ROTOR BEARING SOLUTIONS INTERNATIONAL, LLC

www.rotorsolution.com

Advanced Magnetic Bearing Systems

- A 3.5 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

Sponsored By:
Rotor Bearings Solutions International (RBSI)

Guest Lecturer: Mike Swann
Waukesha Magnetic Bearings

Held in: Houston, Texas
Crown Plaza Houston Northwest - Brookhollow

Course Dates: April 22-25, 2014
Agenda: Draft 5, January 18, 2014

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. Then numerous industrial examples of magnetic bearing industrial machines are presented by Waukesha Magnetic Bearings. 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. Also, the design of rotating artificial hearts supported in magnetic bearings and other examples are presented. The details of rotor dynamic analysis of rotor drops on auxiliary bearings are presented for various examples. 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.

Continuing Education Credit

Certificates for 2.4 CEUs (continuing education units) will be provided for attendees of the short course.

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Advanced Magnetic Bearing Short Course
April 22-25, 2014

Session 1 – Introduction to Magnetic Bearings
Session 2 – Magnetic Bearing Design and PID Control
Session 3 – Industrial Applications I
Session 4 – Industrial Applications II
Session 5 – Magnetic Bearing Characteristics, Modern Control Plus Energy Storage Flywheel
Session 6 – Auxiliary Bearings, Rotor Drop Analysis, and Artificial Heart Pump
Session 7 – Modern Control Applications

Lecturers

1. Paul Allaire, Chief Technical Officer, Rotor Bearing Solutions International
Also, University of Virginia, Retired – Long Time Director of Rotating Machinery and Controls Laboratory

2. Mike Swann, General Manager, Waukesha Magnetic Bearings

3. Tim Dimond, PE, President, Rotor Bearing Solutions International,
Formerly – Principal Scientist, Rotating Machinery and Controls Laboratory, University of Virginia

Contributors

1. **Simon Mushi, Director of Magnetic Bearings and Controls, Rotor Bearing Solutions International**
2. **Jianming Cao, Director of Rotor Dynamics, Rotor Bearing Solutions**
3. **Arun Kailasan, Magnetic Bearing Specialist, Gardner Denver**
4. **Pablo Yoon, Research Scientist, University of Virginia**

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. Mike Swann has also been an active participant in the magnetic bearing industry for many years and is now the general manager of one of the leading AMB vendor companies with world wide sales. He has participated in numerous AMB short courses over the years. Tim Dimond has worked in magnetic bearings research over the past 8 years and participated in numerous AMB short courses.

Day *0: Registration (Monday, April 21, 2014)*

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

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Advanced Magnetic Bearing Short Course
April 22-25, 2014

Session 1 – Introduction to Magnetic Bearings
(Day 1: Morning - Tuesday, April 22, 2014)

Welcome to Short Course

8:00 am - Talk 1: Introduction to Magnetic Bearings (Allaire)

This talk presents thrust and radial magnetic bearing designs, industrial bearing designs, example rotor dynamic modeling and control of industrial magnetic bearings.

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.

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.

Lunch

Session 2: Magnetic Bearing Design and PID Control
(Day 1: Afternoon – Tuesday, April 22, 2014)

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.

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: **Proportional-Derivative Control of Magnetic Thrust Bearing (Dimond)**

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.

Advanced Magnetic Bearing Short Course
April 22-25, 2014

Talk 8: Magnetic Bearing Supported Rigid Rotor with Proportional, Integral, and Derivative (PID) Control (Allaire)

This talk concerns the proportional, integral, and derivative (PID) control parameters, as employed in most industrial applications, are explained in detail and applied to a rigid rotor test rig. However, the PID parameter selection method is not clear. Then, common PID tuning methods such as frequency response methods, pole placement, lambda tuning, optimization, and robust loop shaping are explained.

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Session 3 – Industrial Application of Magnetic Bearings I
(Day 2: Morning – Wednesday, April 23, 2014)

Talk 9: Industrial Case Study (NAM GLT) and Justification for Active Magnetic Bearings

This talk discusses a large industrial application of magnetic bearings in a major industrial machine. The engineering advantages and financial cost advantages are presented for this successful application. GLT is Groningen Long Term, the project name for the compressor installations Waukesha did for NAM - Nederlandse Aardoile Maatschappij B.V. - the joint venture between Shell and Exxon.

Talk 10: Gazprom Industrial Case Study of Gazprom and Major AMB Applications in Russia (Swann)

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.

Talk 11: Modal Rotor Dynamics and State Space Representation of Rotor/AMB System (Dimond)

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.

Talk 12: Gas Cooled Nuclear Power Plant Case Study (Swann)

New applications of magnetic bearings to large gas cooled nuclear power plants in China and other countries are under development. This talk presents several examples of the machinery using magnetic bearings in these applications.

Lunch

Advanced Magnetic Bearing Short Course
April 22-25, 2014

Session 4 - Industrial Application of Magnetic Bearings II
(Day 2: Afternoon – Wednesday, April 23, 2014)

Talk 13: Trends in Upstream Oil and Gas Applications with Magnetic Bearings (Swann)

Magnetic bearings are increasingly employed in the oil and gas industry, including in the upstream segment for rotating machinery. This talk presents some industrial applications of magnetic bearings in this area.

Talk 14: Magnetic Bearing Technology New Developments Including Auto Tuning (Swann)

Active magnetic bearing technology continues to advance with new developments such as advanced control, remote monitoring, and auto tuning. This talk outlines some of these major advances now in industrial applications or coming in the near future.

Talk 15. 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 as well as the new API standards for auxiliary bearings and their performance.

Talk 16: Third Generation AMB Technology and Development of AMB (Swann)

The first generation of magnetic bearings employed analog amplifiers and controls. The second generation used digital amplifiers and digital controls to improve system accuracy and reliability a great deal. Now, the third generation of active magnetic bearing systems is taking advantage of many advanced features of more highly adaptable and reliable technology that are illustrated in this talk.

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Session 5 – Magnetic Bearing Characteristics, Modern Control Plus Energy Storage Flywheel
(Day 3: Morning – Thursday, April, 24, 2014)

Talk 17: Control and Sensitivity Functions for Magnetic Bearings (Allaire)

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 API/ISO specifications.

Talk 18: Modern Control of Flexible Rotor on Magnetic Bearings (Allaire)

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.

Talk 19: 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.

Talk 20: Design and Characterization of Flexible Rotor on Active Magnetic Bearings (Allaire)

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.

Lunch

Session 6 – Auxiliary Bearings, Rotor Drop Analysis, Artificial Heart Pump
(Day 3: Afternoon – Thursday, April 24, 2014)

Talk 21: Auxiliary Bearings for Rotor Drop in Magnetic Bearing Systems (Dimond)

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 22: Rotor Drop Analysis of Axial and Horizontal Rotor/AMB Systems (Dimond)

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. A specific compressor application is presented.

Talk 23: Rotor Drop Analysis on Auxiliary Bearings in AMB Test Rig (Dimond)

This talk presents the rotor drop analysis of an rotor/AMB system both with and without fluid film bearing. Nonlinear transient analysis was carried out to determine if damage to the auxiliary bearings might occur.

Talk 24: 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.

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Session 7 – Modern Control Applications
(Day 4: Morning – Friday, April 25, 2014)

Talk 25: Comparison of Advance Control Methods for Flexible Rotors (Dimond)

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.

Advanced Magnetic Bearing Short Course
April 22-25, 2014

Talk 26: Advanced Control of Flexible Rotor with Aerodynamic Cross Coupled Stiffness Effects and Uncertainty (Allaire)

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 Talks 20 and 25. Sensitivity and complimentary sensitivity functions are evaluated for the system and predicted performance results were experimentally evaluated via the test rig.

Talk 27: Surge Control with Magnetic Bearings in Centrifugal Compressors (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 paper 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.

End of Short Course – 11:30 am

Advanced Magnetic Bearing Short Course
April 22-25, 2014

Registration and Fees

Advanced registration for the short course should be sent to:

Dr. Tim Dimond
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3277 Arbor Trace
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+1-434-632-8469
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Additional information is available at:
www.rotorsolution.com

The fee for the course is $2,700 with advanced registration or $2,900 on site. There is a 2.5% discount for payment by cash, check, or purchase order.

Advance registration may be made via check or purchase order. Credit card payments are also available at www.rotorsolution.com

Lecture Materials

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.

Conference Hotel

The hotel will be the Crown Plaza Houston Northwest – Brookhollow. The lectures will be held in a conference room and guest rooms reserved in the same hotel. Coffee breaks and lunches will be provided. The attendees are responsible for registering at the hotel on their own. Detailed information about the hotel and room reservation information will be available soon on the RBSI website.

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