Magnetic Bearings

• It was first proven mathematically in the late 1800s by Earnshaw that using only a magnet to try and support an object represented an unstable equilibrium; however, it was found in the 1930s that by using an electromagnet and measuring the air gap and using it as a feedback parameter, the system could be stabilized.

• Although it is beyond the scope of this book to discuss how magnetic bearings are designed, an attempt will be made to introduce the reader to some of the characteristics of magnetic bearing-supported systems.

• Magnetic bearings will most likely become more commonplace in the machine design engineer's world as the quest begins for machines with nanometer accuracy to manufacture next generation microelectronic and optical components.
Magnetic Bearing

- Magnetic bearings support moving machinery without physical contact, for example, they can levitate a rotating shaft and permit relative motion without friction or wear.
- Long considered a promising advancement, they are now moving beyond promise into actual service in such industrial applications as electric power generation, petroleum refining, machine tool operation and natural gas pipelines.

Basic Operating Principles

- Magnetic bearings are most often used to support radial and thrust loads in rotating machinery.
- Common design configurations are shown in Figure 9.4.1. The coils in magnetic bearings have virtually infinite life, but the control system can be affected by power outages or component failure; thus auxiliary rolling element bearings must be incorporated into the design as shown in Figure 9.4.2.
- The rolling element bearings operate at half the magnetic bearing air gap.
Basic Operating Principles

• Magnetic bearings provide attractive electromagnetic suspension by application of electric current to ferromagnetic materials used in both the stationary and rotating parts (the stator and rotor, respectively) of the magnetic bearing. This creates a flux path that includes both parts, and the air gap separating them, through which non-contact operation is made possible.

• As the air gap between these two parts decreases, the attractive forces increase, therefore, electromagnets are inherently unstable. A control system is needed to regulate the current and provide stability of the forces, and therefore, position of the rotor.
Basic Operating Principles

- The control process begins by measurement of the rotor position with a position sensor. The signal from this device is received by the control electronics, which compares it to the desired position, input during machine start-up. Any difference between these two signals results in calculation of the force necessary to pull the rotor back to the desired position. This is translated into a command to the power amplifier connected to the magnetic bearing stator. The current is increased, causing an increase in magnetic flux, an increase in the forces between the rotating and stationary components, and finally, movement of the rotor toward the stator along the axis of control.
- The entire process is repeated thousands of times per second, enabling precise control of machinery rotating at speeds in excess of 100,000 rpm.

Figure 9.4.2 Conceptual design of a magnetic bearing spindle.
Basic Operating Principles

- Magnetic bearings can also be used to support linear motion devices.
- A planer version of the horseshoe-shaped magnets often used to support rotating shafts can be used, but this causes vertical motion control to be coupled with angular motion control.
- An alternative is to use a number of round bearings, similar to those used to resist shaft thrust loads and shown in Figure 9.4.3, in a kinematic configuration. This particular bearing has a bias force of about 30 N supplied by the permanent magnet and a control force of about 15 N supplied by the coil. It is discussed further in Section 9.4.2.

Figure 9.4.3 Magnetic bearing design used in a kinematic arrangement of magnetic bearing for supporting a precision linear motion.
Basic Operating Principles

• Regardless of the type of load supported, magnetic bearings require a closed-loop control system for stability, as shown schematically in Figure 9.4.4.

• Typically, an analog control loop is used for coarse position control and a digital loop is superimposed on it for fine motion control and compensation for analog component drift.
  - Analog control system: an analog sensor
  - Digital control system: a laser interferometer

Block Diagram
Basic Operating Principles

- Some magnetic bearings use a permanent magnet to provide a bias force. The magnetic flux produced by the permanent magnet acts only to levitate a portion of the object's weight in order to minimize the power expended by the active coil. The control force exerted on the object is thus proportional to the current supplied to the coil.
- The attraction force between the bearing and the object is produced when energy stored in the magnetic field and in the air gap is transformed into mechanical work.
General Properties

• Speed and Acceleration Limits
  ➢ Magnetic bearings do not limit the speed or acceleration of components they support. Systems of 100,000 rpm and higher have been built for applications ranging from special pumps to spindles for ultrahigh-speed machining.

• Range of Motion
  ➢ Linear motion magnetic bearings can be used to support a carriage that moves linearly. In general, if the coils are stationary, then range of motion will be limited by the variation in force produced as the center of gravity moves with respect to the coils. Magnetically levitated trains have been proposed that use a whole series of coils that are energized as the train passes by them; however, the economics of such a design have yet to be proven. Other designs transfer power to coils on the train via a live rail. Perhaps high-temperature superconducting materials would help make magnetically levitated trains an economical reality. Rotary motion magnetic bearing-supported systems are more common in industrial environments and are not motion limited.

General Properties

• Applied Loads
  ➢ Virtually any magnitude load can be supported by a suitable magnetic bearing, depending on how much one wishes to pay and how much room one has.
  ➢ Increasing the proportion of the load that is supported by permanent magnets decreases the current that must pass through the coils and the resultant heat generated.
  ➢ The magnitude and frequency of applied disturbance forces combined with the controller bandwidth has an effect on achievable resolution as discussed below.
General Properties

• Accuracy
  
  Typically, achievable rotational accuracy is $50 \, \mu m$ and $0.1 \, \mu m$ systems have been built. Since magnetic bearings depend on a closed-loop servosystem to achieve stability, the performance of the position sensor and servocontroller will directly affect the accuracy of the system. With new high-speed digital signal processor technology and better sensors for fine-position sensing, there is no reason why nanometer and better accuracy cannot be obtained if one wanted to pay for it. Note that magnetic bearings generate a relatively large amount of heat, so thermal control plays an enhanced role in achieving accuracy with magnetic bearings.

• Repeatability
  
  Repeatability of a magnetic bearing system depends on the sensor and control system.
  
  Impedance probes are commonly used as analog position sensors, so typical repeatability is in the micron range unless precision position sensors are used.
General Properties

• Resolution

- Motion control resolution of the bearing gap is also limited by the sensor and control system. There is virtually no mechanical damping in a magnetic bearing-supported system unless the suspended object is also in contact with a viscous fluid.
- Hence disturbance forces acting on the system play an important role in determining motion control resolution of the bearing gap.
- At low frequencies, performance is determined almost completely by the ability of the controller to cancel disturbances.
- The primary control system parameter affecting disturbance cancellation is the controller gain, which determines suspension stiffness.
- The higher the suspension stiffness, the greater the ability to reject force disturbances. Depending on the nature of the source, at high frequencies, the disturbance forces are generally absorbed by the supported object's inertia and internal damping characteristics.

• Resolution

- Since there is no friction with magnetic bearings, motion resolution of an object supported by them is limited only by the actuator, sensor, and control system used.
- Magnetic bearings are efficient only in the attraction mode. In order to obtain high performance in systems with randomly oriented force components, magnetic bearings should be used in an opposed mode design.
- For precision instrument plattens, it is feasible to use gravity to preload the bearing system.
General Properties

Figure 9.4.5 Achievable suspension resolution for a 10 kg platten and bearings with 150 N force capability. (Courtesy of SatCon Technology, Inc.)

19-21

General Properties

Figure 9.4.6 Achievable suspension resolution for a 10 kg platten and bearings with 150 N force capability. (Courtesy of SatCon Technology, Inc.)

19-22
General Properties

- **Stiffness**

  ➢ *The steady-state stiffness of magnetic bearings can be essentially infinite, depending on how the closed-loop control system is designed.*

  ➢ *Magnetic bearing dynamic stiffness depends on the frequency of the applied load and the bandwidth of the control system.*

Figure 9.4.7 Slide disturbance force for a 10 kg platten and bearings with 150 N force capability. (Courtesy of SatCon Technology, Inc.)
General Properties

• Vibration and Shock Resistance

➢ There are several modes in which a magnetic bearing can be operated in order to actively.

➢ Inertial axis control. The frequency of rotation is measured, amplified, and subtracted from the control signal sent to the coils. This creates a zero stiffness condition for the bearing at the frequency of rotation. As a result, quasi-static and disturbance forces are still resisted, but the rotor is then free to spin about its inertial axis. This virtually eliminates dynamic rotor imbalance.

➢ Peak of gain. Instead of subtracting the rotational frequency component from the control signal, it can be added to achieve very high stiffness at the rotational frequency. This is in effect a feedforward control system which can greatly minimize total radial error motion for low-speed (<1000 rpm) systems.

Vibration control. A magnetic bearing's closed-loop control system can be used in conjunction with feedback from accelerometers to produce forces opposite to those created by vibration. The net effect is to cancel the vibration. Vibration can be reduced by 20 dB using this type of system.

➢ Alignment. Often just achieving proper alignment between rotating components can do wonders to minimize vibration.

➢ Dynamic balancing. Magnetic bearings can be used for in-situ dynamic balancing of components. Rotor speed, angular position, and gap displacement measurement information can be collected and used to determine how to balance the rotor.
General Properties

• Damping Capability
  ➢ A magnetic bearing's damping capability is attained from the closed-loop control system. Additional magnetic bearing modules can be added at various points along a shaft and used as vibration dampers. In this mode, the gap measurement signal is differentiated and used as a velocity feedback signal.
  ➢ There is no friction, static or dynamic, associated with magnetic bearings. However, at high speeds hydrodynamic drag may become a problem if the bearing gap is too small.

General Properties

• Thermal Performance
  ➢ Magnetic bearings can generate significant amounts of heat and therefore may require external cooling devices, such as recirculating chilled water jackets.
  ➢ For systems where the load does not vary greatly, a large percentage of the load can be supported by permanent magnets which minimize coil size and current required to levitate the load.
General Properties

• Environmental Sensitivity
  ➢ As long as the coils are protected (e.g., hermetically sealed), magnetic bearings can operate in virtually any environment. They have been used successfully in the following environments: air with temperatures ranging from -235 to \( \text{-235}^\circ \text{C}, \text{10}^{-7}\ \text{torr to 8.5 MPa}, \) water, seawater, steam, helium, hydrogen, methane, and nitrogen.
  ➢ One must ensure that in a corrosive environment the system's materials do not fail to perform their structural or sealing functions.

• Seal-ability
  ➢ In a normal environment there is really no need to seal magnetic bearings; however, it is a good idea to protect the auxiliary bearings from becoming damaged by contamination.

• Size and Configuration
  ➢ Magnetic bearings are typically 2-10 times larger than the rolling element bearings they can replace; however, in many applications, accommodating a magnetic bearing's larger size is not too much of a problem.
General Properties

• Weight

Magnetic bearings are very heavy compared to the rolling element bearings they replace. In some applications, such as precision mechanical gyroscopes, the forces encountered by the bearing are so small that the weight of the required bearing is inconsequential anyway. In large stationary industrial applications, such as pipeline compressors or print roll diamond turning machines, bearing weight is not a primary design consideration.

General Properties

• Support Equipment

Magnetic bearings require a closed-loop servo system to make them stable. The servo system must have precision displacement sensors to measure the bearing gap and amplifiers for the output signal from the controller. To increase reliability, redundant control and power supply systems are often used on critical magnetic bearing applications such as those used in pipeline compressors.
General Properties

• Maintenance Requirements
  ➢ Magnetic bearings have virtually no maintenance requirements. This makes them especially suitable for equipment that must be kept continually running, such as pipeline compressors.

• Material Compatibility
  ➢ Magnetic bearings require wound coils (typically, copper wire) for the stator, and an iron rotor or iron rotor laminations (to minimize eddy current losses). It is possible to hermetically seal the copper windings in a can to protect them from hostile environments. Similarly, it is possible to plate the iron rotor or laminations with a noncorroding material (e.g., chrome or nickel). Since magnetic bearings are noncontact devices and run dry, problems with material compatibility are usually not encountered.

General Properties

• Required Life
  ➢ Since magnetic bearings are noncontact devices, they can have essentially infinite life.

• Availability, Designability, and Manufacturability
  ➢ Magnetic bearings are generally custom designed for the application and are thus as yet not available off the shelf except for some preengineered complete spindle assemblies. There are many successful commercial applications of magnetic bearings, such as:

  Pipeline compressor:
  Speed: 5250 rpm.
  Radial load: 14 kN.
  Axial load: 50 kN.
  Environment: Rough industrial.
  Advantages: Drive power reduced from 26 kW to 3.4 kW.

  Print roller diamond turning machine:
  Speed: 0-1500 rpm.
  Radial load: 18 kN.
  Environment: Machine shop.
  Advantages: High rotational accuracy (better than 1 μm) independent of load.

  Turbomolecular vacuum pump:
  Speed: 0-30000 rpm.
  Radial load: 75 kN.
  Environment: Room temperature high vacuum.
  Advantages: Reduced pump size by allowing higher speeds.
General Properties

• Cost

  Magnetic bearings are probably the most expensive type of bearing one can use; however, for the problems they solve, effective system cost can be low compared to design solutions that use other bearings.

Magnetic Bearing Technology

• Magnetic bearing systems incorporate 3 distinct technologies:
  - Bearings & sensors are the electromechanical hardware by which input signals are collected, and supporting forces applied to the machine on which they are installed.
  - The control system provides the power and control electronics for signal conditioning, calculation of correcting forces, and resultant commands to the power amplifiers for each axis of control.
  - Control algorithms are the software programs used in digital magnetic bearing system control including the processing of the input signals after conditioning, and calculation of the command signals to the power amplifiers.