Advances in Magnetic Bearings

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Introduction

Active magnetic bearings are replacing oil-lubricated bearings in many applications. The benefits of using magnetic bearings in rotating machinery include higher reliability with little or no maintenance, reduced frictional losses, no contaminating or flammable lubricants, reduced machine vibration, and improved health monitoring and diagnostics. However, despite these advantages, the application of magnetic bearings has been limited in the past by the large size of the magnetic bearings, the complexity of integrating the magnetic bearings into the machine, the need for a large external control system, and the high cost. Recent advances in magnetic bearing technology, including miniaturization, simplicity and integration have overcome many of these limitations. As a result, magnetic bearings are replacing oil-lubricated bearings for many new types of machines in a variety of industries.

How a Magnetic Bearing Operates

The basic layout of a magnetic bearing system is shown in Figure 1. Stationary electromagnets are positioned around the rotating assembly of a machine. Typically, two radial magnetic bearings are used to support and position the shaft in the lateral (radial) directions and one thrust bearing is used to support and position the shaft along the longitudinal (axial) direction. A shaft that is completely supported by magnetic bearings is said to provide support along five axes because the bearings react to motion along the three translational axes and two angular axes. Ideally, the magnetic bearing offers little frictional resistance to motion along the rotational axis.

An active magnetic bearing consists of a stator, which contains the electromagnets and the position sensors, and the rotor, which rotates with the shaft. When the magnetic bearing is operating, each magnetic bearing rotor is ideally centered in the corresponding stator so that contact does not occur. The position of the shaft is controlled using a closed-loop feedback system. The position sensors detect the local displacements from the shaft, and these signals are sent to a digital controller. The controller processes these signals, and calculates how to re-distribute the currents in the electromagnets to restore the shaft to its centered position. Power amplifiers in the controller then readjust the currents in the electromagnets according to these calculations. This cycle is repeated approximately 15,000 times per second.

Like other kinds of bearings, the magnetic bearing provides stiffness and damping. However, unlike other bearings, the stiffness and damping vary as a function of disturbance frequency. It is often convenient to describe the bearing as a transfer function with an amplitude and phase that vary with frequency. The optimization of this transfer function is a critical step in ensuring that the

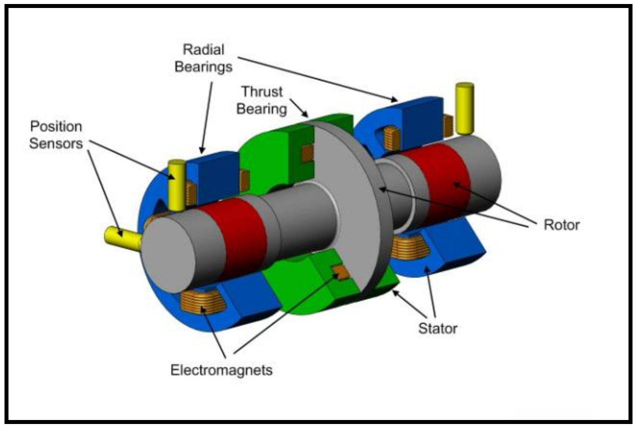

Figure 1: Basic Layout of Magnetic Bearing System

magnetic bearing performance has adequate stability and force rejection capability over a range of frequencies. The stiffness and damping can be optimized by simply changing the control algorithm.

Reducing the size of the magnetic bearing

The load capacity of a radial bearing is the product of the rotor diameter, the active length, and the equivalent bearing pressure. Because the bearing pressure of a magnetic bearing is many times less than the bearing pressure of alternatives such as oil-lubricated fluid film bearings, the size will in general be greater for the same load capacity. Also, the end windings and position sensors increase the length of the magnetic bearing beyond the active length.

Through recent design innovations, the size of radial magnetic bearings has been reduced by more than 30 percent. The bearing pressure for radial bearings has been improved by increasing the amount of electrical steel at the bore of the stator where the force is created. At the same time, the outer diameter of the stator has been reduced by splitting the flux paths and isolating the electromagnets. Finally, the length of the radial magnetic bearing has been reduced by developing position sensors that can be integrated into the electromagnets.

Reducing the size of the controller

The controller consists of sensor conditioning electronics, analog-to-digital (A/D) converters, digital processors, digital-to-analog (D/A) converters, power amplifiers and a communications interface. Design innovations have systematically miniaturized or eliminated each of these components.

By employing frequency-modulated (FM) sensing techniques, the size of the sensor electronics has been reduced and the signal-to-noise ratio greatly increased. FM sensing also eliminates the need for the sensor A/D converters. Instead, the position signal is converted using high speed digital counters.

The digital processing system is also reduced in size and the performance is increased by using an integrated architecture that handles network communications, performs the digital processing, and generates the timing signals to switch the transistors in the power amplifiers. This also eliminates the need for D/A converters between the processor and the amplifiers. Finally, the size of the power amplifiers has been reduced though new control algorithms that make it possible to achieve stable performance of the magnetic bearing while reducing the required volt-amp rating of the amplifiers.

These innovations have dramatically reduced the size of the controller, once as bulky as a household refrigerator, to little more than the size of a DVD player. The size reduction also means that the controller can be integrated into or mounted on the rotating machine, thereby eliminating the need for a separate enclosure and controller. Carrying this miniaturization and integration one step further, it is now possible to buy magnetic bearings with the controller completely integrated into the bearing, totally eliminating the need for a separate controller of any kind.

Reducing the complexity of the system

In the past, engineers encountering a magnetic bearing system for the first time were often shocked by the quantity and complexity of the cables and connectors. For a five axis suspension, the electromagnets require two wires for each coil and two coils per axis for a total of 20 wires. The sensors also typically require between three and four wires per axis which adds another 15 or 20 wires.

Temperature probes also require additional wires. These wires must be routed through the machine and exit. If the bearings are in the process gas or fluid, a hermetic feedthrough must be used for the wires. The wires are then routed up to 300 feet to remote control rooms where the large, magnetic bearing controller was located. The coil wires may carry large currents (20 – 50 A) and have substantial high frequency content due to the switching power amplifiers. This means the wires are large and care must be taken to properly shield them to reduce emitted electromagnetic interference (EMI). The sensor wires also have high frequency voltages, and are susceptible to noise from the coil wires and other sources.

Each electromagnet has a dedicated power amplifier in the controller, and each power amplifier is supplied with DC power. In general, the current that flows to each electromagnet is an order of magnitude greater than the current supplied to each amplifier. This is because the power supplied to the coils is reactive power, i.e., the current lags the voltage by about 90 degrees due to the inductance of the coil. The small amount of real power that is consumed is due to losses in the bearing. Because of this, ideally the power amplifiers should be located close to the coils so that the wires carrying the largest currents are as short as possible. The wires carrying the power to the amplifiers, on the other hand, can be long because the currents are fairly low, and the high frequency content is negligible.

The new, compact controllers may be integrated into the casing of the machine, mounted on the exterior of the machine, or integrated into the magnetic bearing. The controller may be supplied with between 48 VDC and 300 VDC of power from a power supply located far from the machine. Because the wires between the controller and the magnetic bearings are short, cabling and connectorization are greatly simplified, EMI is reduced and no special tuning of the sensors is required.

Improving Health Monitoring

In the past, health monitoring of a rotating machine required a dedicated vibration monitoring system. These large, expensive systems consist of proximity probes, conditioning electronics, high speed data acquisition systems, digital processors and alarming hardware.

However, a machine already equipped with a magnetic bearing system can also perform health monitoring without additional hardware investment. Inherent in the magnetic bearings are high resolution position sensors, digital processing and communications. The position sensors are located at each bearing, and can be used to determine the shaft orbits (X-Y trajectories) in the bearings without the need for additional sensor hardware.

Also, much of the processing of the vibration data can be performed in the magnetic bearing controller itself rather than a separate data acquisition system and processor. The results of these calculations can then be sent over high speed Ethernet networks. When networked to an external computer, visualization of orbits, advanced diagnostics, trending, archiving and alarming are all possible. Health monitoring is achieved by simply extending the functionality with additional computer software.

Reducing the Cost

Historically, the relatively high cost of magnetic bearings has limited the technology's application. However, through standardization, integration and manufacturing advances, the cost of magnetic bearings has declined. While the engineering effort to develop a new magnetic bearing system is often higher than past systems, once developed, the systems can be supplied to OEMs and end users at a much lower price than past systems. Also, the engineering effort to integrate the magnetic bearings into a machine is greatly reduced. The net result is that magnetic bearings have become much more economical to use in new and existing rotating machinery.

Advances in Magnetic Bearings

Examples of Magnetic Bearing Systems

The reductions in size, complexity and cost of magnetic bearings make new applications possible. Below are examples of our new spin on magnetics:

High Speed Drive Trains

Figure 2 shows a 400 kW, 20,000 rpm drive train with magnetic bearings. The drive train incorporates a high efficiency permanent magnet motor/generator. A stub shaft, extending from one end of the drive train, can be used for mounting a pump, compressor, or turbine wheel. The stub shaft can also be used to couple the drive train to another machine that is supported on its own set of bearings. The drive train was originally designed for a high speed compressor, but can be used to power a pump. It can also be used as a direct-drive (gear-less) generator by shaft mounting a turbine or coupling the drive train to a gas turbine engine.

Because of the small size of the magnetic bearing controller, it integrates into the housing of the drive train so that the only required connections to the controller are DC power and an Ethernet network cable. A separate feedthrough for the power leads to the motor/generator is provided. A separate feedthrough for the power leads to the motor/generator is shown at the top of the machine. The magnetic bearing controller can also control other aspects of the machine, such as the position of inlet guide vanes and machine protection functions. Spare I/O and processing capability is reserved for this. The built-in intelligence of the drive train often eliminates the need for an external controller.

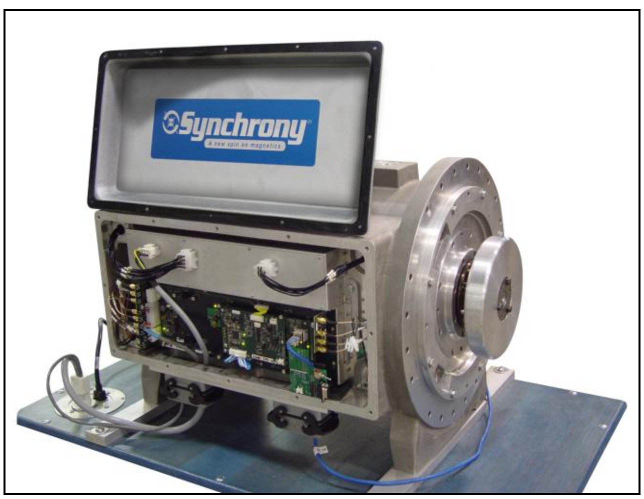

Figure 2: High speed drive train on magnetic bearings. Motor shown is 400-kW, 20,000-rpm.

Figure 3: Fusion® radial and thrust bearings with integrated control electronic.

Integrated Magnetic Bearings

Figure 3 shows Synchrony's Fusion® radial and thrust bearings in which the control electronics are completely integrated into the bearing. The radial bearing shown has a load capacity of 300 lb and the thrust bearing has a load capacity of 1000 lb. Despite the integration of the control electronics, the size of the Fusion® bearing is less than past magnetic bearings that additionally required a large, external controller.

The bearing is powered with 48 VDC power and each bearing includes a dedicated Ethernet port for high speed communications and health monitoring. The small size and simplified mechanical and electrical interface makes it very easy to integrate the Fusion® bearing into rotating machines such as motors, pumps, fans, and turbines.

Figure 4 shows a 250 hp industrial motor supported on Fusion® bearings. The integration was achieved by modifying the shaft and bearing end bells of the original motor to accommodate the Fusion® radial bearings. The motor can be supplied with a thrust bearing for those applications requiring axial force capability such as vertical motors.

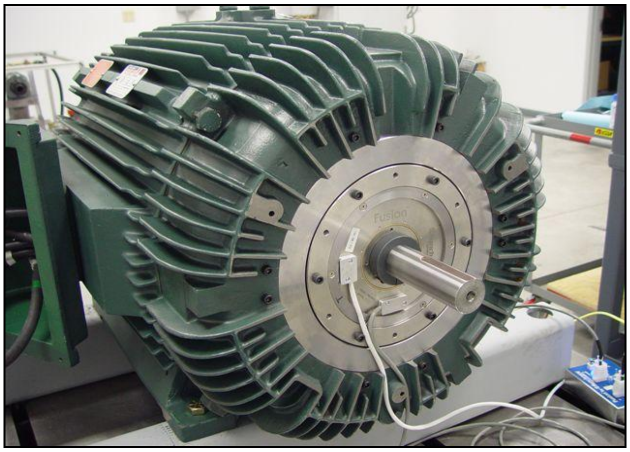

Figure 4: Industrial motor supported on Fusion® bearings.

Compact Magnetic Bearing Controller

Figure 5 presents a compact magnetic bearing controller that can be located close to or directly on a rotating machine. The controller includes all signal conditioning, digital processing, power amplification and high speed network communications. Despite its small size, each power amplifier is rated at 7500 VA. Machine mounting the controller eliminates long cable runs for the coil and sensor wires, simplifies connectors, reduces EMI and eliminates special sensor tuning.

Figure 5: Controller for Magnetic Bearings

The controller box may be purged if located in an explosive environment. The external connections to the controller include DC power cables and an Ethernet network cable. Also included in the compact controller are spare I/O and spare processing power which facilitate the industrial trend toward locally-controlled, intelligent machinery.

Conclusions

Through technical advances, magnetic bearings now offer advantages for a much broader range of machines and applications. Design innovations related to miniaturization, integration and standardization continue to increase the general acceptance of magnetic bearings for many new and existing applications—setting the standard for better, smaller and greener.

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