Lecture 20

Case Study –
Designing Magnetic Bearings

Outline

• Designing Magnetic Bearings in Rotating Machinery Analysis, Inc.
• SKF Magnetic Bearings
Designing Magnetic Bearings

- Magnetic bearings are used to levitate flywheels so they can spin at high speeds without mechanical contact.
- The design of a bearing set to control a flywheel weighing 5100 lbs and spinning at 15,000 revolutions per minute was described in the paper, “Permanent Magnet Bias, Homopolar Magnetic Bearings for a 130 kW-hr Composite Flywheel,” by B. Murphy, H. Ouroua, M. Caprio, and J. Herbst.
- The paper was presented at the Ninth International Symposium on Magnetic Bearings. Among the interesting results presented include the connection among the hysteresis in the lamination material used in the bearings, torque on the rotor, and losses in the operation as well as the division of the vertical thrusts between elastomeric mechanical mounts and a magnetic thrust bearing.

http://www.utexas.edu/research/cem/archive_J_A_S_04.html
Testing Magnetic Bearings for Mobile Applications

• Magnetic bearings used on flywheels in transportation systems must react appropriately to levels of shock and vibration that are not usually present in other flywheel applications.

• Tests at the University of Texas at Austin have been conducted that provide information about safe design of such systems. The work was summarized in the paper, “Spin Commissioning and Drop Tests of a 130 kW-hr Composite Flywheel,” by M. Caprio, B. Murphy, and J. Herbst that was presented at the Ninth International Symposium on Magnetic Bearings in August.

Testing Magnetic Bearings for Mobile Applications

• A key technical finding is that steps must be taken to manage forward whirl if a high-speed rotor suddenly impacts on a backup bearing. High-speed flywheels are typically levitated on magnetic bearings to minimize loss. High-speed mechanical bearings (backup bearings), of slightly larger radius than the magnetic bearings, are used to provide a way to safely coast to a stop if a magnetic bearing fails.

• This work shows an approach to eliminate the potentially serious forward whirl, i.e. the precession of the rotor around the outside of the mechanical bearing in the same direction as the flywheel is spinning around its axis, that can occur if a spinning rotor engages the backup bearing.
Energy Storage Flywheel

Flywheel Batteries
The magnetic bearings are homopolar, permanent magnet bias bearings. The combo bearing in Figure is a three-axis combination radial/thrust bearing. This design uses a single radially polarized permanent magnet ring to provide bias flux for both the radial and axial flux paths. Three separate pairs of control coils allow individual control of each axis.

The radial bearing (Brg 2) is a two-axis radial bearing. The basic operation and Adams, 1997), (Tsotras and Knospe, 1997). of this bearing was described by Meeks (1990). Some characteristics of the magnetic bearings are given in Table 1.
# CEM-UT Flywheel

## Table 1. Magnetic Bearing Characteristics.

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Combo Bearing (Radial)</th>
<th>Radial Bearing</th>
<th>Combo Bearing (Axial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Reference Name</td>
<td>Brg 1</td>
<td>Brg 2</td>
<td>Thrust</td>
</tr>
<tr>
<td>Channel Names</td>
<td>1, 2</td>
<td>3, 4</td>
<td>5</td>
</tr>
<tr>
<td>Coordinate Names</td>
<td>(x_1, y_1)</td>
<td>(x_2, y_2)</td>
<td>(z)</td>
</tr>
<tr>
<td>Peak Load Capacity, N (lbf)</td>
<td>1115 (250)</td>
<td>670 (150)</td>
<td>2230 (500)</td>
</tr>
<tr>
<td>Force Constant, N/A (lbf/A)</td>
<td>156 (35)</td>
<td>94 (21)</td>
<td>303 (68)</td>
</tr>
<tr>
<td>Negative Stiffness, N/mm (lbf/in)</td>
<td>1751 (10,000)</td>
<td>963 (5500)</td>
<td>3502 (20,000)</td>
</tr>
<tr>
<td>Air Gap, mm (in)</td>
<td>0.508 (.020)</td>
<td>0.508 (.020)</td>
<td>0.508 (.020)</td>
</tr>
<tr>
<td>Backup Brg Clearance, mm (in)</td>
<td>0.254 (.010)</td>
<td>0.254 (.010)</td>
<td>0.254 (.010)</td>
</tr>
</tbody>
</table>

## Nominal Duty Cycle For Space Station Flywheel Battery

*Turnaround Efficiency = 93.7%*
## Comparison of Lead-Acid Batteries, Flywheel Batteries, and SMES

<table>
<thead>
<tr>
<th></th>
<th>Lead-Acid Battery</th>
<th>Flywheel Battery</th>
<th>SMES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Storage mechanism</strong></td>
<td>Chemical</td>
<td>Mechanical</td>
<td>Electrical</td>
</tr>
<tr>
<td><strong>Life (years in service)</strong></td>
<td>3 – 5</td>
<td>&gt;20</td>
<td>~20</td>
</tr>
<tr>
<td><strong>Technology</strong></td>
<td>Proven</td>
<td>Promising</td>
<td>Promising</td>
</tr>
<tr>
<td><strong>Number of Manufacturers</strong></td>
<td>~ 700</td>
<td>~ 5</td>
<td>~1</td>
</tr>
<tr>
<td><strong>Annual Sales ($ in millions)</strong></td>
<td>~ 7000</td>
<td>~ 2</td>
<td>A few</td>
</tr>
<tr>
<td><strong>Temperature Range</strong></td>
<td>Limited</td>
<td>Broader, but still limited</td>
<td>Controlled</td>
</tr>
<tr>
<td><strong>Environmental concerns</strong></td>
<td>Disposal issues</td>
<td>Small</td>
<td>Small</td>
</tr>
<tr>
<td><strong>Relative size</strong></td>
<td>Larger</td>
<td>Smallest</td>
<td>Smaller</td>
</tr>
<tr>
<td><strong>Maximum time to hold a charge</strong></td>
<td>Years</td>
<td>Hours</td>
<td>Days</td>
</tr>
<tr>
<td><strong>Price ($/kW)</strong></td>
<td>50 – 100</td>
<td>300 – 400</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

### Research Needs for Flywheel Batteries

- **Flywheel Materials**
- **Magnetic bearings**
- **Power conditioning**
Advanced Reading Papers


SKF Magnetic Bearings


http://www.skf.com/portal/skf_rev/home/technology?contentId=079613&lang=en#
Applications - Compressors

- Compressors
  - Description of magnetic bearings operating in various turbo compressor applications.
  - SKF magnetic bearings are ideal for many types of industrial turbo compressors in a variety of compressed gas applications. Magnetic bearings are particularly suited for the natural gas, hydrogen, refrigeration and air process applications.
Applications - Compressors

• Key Benefits and Advantages:
  ➢ Environmentally friendly solutions
  ➢ Oil free operation
  ➢ Eliminates process contamination
  ➢ Simple compact systems
  ➢ Reduced footprint
  ➢ Increased reliability and availability
  ➢ Reduced energy consumption
  ➢ Reduced maintenance and spare parts
  ➢ Reduced life cycle cost
  ➢ Minimized housing vibration
  ➢ Advanced condition monitoring
  ➢ Remote monitoring
  ➢ No minimum speed requirement

Natural Gas Compressor

This centrifugal compressor is designed for natural gas pipeline applications. This unit is designed to run at 11,429 RPM moving 21.3 x 106 m³ per day (755 MMSCFD) of natural gas.
Natural Gas Compressor

• Key benefits from applying SKF's magnetic bearing solution
  
  ➢ *Reduced space required for installation because the need for a bearing lube oil system is eliminated. This is especially beneficial if it is combined with a gearless electric motor drive also running on magnetic bearings.*
  
  ➢ *Reduced long term costs for maintenance and spare parts.*
  
  ➢ *Reduced bearing-related losses.*
  
  ➢ *Increased reliability and availability.*
  
  ➢ *Improved machine monitoring capabilities.*

Refrigeration Compressor

• This is an hermetic, oil-free compressor for refrigeration and chiller applications using new CFC-free refrigerants.

• Oil-free operation is essential to maintain high cycle efficiency with this new class of refrigerants. In addition, there is no oil in the system to decrease the heat transfer efficiency of heat exchangers. Magnetic bearings were chosen as an enabling technology.
Hydrogen Compressor

- The VH106 is a beam-type multi stage compressor for hydrogen service in process industries.
- Implementation of magnetic bearings in this product, coupled with the existing dry gas seal system, offers a completely oil-free compressor. This unit is designed to run at 12,054 rpm.
Hydrogen Compressor

- Benefits of the magnetic bearings:
  - Increased reliability and availability.
  - Reduced space required for installation because the bearing lube oil system is eliminated.
  - Reduced long term costs for maintenance and spare parts.
  - Improved efficiency through reduced bearing-related losses.
Hydrogen Circulator

- This cryogenic pump circulates supercritical hydrogen in a hermetic design to eliminate shaft seals and fluid leakage. Magnetic bearings enable this cryogenic circulator to operate at high speed and with a wide operating range to maintain hydrogen at a supercritical phase.
- SKF Magnetic Bearings has provided an optimized rotordynamic shaft design that has allowed a long extension shaft for the impeller.
- Magnetic bearings deliver the reliability demanded by critical cold neutron source facilities such as Oak Ridge National Laboratory and The Spallation Neutron Source (SNS).
Applications - Distributed Power Generation

- Distributed Power Generation
  - Description of magnetic bearings in the distributed power generation industry
  - The world's increasing demand for affordable, high quality energy is pushing distributed generation products to new standards in overall performance, reliability, robustness and ease of operation. SKF magnetic bearings are ideally suited to meet and exceed the challenges set forth by these new power generating products.
High Speed Generator

- This generator is designed for direct coupling to an industrial gas turbine for the distributed power generation market. Implementation of magnetic bearings in this machine provides end user/operators of power generating equipment with a highly reliable, low maintenance, compact solution. The generator outputs 1.2 MW of electric power, operates at 20,000 rpm, is self cooled, weighs 350 kgs and the size is only 1010 mm x 570 mm.

1.2 MW generator

Magnetic bearing cartridge
High Speed Generator

• Magnetic bearing solution provides:
  ➢ High reliability
  ➢ Cost effective design with simple compact bearings
  ➢ Improved rotor dynamics as a result of the compact bearing design
  ➢ Oil free operation
  ➢ Vibration free operation
  ➢ Advanced condition monitoring capability
  ➢ Full integration into customers packaged control and monitoring systems
  ➢ The lowest life cycle costs

Applications - Vacuum Equipment

• Vacuum Equipment
  ➢ Description of vacuum equipment operating on magnetic bearings
  ➢ SKF Magnetic Bearings has the solutions for rotating equipment operating in vacuum ranging from high vacuum environments up to atmospheric pressure. Industrial equipment applied to processes that are under vacuum must meet high operating standards for contamination, outgassing, and heat generation.
  ➢ Hydrocarbon lubricants are particularly undesirable. Vacuum equipment is found across a wide range of industrial applications such as biotechnology processes, analytical equipment and blowers for gas lasers. In addition to being lubrication free, magnetic bearings and motors may be canned to bring outgassing to a minimum.
Applications - Vacuum Equipment

• Key Benefits and Advantages:
  - Lubrication free operation
  - Increased reliability and availability
  - Contamination free
  - Non-contacting rotation eliminates wear particles
  - Reduced life cycle cost
  - Minimized vibration levels
  - Extremely low loss bearing design for operation in vacuum environment

Vacuum Blower

Magnetic bearings enable the pump to operate with high reliability and efficiency at high speed in a salt water and vacuum environment.
TMP - Turbo Molecular Pump

• Turbo molecular pumps are used in semiconductor processing. High and ultrahigh vacuum levels are required in processes such as ion implantation, coating, etching, evaporation, CVD/LPCVD, RTP, microlithography, and load lock chambers.

• In analytical instrumentation, turbo molecular pumps are used in mass spectrometers, gas analyzers and electron microscopes. In materials research, turbo molecular pumps are used in neutron scattering facilities, proton accelerators and supercolliders.

• Magnetic bearings are used to provide reliable high speed operation without any lubrication. The lack of contact and absence of volatile lubricant ensures that no wafer damaging particles are generated.
Hyperspin Spindles

- Hyperspin is a spindle range that includes magnetic bearings, motor (synchronous or asynchronous), housings, controller and cabling. Hyperspin is available in speeds up to 60,000 rpm and power rating from 0.3 to 55 kW.
- The shaft has a versatile interface for mounting different types of payload. Shaft extensions can be customized to suit each application's payload requirements whether it's a turbopump impeller or a unique neutron absorbing disk.

Canned Motor

- This motor, designed to operate in an environment of highly corrosive gases, delivers 4.5 kW of power at 5000 rpm.
- SKF's expertise in magnetic materials, motor design software, and magnetic FEA have allowed us to create this motor. It features both a canned rotor and stator, a very high power density, and yet is over 90% efficient and operates at less than 60°C.
- To prevent the release of harmful gases and ensure safe operation the motor has a secondary containment system that is equipped with a pressure switch to detect any leaks.
- This motor is a sensorless design to increase reliability, decrease cost and reduce cable size.
Canned Motor

• Motor Specifications
  ➢ 4.5 kW at 5000 rpm
  ➢ Primary containment pressure rated from 1 Torr to 5.5MPa (800 psig)
  ➢ Input 200-240 V, 3 phase, 50/60 Hz, 31 Arms
  ➢ Stator and Rotor canned with Monel 400
  ➢ Winding temperature class H (180 °C)

Canned Motor

• Application Specifics
  ➢ This product was jointly developed by SKF Magnetic Bearings and Cymer, Inc. (with offices in San Diego, California) for use in fluorine containing gas discharge lasers produced by Cymer. SKF Magnetic Bearings is licensed by Cymer to manufacture and sell the motor for markets other than the electric discharge laser market.
  ➢ This design is suitable for any toxic process, or where contamination of the process is not tolerated.
Applications - Test Stands

- Test Stands
  - Description of how magnetic bearings are used in test stands.
  - SKF’s magnetic bearings are ideal for many types of research and test applications to assist in the design of turbomachinery, enhance manufacturing processes and assist in the development of advanced control and monitoring systems.
  - SKF has a broad range of experience in applying magnetic bearing technology to enhance research and development of the next generation of machines for Industrial applications. As a result it can assist in the design of your test stand to maximize the benefits of your research.
  - Advanced rotordynamic modeling and simulation can greatly improve your chances of achieving your test stand goals.
Applications - Test Stands

• Key Benefits & Advantages:
  ➢ Direct force measurement
  ➢ Shaft motion control
  ➢ Force input control
  ➢ Vibration control
  ➢ Advanced condition monitoring
  ➢ Reduced energy consumption

• Test Stands
  ➢ Pump Test Stand
  ➢ Rotordynamics Test Stands
  ➢ Milling spindle Test Stand - Boeing
  ➢ Turbo Compressor Test Stand
Force Measurement

- Test rigs often utilize magnetic bearings to assist in the design of turbomachinery.
- In an example application, the magnetic bearing system levitates the shaft and measures the magnetic forces induced by a pump impeller mounted to the test rig. Three types of forces are measured: steady state loads from rotor weight, dynamic loads from blade pass frequencies, and forces caused by turbulent flow.
- Magnetic bearings can continuously monitor force by measuring the position of the shaft, and the current in the actuator coils.
- SKF's Magnetic Bearing control system and software allow analog signals to be injected to create specific force inputs and/or shaft motion. This capability has lead to increased understanding of pump impeller performance under controlled operating conditions.
Spindle Test Stand

• Global competition in the commercial aircraft industry has pushed the demands for metal removal rates and parts yield to higher and higher level. Machine tool spindle manufacturers have met this demand offering continually higher speed and power spindles.
• The productivity gain inherent in the new generation spindles has not been realized due to performance and reliability problems. In response to these issues, SKF has developed a magnetic bearing based spindle test stand that can simulate cutting conditions to fully test a spindle prior to implementation in production operations.

Spindle Test Stand

• Key Capabilities
  ➢ Simulate cutting forces up to 2 kN and 1.25 kHz
  ➢ Apply torsional loads up to the spindle torque rating
  ➢ 40 high speed data acquisition channels at 50kHz sampling rate
  ➢ 60 low speed data acquisition channels at 100kHz sampling rate
  ➢ Real time viewing of data
  ➢ Spindle control and test sequencing
  ➢ Fully programmable test cycles to simulate cutting programs
  ➢ Spindle endurance testing
  ➢ Measurement of spindles model frequencies
Applications - Machine Tools

• Machine Tools
  - Description of magnetic bearings in various machine tools.
  - The trend in industry toward flexible manufacturing and reduced time to market for new product, has pushed the limits of machining enters and machine tools. The trend has created new demands for finishing operations in the machining center to reduce parts handling and improve productivity.
  - In response to this demand, SKF has developed advance high speed magnetic bearings machine tool spindles for grinding and finish machining operations.

Applications - Machine Tools

• Key benefits and advantages
  - Monitor cutting forces
  - Compensate for tool deflection
  - Monitor tool wear during cutting operations
  - Detect tool breakage even with very small tools
  - Inherent crash detection
  - No bearing wear
  - Stable modul characteristics throughout the life of the spindle
  - Reduced maintenance
  - Oil free operation
  - Longer spindle life
100,000 rpm Milling Spindle

- 100,000 rpm machine tool spindle for high speed three axis machining center. This spindle is a prototype demonstration.
- Magnetic bearings were necessary to achieve the extremely high speed. However, the primary concern is consistent, high quality surface finish.
- Magnetic bearings will allow a much longer service interval than the rolling element bearings normally used.
Grinding Spindle

- This high speed motorized spindle is designed for operation in a computer controlled grinder used in rolling bearing production.
- Magnetic bearings give this spindle a much wider operating range, allowing one spindle to be used where two conventional spindles are used. This improves productivity by reducing resetting time.
- It is hoped that the magnetic bearings can be used to actively improve grinding performance using process feedback concepts.
High Speed Milling Spindle

• This prototype spindle was constructed for use in a high speed machining center.
• Although not yet in production, the spindle demonstrates many benefits of magnetic bearings in this application.
• Magnetic bearings allow a high speed, high power spindle to deliver consistent performance. Performance is not affected by thermal issues or by wear.
• Service intervals are greatly increased over conventional bearings.
• The magnetic bearings automatically detect overload situations and instantly shut down the machining operation.
Applications - Neutron Choppers

• Neutron Choppers
  - Description of neutron choppers where SKF's magnetic bearings have been applied
  - SKF magnetic bearings are ideal for all types of neutron choppers (E0, T0, single or multi-disk bandwidth). Magnetic bearings enable neutron choppers to operate maintenance free with extremely high reliability and without hydrocarbon contamination in a vacuum environment.
  - SKF’s digital magnetic bearing/motor control system not only levitates the shaft but also locks phase with the reference timing signal. This provides phase control of the slit package or disk assembly to ±0.25 ms at 600 Hz (i.e. within 0.05 degrees of alignment with minimum 99% repeatability). The SKF control system provides the best timing performance and operation in neutron scattering spectroscopy.

• Key Benefits and Solutions:
  - Non-contacting rotation eliminates wear - extremely high bearing reliability
  - Minimal housing vibration regardless of shaft balance (< 0.1 microns)
  - 60 Hz to 600 Hz operation with sub-synchronous phase locking (1/2, 1/3, 1/4, 1/5, 1/6, 1/10)
  - DC brushless motor
  - Extremely low loss bearing design for operation in vacuum environment
  - No water cooling for low speed operation
  - Gamma radiation compatible to 3.5x10^6 rads
  - Commercially available
Fermi Chopper

- The United States National Laboratories are leaders in using neutron scattering to unlock the secrets of superconductors, magnetic materials, advanced polymers, and other materials of crucial interest to industry.
- Neutron choppers are used to create homogeneous beams of neutrons of specific energy in a neutron spectroscope.
- Magnetic bearings enable the neutron chopper to operate with high reliability and efficiency at high speed in a vacuum environment.
AVCON Magnetic Bearing

• Magnetic bearing in Space Shuttle Main Engine turbopump


AVCON Magnetic Bearing

• Among other advantages cited are virtually zero friction and therefore no lubricant requirement; no wear, no vibration; longer service life; and very high reliability because single point failure modes are eliminated.