ROTOR BEARING SOLUTIONS INTERNATIONAL, LLC

www.rotorsolution.com

Introductory/Advanced Magnetic Bearing Systems

- A 3 Day Short Course

Basic Technology, Industrial Applications,
Bearing Design and Optimization, Rotordynamic Modeling,
PID and Modern Control, Numerical Examples
Auxiliary Bearings and Rotor Drop Analysis

Held in: Poway, California
At EPC Power
13125 Danielson St., Suite 112, Poway, CA 92064
Google EPC Power for Street Map and Location
(Near San Diego, California)
Tel: 858-748-5590

Course Dates: July 21, 22, 23, 2015

Agenda: Draft 6, April 9, 2015

Course Objectives and Description

The use of magnetic bearings is increasing in industrial applications but they are often not well understood by mechanical engineers. This course will provide the basic background in electro-magnetic systems and controls. Some examples of magnetic bearing industrial machines are presented in the course. A number of basic and advanced topics on magnetic bearing design and feedback control are provided but it is not expected that attendees are experts in controls technology. Finally, a few additional topics on modern control for flexible shaft-AMB machines such as high pressure compressors and surge control in compressors using magnetic bearings is presented. API/ISO specifications for magnetic bearing supported rotating machines are presented. The details of rotor dynamic analysis of rotor drops on auxiliary bearings are presented for various examples. Also, the design of rotating artificial hearts supported in magnetic bearings and other examples are presented.

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Session 1 – Introduction to Magnetic Bearings
Session 2 – Magnetic Bearing Design, Simple Control and Flywheel Application
Session 3 – Control Parameters, Standards, Modeling and Characteristics of Magnetic Bearing Systems
Session 4 – Digital Control Design and Hardware, Auxiliary Bearing Systems and Rotor Drop Analysis
Session 5 – Rotor Drops, Auxiliary Bearing Systems, and Example Applications
Session 6 – Surge Control and Industrial Applications of Magnetic Bearings

Lecturers

1. **Paul Allaire,** Chief Technical Officer, Rotor Bearing Solutions International
   Also, Professor, University of Virginia, Retired – Long Time Director of Rotating Machinery and Controls Laboratory, Ph. D. Northwestern University
2. **Simon Mushi,** Director of Magnetic Bearings and Controls, Rotor Bearing Solutions International, Ph. D. University of Virginia
3. **Jianming Cao, P.Eng.,** Director of Rotor Dynamics, Rotor Bearing Solutions International, Ph. D. University of Virginia
4. **Tim Dimond, P.E.,** President, Rotor Bearing Solutions International, Ph. D. University of Virginia, Formerly – Principal Scientist, Rotating Machinery and Controls Laboratory, University of Virginia

Additional Contributors

1. **Arun Kailasan,** Magnetic Bearing Specialist, Gardner Denver, Ph. D. University of Virginia
2. **Pablo Yoon**, Assistant Professor, University of New Hampshire, Ph. D. University of Virginia
3. **Mike Swann**, General Manager, Waukesha Magnetic Bearings
4. **Tobias Denner**, Cerobear
5. **Weimin Wang**, Professor, Beijing University of Chemical Technology

The course lecturers and contributors have the combined experience and ability to explain rotor-AMB systems making this short course unlike any other short course found in today's world. Paul Allaire has 42 years' experience in research and teaching rotor dynamics and magnetic bearings. He has taught more short courses on magnetic bearings to engineers in industry than anyone else. He has refined the basic lectures on magnetic bearings over the past 30 years as well as built the largest academic AMB laboratory in existence.

Simon Mushi is the Director of Magnetic Bearing Systems for RBSI. He has been working on magnetic bearings and high speed rotors for the past 9 years. Jianming Cao is the Director of Rotor Dynamics and has worked on nonlinear transient rotor dynamics for the past 9 years. Tim Dimond is the President of RBSI and formerly was the Principal Scientist of the ROMAC Laboratory. He also worked for 9 years as a design engineer at Newport News Shipbuilding. He has now been in magnetic bearings research over the past 10 years and participated in numerous AMB short courses.

Day *0: Registration (Monday, July 20, 2015)*

4:00-5:00 pm: Registration – Pre-Registered Attendees (Pick Up Materials)
- On Site Registrations

Session 1 – Introduction to Magnetic Bearings
(Day 1: Morning - Tuesday, July 21, 2015, 8:00 a.m. – 12:00 p.m.)

Welcome to Short Course

Talk 1: Introduction to Magnetic Bearings (Allaire)
This talk presents an introduction to thrust and radial magnetic bearing designs, industrial bearing designs, example rotor dynamic modeling and control of industrial magnetic bearings.
It gives an overview to the rest of the short course.

Talk 2: **Electromagnetic Fields, Flux, and Material Properties (Allaire)**
The basic principles of electromagnetic fields and magnetic flux are presented as applied to active magnetic bearings. Wire sizing and coil current density limits are discussed. Material properties of active magnetic bearings are discussed.

Talk 3: **Magnetic Actuator Properties (Allaire)**
Active magnetic bearing systems are presented. The major components: magnetic actuator, rotor, proximity sensor, power amplifier, and controller are discussed. Example industrial thrust bearings are evaluated. Magnetic flux density and magnetic forces in thrust bearings are presented with numerical examples.

Break

Talk 4: Magnetic Bearing Materials and Design (Dimond)
The talk discusses the magnetic steel material properties, hysteretic and eddy current losses. Copper winding current density, and inductance are presented. Common radial bearing geometries, designs, and rotating stresses as well as air windage and air drag properties are evaluated.

Talk 5: **Magnetic Thrust Bearing – Forces, Coils, Amplifiers, Slew Rate (Allaire)**
Magnetic thrust bearing forces, coil properties, double sided linearization operation are presented. Also, magnetic bearing amplifier/coil matching, power amplifier properties, coil power loss and dynamic system properties are discussed with several numerical examples from industrial pumps and textile spindles.

Lunch

Session 2: Magnetic Bearing Design, Simple Control, and Specifications (Day 1: Afternoon – Tuesday, July 22, 2015, 1:00 p.m. – 5:00 p.m.)

Talk 6: Design of High Load Capacity Magnetic Bearing (Dimond)

The advanced design of radial active magnetic bearings is presented for both a magnetic circuit analysis and finite element analysis is presented. Eight, twelve and sixteen pole radial bearing forces are evaluated and optimized for the same size bearing. Properties of current gain and open loop stiffness are evaluated.

Talk 7: How to Design a Magnetic Thrust Bearing (Allaire)

A magnetic circuit model is used to illustrate how a typical magnetic thrust bearing is modeled and designed. This design process includes stator and thrust disk geometry, coils, wire sizing, load capacity, slew rate and other bearing properties.

Break

Talk 8: **Proportional-Derivative Control of Magnetic Thrust Bearing (Allaire)**

This talk presents the system modeling of active magnetic bearing control for a thrust bearing with Laplace transforms and block diagrams. The formulation of the thrust bearing with amplifier, feedback proportional-derivative control, and sensors is evaluated with numerical values for an industrial magnetic bearing. Equivalent system mechanical stiffness and damping are determined. Again, simple numerical examples are provided for industrial AMB systems.

Talk 9: High Speed Energy Storage Flywheel Design – Composite Rotor, AMB Support System, Motor-Flywheel-AMB System Design (Dimond)

This talk describes the design of a small energy storage flywheel with a novel integrated inside-out motor, flywheel, magnetic suspension design. The flywheel design with example numerical values is presented.

Session 3 –Control Parameters, Modeling and Characteristics of Magnetic Bearing Systems (Day 2: Morning – Wednesday, July 23, 2015, 8:00 a.m. – 12:00 p.m.)

Talk 10: Control and Sensitivity Functions for Magnetic Bearings (Mushi)

The systematic concept of control is presented. One of the major keys to control - sensitivity and complimentary sensitivity functions as applied to rotor/AMB systems are introduced and examples provided. This talk is related to the following talk on API/ISO specifications.

Talk 11. API/ISO Vibration Standards for Magnetic Bearing Systems (Allaire)

The American Petroleum Institute and the International Standards Organization have similar vibration standards for industrial AMB supported machines. This talk presents the classes of operation and the

interpretation of those standards for these machines. The new API standards for auxiliary bearings and their performance are presented in a later talk.

Talk 12: Modal Rotor Dynamics & State Space Modeling of Rotor/AMB System (Dimond/Mushi)

Magnetic bearing control designs are carried out with modal state space methods and Matlab using a relatively small numbers of degrees of freedom. An example flexible rotor is used to illustrate the process. The normal second order rotor dynamics critical speeds and mode shapes are used to create the state space equations of motion. The final assembly of the rotor/AMB system model is shown, including the linearized model of the magnetic bearings.

Break

Talk 13: Comparison of Advance Control Methods for Flexible Rotors (Mushi)

This talk presents the challenges of advanced control of flexible rotor/AMB systems and several controller methods – LQG, H-Infinity and Mu Synthesis. Gain and phase margins are discussed using natural frequencies and mode shapes including gyroscopic forces and mode uncertainty. Unbalance response and stability of the example rotor is shown. Robust stability and controller tuning for PID vs. advanced control are evaluated and compared.

Talk 14: Modern Control of Flexible Rotor on Magnetic Bearings (Mushi)

Modern control brings many advantages to rotor/AMB systems over PID control – it is the way most flexible rotor/AMB systems will be controlled in the future. It reduces the need for system tuning and accommodates machine changes. Also, it allows for uncertainty in the rotor/AMB system parameters without loss of performance. These topics are discussed in this talk.

Lunch

Session 4 – Digital Control Design and Hardware, Auxiliary Bearing Systems and Rotor Drop Analysis
(Day 2: Afternoon – Wednesday, July 23, 2015, 1:00 p.m. – 5:00 p.m.)

Talk 15: Design and Characterization of Flexible Rotor on Active Magnetic Bearings (Mushi)

An advanced flexible rotor test rig on four AMBs is described. It has been use to evaluate the performance of high pressure industrial compressors subject to external excitations as presented in talk 26. Modal analysis was used for the control design. The magnetic bearing, power amplifiers, and position sensors are all evaluated experimentally. Finally, the analytical model is compared to the initial levitation experimental results with PID controls.

Talk 16: Principles of Digital Electronic Control Hardware (Mushi)

General principles of the digital electronic control systems used for magnetic bearings are discussed. This includes typical power amplifier, sensor, power supply, backup power supply and other components as employed in industrial magnetic bearing systems.

Break

Talk 17: Advanced Control of Flexible Rotor with Aerodynamic Cross Coupled Stiffness Effects and Uncertainty (Mushi)

When employed in industrial high pressure compressors, AMBs have to be capable of handling unexpected loads. This is best approached with modern control methods such as mu synthesis which are designed to handle the type of uncertainty due to these high loads and other system issues. This paper presents the typical design of functions used for modeling uncertainty for on-site industrial conditions that can be planned for in advance. This approach was applied to the high speed 4 AMB test rig described in detail in earlier talks. Sensitivity and complimentary sensitivity functions are evaluated for the system and predicted performance results were experimentally evaluated via the test rig.

Talk 18: Auxiliary Bearings for Rotor Drop in Magnetic Bearing Systems (Cao/Denner)

Magnetic bearing support systems must have an auxiliary bearing system to support the rotor in the case of an electrical power loss. This talk describes the typical radial and axial auxiliary bearing configurations in industrial applications.

Talk 19: Principles of Nonlinear Transient Analysis of Auxiliary Bearings (Cao/Denner)

API specifications for rotor drop analysis are presented. The equations of motion for auxiliary bearings including the impact of rotor drop on angular contact ball bearings, the inner race and outer race motions, and ball motions are developed. Stresses in races and balls in nonlubricated motion are evaluated using local Hertzian stresses during the drop. The principles of the auxiliary bearing sport system including springs and damping is illustrated. Properties of Cerobear angular contact double row preloaded ceramic ball bearings are featured.

Session 5 – Rotor Drops, Auxiliary Bearing Systems, and Example Applications (Day 3: Morning – Thursday, July 24, 2015, 8:00 a.m. – 12:00 p.m.)

Talk 20: Rotor Drop Analysis of Vertical Rotor & Design of Auxiliary Bearing System (Cao/Denner)

The nonlinear transient rotor drop analysis in a vertical rotor is presented. The analysis includes the motion and stress occurring in the inner and outer races of the auxiliary ball bearing as well as the balls during the drop. The spring/damping support system design is outlined. The approach to minimizing the impact of the rotor during the drop and increasing auxiliary bearing life is presented. Cerobear auxiliary bearing designs are included.

Talk 21: Rotor Drop Analysis and Auxiliary Bearing System Design in a Horizontal Industrial Compressor Rotor/AMB System (Cao)

The vibration behavior of a horizontal AMB rotor dropping on auxiliary bearings is quite important concerning the number of drops that the auxiliary bearings can withstand. The issue is to calculate whether the rotor undergoes small amplitude orbits when dropped or large amplitude orbits and large stresses which severely damage the auxiliary bearing. The analysis of the motion and stress occurring in the inner and outer races of the auxiliary ball bearing as well as the balls during the drop is illustrated. The spring/damping support system design is outlined. A specific industrial multistage high speed compressor application is presented.

Break

Talk 22: Design and Operation of Artificial Heart Pump Magnetic Suspension (Allaire)

An example axial flow artificial heart pump supported on a combined active and passive magnetic suspension system is presented. The two radial bearings are actively controlled but have a permanent magnet bias for low power consumption. The axial permanent magnet bearing is combined with the radial bearing bias for a compact construction allowing an unobstructed blood flow path for the ventricular assist device.

Talk 23: Design of Magnetically Suspended High Speed Blower (Dimond)

A prototype high speed blower/generator operating at 26,000 rpm has been developed by Kinetic Traction. The blower/generator design concept is presented and an overview of the magnetic bearing suspension is presented.

Lunch

Session 6 –Surge Control and Industrial Application of Magnetic Bearings (Day 3: Afternoon – Thursday, July 24, 2015, 1:00 p.m. – 5:00 p.m.)

Talk 24: Surge Control Test Rig with Magnetic Bearings in Centrifugal Compressor (Yoon/Allaire)

Compressor surge is a common problem in industrial high pressure compressors. An experimental AMB test rig including a thrust bearing and full pressure instrumentation was developed to study compressor surge control. This talk develops the characterization of surge in the single stage compressor test rig.

Talk 25: Surge Control with Magnetic Bearings in Centrifugal Compressor (Yoon/Allaire)

This talk presents the methodology for controlling surge with excited axial motions of the thrust bearing and some experimental test results. The results show that this method permits compressor operation right on the surge onset line or even in the normal surge region. Extensive experimental results are presented.

Talk 26: Use of Magnetic Bearings to Identify Damping of Flexible Rotors in Fluid Film Bearings (Dimond)

In some cases, fluid film bearing supported machines need to have their stability evaluated on the test bed or on site. This work describes the experimental measurement process of evaluating the flexible rotor/bearing system at various operating speeds using a magnetic bearing placed in the rotor. The measured results are compared to full theoretical models of the rotor, fluid film bearings and the support structure.

Break

Talk 27: Determination of Compressor Rotor/Tilting Pad Bearing Stability Using a Magnetic Exciter (Wang/Dimond/Allaire)

This talk develops new methods for the forward and backward mode excitation of industrial compressor rotors on tilting pad bearings to identify rotor stability. Numerical results and an extensive experimental investigation is presented. The new method is a more accurate approach to this type of stability measurement.

Talk 28: Design and Control of Magnetic Bearings in a High Speed Industrial Compressor (Allaire)

This talk discusses the design of magnetic bearings and their control for a multistage high pressure industrial compressor. The magnetic bearing design details are presented and the integration into the compressor discussed. The modern control analysis of the compressor is developed and the compressor stabilized.

Talk 29: Gazprom Industrial Case Study of Gazprom and Major AMB Applications in Russia (Swann/Allaire)

Active magnetic bearings are employed in Russian industrial sectors. This talk presents a major large rotor application and several other major applications in that country with photographs of those applications.

End of Short Course – 5:00 pm

Registration and Fees

Advanced registration for the short course should be sent to Dr. Tim Dimond at tim.dimond@rotorsolution.com or Rotor Bearing Solutions International (RBSI), 3277 Arbor Trace, Charlottesville, Virginia, 22911. Additional information is given on the Rotor Bearing Solutions International website at www.rotorsolution.com. The RBSI telephone number is 434-632-8469 or 434-284-1850 (cell). The fee for the course is $1,950 with advanced registration or $2,150 on site. On site registration payments can be made with cash or credit card. If requested in advance via a purchase order, billing to an individual company will be accepted.

Lecture Materials and Continuing Education Credit

The material for all talks will be provided to attendees on a memory stick. Detailed questions on the course topics in particular and magnetic bearings in general will be answered. Certificates for 24 PDHs (Professional Development Hours) will be provided for attendees of the short course upon request. Please let Dr. Dimond know if you need a certificate.

Recommend Area Hotels

Recommended hotels in Poway are:

Hampton Inn & Suites
San Diego – Poway
14068 Stowe Dr.
Poway, CA 92064
(858) 391-1222

Best Western Inn
Poway/San Diego Hotel
13845 Poway Rd.
Poway, CA 92064
(858) 748-6320

Ramada Poway
12448 Poway Rd.
Poway, CA 92064
(858) 748-7311

Springhill Suites
San Diego Ranch Bernardo/Scripps Poway
12032 Scripps Highlands Dr.
San Diego, CA 92131
(858) 635-5723

Residence Inn
San Diego Ranch Bernardo/Scripps Poway
12011 Scripps Highlands Dr.
San Diego, CA 92131
(858) 635-5724

The attendees are responsible for registering at the hotel on their own at one of the above hotels.

Short Course Lecture Location

All lectures will be held in a conference room at EPC Power. Food and drinks for breaks will be provided in the conference room.

Notes: There may be some small changes in the agenda as talks are finalized.

RBSI Experience and Current Status on Magnetic Bearings Design and Manufacture

The engineering staff at RBSI has many years of experience with magnetic bearing design, research and development. Now RBSI is in the business of custom design and manufacture of magnetic bearing systems for industrial rotating machines as well as on site assistance. This includes magnetic component

design, analysis, and manufacture, electronic digital control hardware, robust control development including unbalance compensation, auxiliary bearing design, rotor drop analysis, system integration, and assistance with machine start up on the manufacturing site and in the field. Rotor drop analysis software for lease to industrial firms is currently under development. Contact us for more information.