and pressure at UVA with the pump impeller, inducer and diffuser in plastic prototype form. The test rig is shown in Fig. 5. The pump flow component configuration is sup-

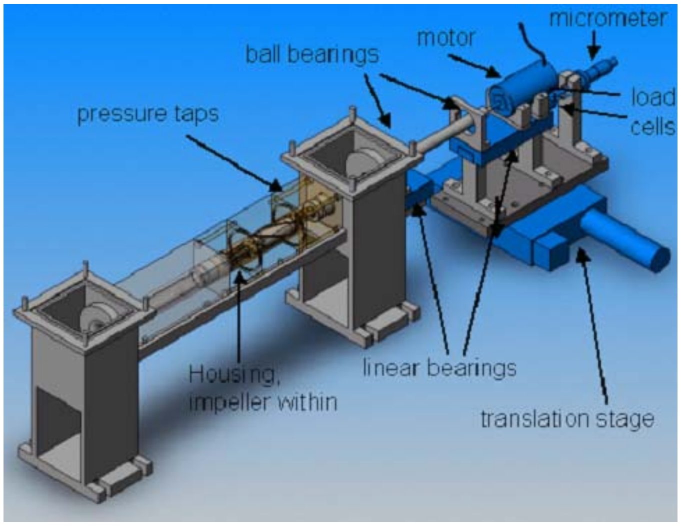


Figure 5 LVAD Pressure and Flow Performance Test Rig at UVA

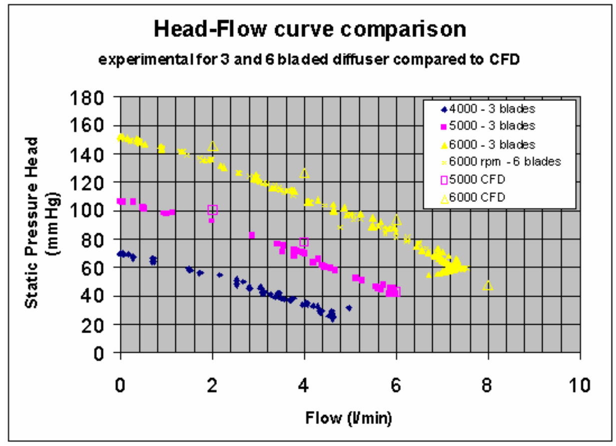


Figure 6 Head-Flow and Axial Force Curve Comparison Between Experimental Results and CFD Predictions for LEV-Plastic Prototype

ported by a shaft at the rear. Pressure taps and flow measurement devices are employed to measure the pump performance.

Figure 6 shows the pressure performance curves for this computational model, meeting the needed pressure rise of 100 mmHg at 6500 for 6 LPM. Each data point corresponds to a steady state simulation for a given flow rate and rotational speed. The pressure performance curves demonstrate the pump's ability to deliver adequate flow with the desired pressure rise. Similarly, the fluid efficiency performance curves were determined as seen in **Figure 6**. The best efficiency points (BEPs) for these rotational speeds and flow rates ranged from 25% to 28% and correlate well with typical efficiencies for rotary blood pumps [109].

"A detailed study using CFD enabled the estimation of performance for the LEV-VAD model"

Current Progress

The first prototype of the pump is currently undergoing design finalization and manufacturing by UVA, Flowserve, and Kipp Engineering. It is expected that the first pumps will be produced in June, 2006, be flow tested and magnetically levitated at UVA in July and tested in animals in August 2006 by UAHI and UVA

2006 ROMAC Annual Conference

Charlottesville, VA

June 11-14, 2006

The 2006 ROMAC Annual Conference will be held in Charlottesville, Virginia at the Omni Hotel. They have offered us a nightly room rate of $120.00 per single/double room. You can visit their website at:

www.omnihotels.com. A Sunday afternoon reception will start the conference on June 11. The meeting will be Monday—Wednesday with breaks and lunches provided each day. There will also be a dinner banquet on Monday night. Members will be receiving their registration packet in March. If you should have any questions, contact Karen Marshall at (434)924-3292. Details are also on our web at: www.virginia.edu/romac/annual_meetings.htm We hope you can join us in Charlottesville!

2006 Rotordynamics Short Course

The 2006 Rotordynamics Short course will be held August 14-17, 2006. The course outline consists of:

Introduction to Rotor Dynamics, Introduction to Bearing Dynamics, Applied Rotor Dynamics for Industrial Rotors, Unbalance Response, Stability of Industrial Compressor Rotors, Advanced Fluid Film Bearing Analysis, Compressible Flow Seals and Rotor Dynamics of Pumps. Water Lubricated Bearings, Liquid Flow Seals, Balancing of Rotors, Support Stiffness Effects, Torsional Vibrations, and Bowed Rotors and Rotor Rubs will also be discussed. The short course will take place at the University of Virginia. A block of rooms have been held at the Hampton Inn and Suites, University. The deadline for registering is July 14, 2006. You can register by phone at (434)924-3292. You can also visit our website at www.virginia.edu/romac/short courses.htm for more information. The course is free of charge to all ROMAC members and $1000.00 for non-members.

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