Moving into larger machines

MAGNETIC BEARINGS ARE A MATURE TECHNOLOGY WITH EXTENSIVE REFERENCES AND INDUSTRY STANDARDS THAT ENSURE RELIABLE OPERATION

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Over thirty years after their first commercial application, magnetic bearings are making inroads into larger and more demanding industrial machines. Product maturity has allowed the successful use of these bearings in dozens of applications where reliability, operational flexibility, availability and maintainability are important considerations. These applications now include steam turbine generators and motor compressors with rotor weights exceeding 10 tons and power ratings in excess of 20 MW. Comprehensive feasibility studies for applications to 100 MW and higher demonstrate that the trend to larger and higher-powered machinery will continue.

Figure 1: Magnetic bearings support rotors in loop-layer applications in steel mills

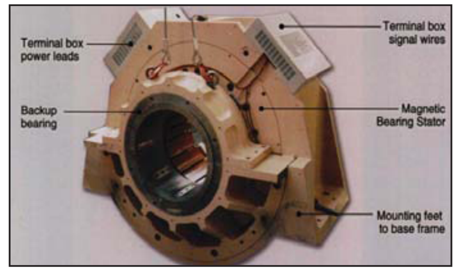

Figure 2: Magnetic bearings can be mounted on pedestals to suit machine arrangements

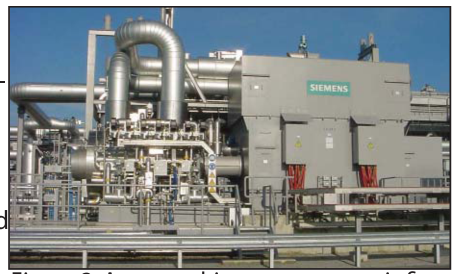

Figure 3: A motor-driven compressor is fitted with magnetic bearings in natural gas pipeline service in northern Holland. The power rating of the system is 23 MW and total rotor weight is about 11 tons

Critics notwithstanding

A good testimony to these successes is the fresh assault made on magnetic bearings by purveyors of an alternate, novel bearing technology (see p. 30). They argue that magnetic bearings are incapable of application in the real world. They charge that the magnetic bearings' low specific-load capacity results in impractical magnetic bearing sizes, leading to poor machine arrangements, low margins of safety against overloads and related rotordynamic problems. Because the magnetic bearing core material may saturate under high load, the critics contend that all load support will be lost under such conditions, resulting in machine damage.

There is no argument in the informed turbomachinery community that magnetic bearings exhibit a load-carrying capacity below that of fluid-film or rolling-element bearings. Using standard electrical steels, the specific loading that magnetic bearings are capable of is around 70 psi across the projected area of a radial bearing length and diameter, and about 60 psi for a thrust bearing across the active surface area. These figures can be nearly doubled with the use of more expensive iron cobalt alloys.

Comparing these figures to minimum fluid-film specific loadings of 200 psi - 300 psi, one can see why magnetic bearings tend to be larger in size. Further, auxiliary bearings are needed to protect the machine during trips from overloads and possible damage when load capacity is exceeded. A consequence of low specific loads is said to be poor machine arrangements and significant compromises in rotordynamic performance. Concessions to rotordynamics could have an exacerbating effect, as these critics would often have it, since the imparted loads to the bearings and demands for additional damping would only increase.

But if there was any truth to the claims of magnetic bearing critics, organizations, such as the International Standards Organization (ISO), would not be publishing worldwide standards on the application of magnetic bearings. And the technology would not be applied to industrial machinery in real-world applications, where load conditions are never completely defined and abnormal operating conditions must be accommodated to maintain acceptable operation.

Moreover, magnetic bearings are currently being applied in critical applications where the consequences of failure or unavailability not only have significant monetary operating penalties, but may also jeopardize the safety and well-being of operating personnel. For example, Waukesha has applied its technology to man-critical, defense applications with variable loads where the factor of safety relative to the static load condition on the radial bearings is almost three, and the rotor runs below its first bending mode (resonance), despite the additional space requirement of the magnetic bearings relative to alternative technologies.

Other systems that Waukesha has fielded in multiple commercial applications include motor-compressors for natural gas pipeline service with supercritical rotors — operating above critical speeds — weighing over 10 tons (Figure 3). The specifications for one project require running above, through and coincident with the first and second rotor bending modes. If magnetic bearings were as inadequate for this type of application as critics maintain, the rotor supported by magnetic bearings would be incapable of passing through critical speeds, let alone operate at a speed coincident with these natural frequencies.

Adapting to applications

To provide an appropriate, maintainable machine arrangement comparable to that used in the fluid-film bearing world, magnetic bearings for some applications are mounted on large pedestals. The individual pedestals each contain a radial magnetic bearing and its associated auxiliary bearing (Figure 2). Conventional designs use flange-mounted bearings.

A better example of the capabilities of magnetic bearings for unusual loading conditions is the Waukesha loop-layer application (Figure 1) in which careful design allows the operation of magnetic bearings at slightly less than 300 °F. Loop layers are used in steel mills to transport red hot wire from the wire mill through the middle of a rotor at 300 mph to a waiting conveyor for cooling. The loop-layer dispenses wire from the

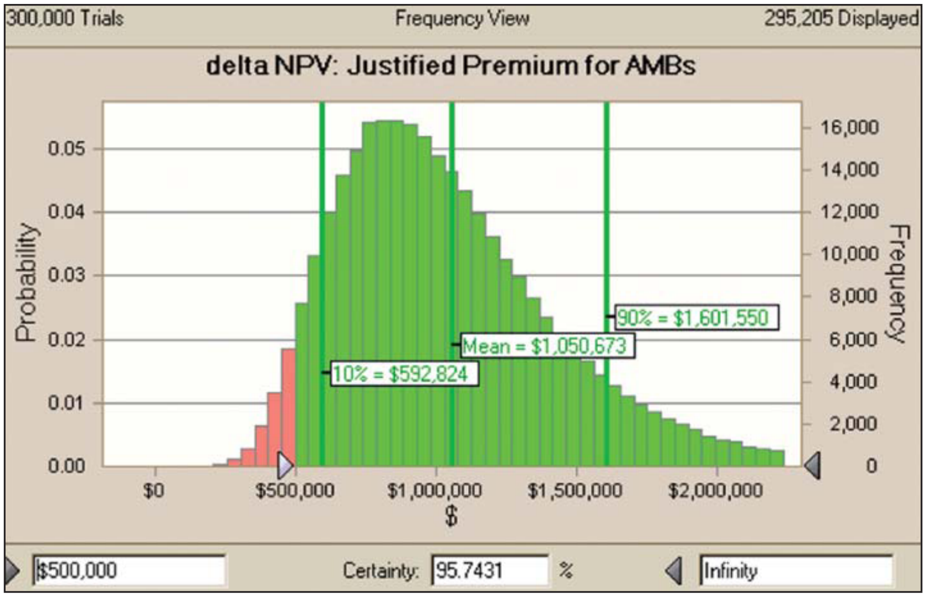

Figure 4: Net Present Value analysis of a 25 MW motor-compressor incorporating Monte Carlo simulation of future operating expenses shows that there is a 95.7% certainty that magnetic bearing systems can earn a premium of over $500,000 over tilt-pad bearings

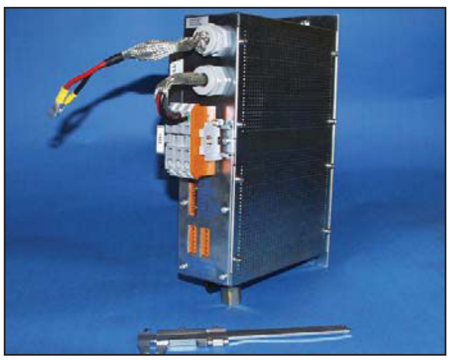

Figure 5: A new amplifier subassembly has been designed for a single bearing drive coil. Increase in power amplifier capacity has led to a six-fold increase in the load capacity of magnetic bearings since the mid 1990s

periphery of a large drum (33 inches diameter on one end and 22 on the other) to a conveyor traveling beneath it.

Rolling-element bearings are the conventional bearing solution for these machines, but they have limited life because of high circumferential speed and temperature. Not only are there large unbalance loads generated in the transverse plane that the radial bearings must accommodate because of variations in the lay and position of the rotating wire, but high dynamic thrust loading is also experienced due to the impulsive loads generated with variations in the wire speed from the mill, especially during starting and stopping.

The loop-layer example illustrates the way in which the larger size of magnetic bearings is more than compensated by its unique capabilities to address specific design and operating limitations of more conventional bearing technologies, which in this case are high speed without contact or wear in a high-temperature environment. Other applications use magnetic bearings for a myriad of different benefits including lower noise (no high-speed oil pumps) and the ability to eliminate seals and attendant emissions.

Magnetic bearings consume less power. For instance, tilt-pad bearings fitted in a 30,000 hp motor-compressor would consume 550 KW, whereas the magnetic bearing system as a whole would consume 70 KW.

Remote operability of magnetic bearings ensures that machine operators may be located miles away from the actual machines and start, run and stop the machines with minimum intervention. There is no need to pre-heat, flush or clean the oil in the lubrication system, and there is no intrinsic limit of the number and frequency of starts and stops.

The superior diagnostic information available from a magnetic bearing system comes from not only vibration data that is an essential part of the rotor feedback, but also from the bearing current that is explicitly linked to the loads that the rotor is seeing. Traditional vibration monitoring systems measure only a manifestation of the loads, while the current used to position shafts in magnetic bearings is a direct indication of the load.

Magnetic bearing applications are growing and their limits are being pushed constantly. The new ISO standards are designed to build on these successes by assuring trouble-free implementation of magnetic bearings. These standards address the problem that, according to the detractors of magnetic bearings, plagues magnetic bearing applications. The standards lay down requirements for machine clearances, vibration response, and rotordynamic stability. They implicitly consider issues of system natural frequencies, rotor mode shapes (including nodal locations) and system damping that are so important in the application of any bearing type. The ISO standards do this by drawing on actual system experience to augment the rigorous analytical treatment of rotordynamic performance.

The benefits of magnetic bearings translate into a financial case for their use. For instance, using Monte Carlo simulation of future uncertain operating expenses, Net Present Value (NPV) analyses show that the financially justifiable capital cost premium for a magnetic bearing system over a fluid-film bearing system for large machines amounts to hundreds of thousands of dollars. This is the premium a potential buyer could justify in his purchase of a magnetic bearing system over the conventional bearing solution of tilt-pad bearings with a lube oil system using the same cost of capital. At this premium the two bearing systems have the same lifecycle cost.

Future operating expenses simulated via statistical descriptions in these NPV analyses include power costs, and planned and unplanned maintenance costs that arise from random system failures that may occur throughout the life of the bearing systems. Actual magnitudes of the supported premium vary with costs due to system size, speed and power, but the premium may easily approach one million dollars or more. There is considerable upside potential and these premiums may readily support software and hardware upgrades, if necessary, to address unexpected obsolescence issues. Statistical confidence intervals have been ascribed to these results. Available operating data support the conclusions of Monte Carlo simulations.

NPV analysis for a 25 MW motor-compressor (Figure 4), where the mean value of all possible outcomes is a premium of over one million dollars, shows that there is a 95.7% certainty that the actual premium over a tilt-pad system will be at least $500,000. The upside potential extends to over two million dollars.

Enabling electronics

Advancements in magnetic bearing technology have coincided with the upsurge in the capabilities of power electronics and data processing technology. Fifteen years ago, power amplifiers were rated no more than 120 V and 60 A. Today, ratings of 600 V and 75 A for a 45 KVA are available per bearing channel. This has resulted in a six-fold increase in dynamic load capacity of magnetic bearings, which is directly proportional to amplifier KVA output (Figure 5).

In the mid-1990s, analog electronic filter networks were used to compensate the rotor feedback information for determination of amplifier commands necessary to stabilize the rotor. The facility to change the equivalent bearing characteristics of stiffness and damping was limited by the available range of discrete component values. Making changes required de-soldering and re-soldering of these discrete components in a time-consuming exercise. But today's digital controllers allow infinite variability in these characteristics across a large range and provide the opportunity to implement advanced control algorithms that are unrealizable in the analog world.

Analytical software to predetermine control parameters in the design phase has kept pace with the control hardware and software capabilities to allow application of magnetic bearings to flexible, large rotors (Figure 3). A family of new controllers have been introduced that allows monitoring and configuration using standard web browsers. Internet connectivity means that monitoring may be local to the controller or remote via dial-up or other TCP/IP data channel enabling remote operability.

The cutting edge

Developments in auxiliary bearing technology has extended magnetic bearing applications. These bearings provide static support for the rotor when delevitated and protect the machine internals from possible damage in the event of a machine trip caused by a system failure. This means that these bearings must be able to instantaneously accept full load and speed without any warning after months or years of inactivity and bring the rotor to standstill.

For instance, the Waukesha Rotor Delevitation System (RDS) has displayed this capability repeatedly in comprehensive testing on high-speed, multi-ton rotors. A key feature of the RDS is that the service condition is remotely observable from the controls by performing simple clearance checks for any wear incurred since the last usage. The auxiliary bush bearings can now absorb transient overloads without tripping the machine or contacting the seal, in the rare case of loads exceeding the factor of safety margin.

Magnetic bearings can be scaled to larger machinery. Additional increases in power amplifier ratings would be welcome. But the rating does not represent an application obstacle, since multiple amplifiers can be ganged together to drive small individual sectors of the bearings. Multiple amplifiers serve redundancy, too.

Ongoing development in high-temperature designs (operating above 650 °F) will allow application to some gas turbine units. However, the synergy is more in motor-driven machinery that eliminates emissions while enjoying low power consumption.

A new class of low-intervention, emission-free machinery is now under development, requiring remote operation, enhanced diagnostics, and an ability to immerse the bearing in the process fluid. Gas-cooled nuclear reactors and sub-sea compressors are examples of the latest in magnetic bearing applications. TI

Author

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