AGE RELATED FAILURES IN MAGNETIC BEARING SYSTEMS

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ABSTRACT

Magnetic bearings continue to be successfully applied throughout industry. As the population of machines using magnetic bearings grows, so does the interest in the appropriate predictive and preventive maintenance (PPM) procedures necessary to deal with both initial startup and aging related problems.

This paper highlights several examples of actual field problems, discusses critical maintenance procedures and intervals, and briefly reviews a portion of the proposed new ISO 14839 relating to allowable vibration levels for magnetic bearing equipped turbomachinery.

INTRODUCTION

Traditional oil lubricated turbomachinery has been around long enough for most users to develop "time tested" programs for predictive and preventive maintenance programs. The push to drive costs down and extend the intervals between major overhauls has always provided a motive to reevaluate these programs, and the huge installed base of equipment provides ample data to work with.

Magnetic bearing equipped machines, on the other hand, comprise a relatively small but growing portion of the total installed base of turbomachinery. In some segments of the industry, such as the turboexpanders used in new or revamped ethylene plants, magnetic bearings have become the norm, rather than the exception. This leads to an increasing number of questions by users and manufacturers alike regarding the modification of existing PPM programs to properly deal with the magnetic bearing system.

The examples outlined in this paper are from multiple sites worldwide, operating in various plant processes. Despite the fact that all examples given are taken from systems installed on turboexpanders, most of the information presented is equally applicable to other forms of rotating equipment.

TURBOEXPANDERS

For those unfamiliar with turboexpanders, a brief description will be given. For the purposes of this paper, a turboexpander will be considered to be a radial inflow turbine connected to a centrifugal compressor by means of a single rigid shaft. The radial and thrust bearings discussed herein are thus located between the expander and compressor impellers, as in Figure 1. Other forms of turboexpanders, such as those in which the expander drives a generator or other load device, will not be considered here. An interesting aspect of most turboexpanders is that the bearings, even oil lubricated bearings, typically operate in a filtered process fluid environment.

While specific processes vary greatly, almost all turboexpanders are used to remove energy from a gas stream, thereby producing power and cooling the gas. The refrigeration effect of this cooling process is normally the main reason that the turboexpander is

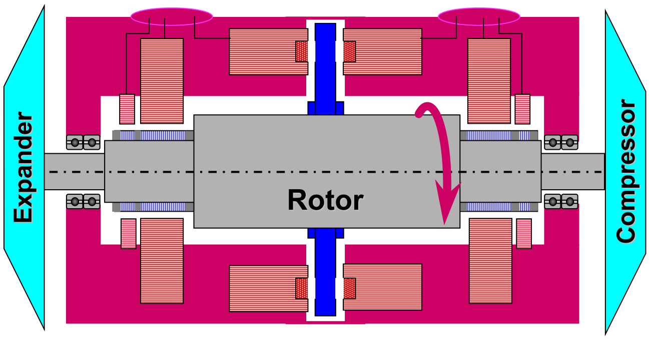

Figure 1. Turboexpander with Magnetic Bearings.

purchased. In addition, the main technical reason that a turboexpander is purchased with magnetic bearings is this eliminates the possibility that the cold box (heat exchanger) will be fouled with oil in the event of a major machine failure or operator error. This oil is difficult if not impossible to completely remove from the heat exchanger. The main commercial reason that magnetic bearings are used is that often the magnetic bearing system is cheaper! In the ethylene industry, for example, most new plants are using magnetic bearing equipped turboexpanders.

In most instances, the inlet gas to the expander is very cold and at or near saturation. This means that the gas passing through the expander will not only get colder, but some of the heavier components will also liquefy. Usually, this liquid contains valuable product that is recovered as a result of the condensation process, making the plant more efficient. The amount of this liquid can vary from about zero to 50 percent of the inlet stream (weight percentage basis), depending on the process conditions. A typical process is shown in Figure 2.

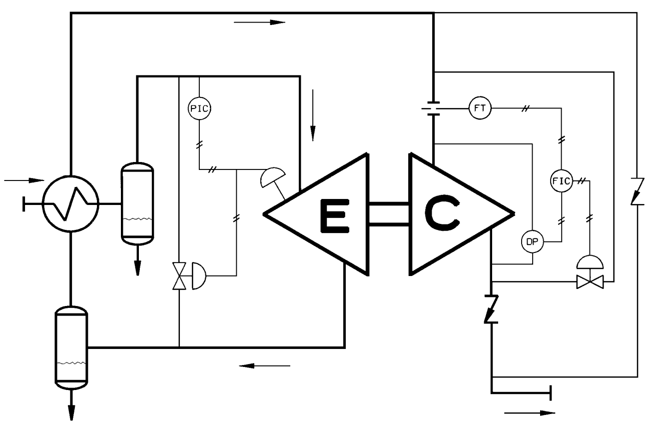

Figure 2. Typical Process Using a Turboexpander.

MAGNETIC BEARING SYSTEM

At one point or another, almost everyone has taken two permanent magnets, held them with like poles facing each other, and felt the repulsive force produced by the magnets. When this principle is used as a bearing, it is referred to as a passive magnetic bearing, since there are no control devices used. For many reasons, industrial magnetic bearings are virtually never based on this principle. In some cases, permanent magnets are used to supply a bias flux in industrial machines, but never as the sole support system.

For the purposes of this paper, magnetic bearings will refer to active magnetic bearings, in which the shaft is held in position using electromagnets arranged in close proximity to the shaft. The current supplied to these electromagnets is modulated by a control system. Thus it can be seen that the forces in an active magnetic bearing are never repulsive; they are always attractive.

For additional information on magnetic bearings, Schmied (1991) provides excellent information on magnetic bearing control systems in a very understandable fashion, and Jumonville, et al. (1991), provide useful photographs of actual magnetic bearing hardware, loading plots, and general design guidelines.

FAILURE-TIME RELATIONSHIP

Initial Problems

In almost any system, a general trend develops that relates the number of failures experienced to the time it takes for the component to fail. Broadly speaking, most systems will look something like the graph in Figure 3. Initially, the failure rate is high. This is one reason that all magnetic bearing control systems are "burned in" for a period of time in an attempt to drive marginal components to failure in a controlled manner. Other problems that can surface soon after initial power up of the system include mislabeled wires, wiring errors, engineering errors, and manufacturing errors. These problems may not cause component failures, but can prevent the system from working properly until they are resolved. Most of these problems surface and are corrected by the time the shop testing at the original equipment manufacturer (OEM) facility has been completed.

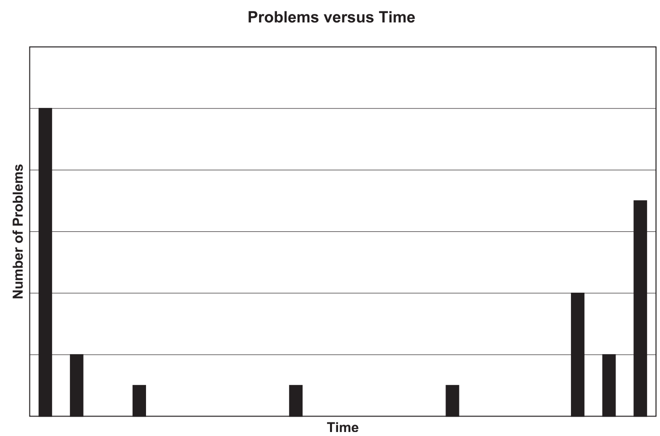

Figure 3. System Failure Versus Time Plot.

Once the equipment is installed in the field, a new group of "initial" problems can occur. At site, new wiring errors can occur, since the control system is again connected to the bearings by a different set of cables than was used in the shop testing. During the construction phase, the machine can be contaminated with dirt or rainwater, causing arcing and rust. The control cabinet may have been damaged during shipping or installation. The initial field run may cause substantial rust and other debris to dislodge from the process piping, causing damage to the equipment. The magnetic bearing control loops may require additional tuning to accommodate actual process conditions. In short, great care is required on the part of everyone involved to avoid problems during the initial startup.

Figure 4 shows a bearing that was flooded with process related liquids that somehow found their way into the bearing housing soon after startup in the field. Figure 5 shows the burned insulation at the point of failure.

Smooth Operation

When all the initial problems have been resolved, there is usually a period of sustained successful operation. The process controls have been fine-tuned, the process itself is stable, and few problems are experienced. This is the area where the PPM program is needed. Done properly, a good PPM program will extend the "smooth running" portion of the curve for a longer period of time.

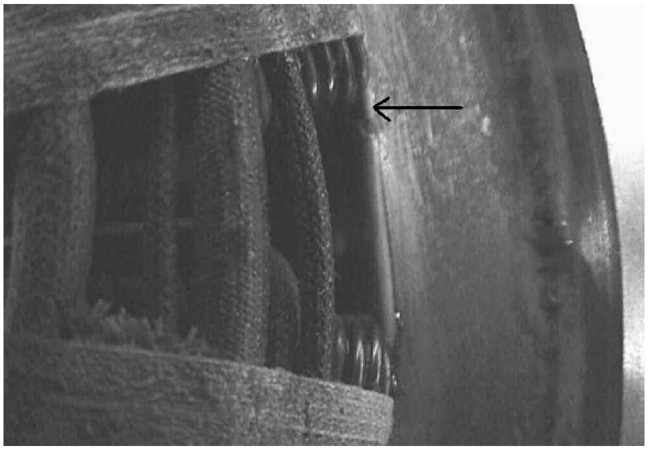

Figure 4. Damaged Coil in Magnetic Bearing.

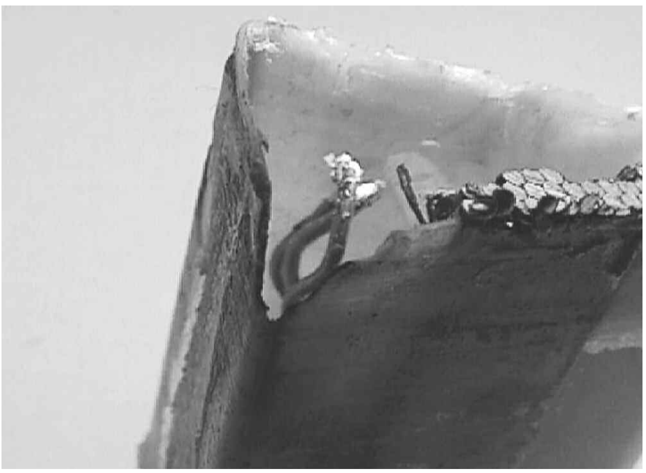

Figure 5. Closeup View of Burned Insulation.

Unfortunately, it is also during this period that the control system can suffer from neglect. Figures 6 and 7 show sand and dirt on top of and inside a magnetic bearing control cabinet. This unit is installed in a small, stand-alone fiberglass building near the turboexpanders. At the time of the original installation, the control system limitations forced the longest cable run to be 100 meters (328 ft) from the machine to the control system. To accomplish this, a special building was installed. In addition to debris that can be blown in when the doors to the building are opened, the filtration system for the building was not properly maintained (Figure 8).

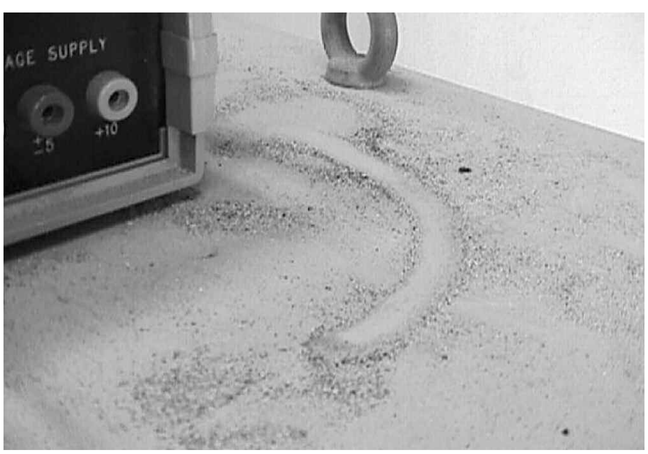

Figure 6. Sand and Dirt on Top of Magnetic Bearing Control Cabinet.

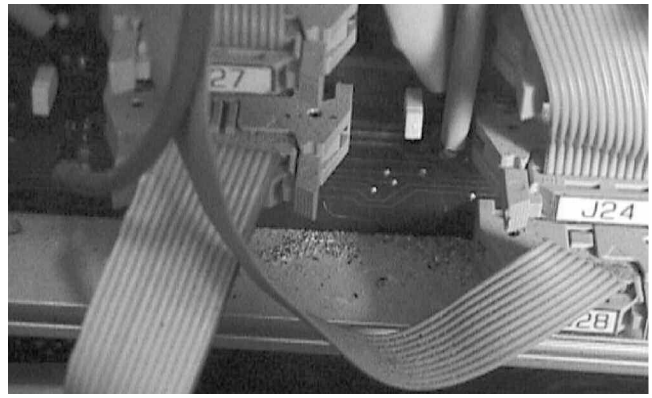

Figure 7. Sand and Dirt Inside Rear of Magnetic Bearing Control Cabinet.

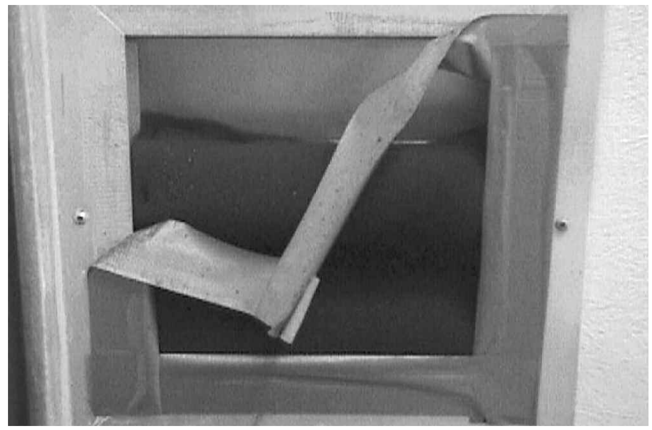

Figure 8. Damaged Air Filter on Building Housing Magnetic Bearing Controller.

Small stand-alone buildings or other nonideal locations are not uncommon for many systems, especially older installations. An additional problem that plagues such systems is the failure of the heating/cooling/humidity control system for these buildings. This can be especially harmful in hot humid climates if the cooling and humidity control portion of the system fails. The electronic components can get overheated and sustain permanent damage. Figure 9 shows a small spacer used in a power supply to ensure good contact between the integrated circuit and the heat sink. Figure 10 shows the result when a similar spacer on a different power supply overheated and melted onto the circuit board below.

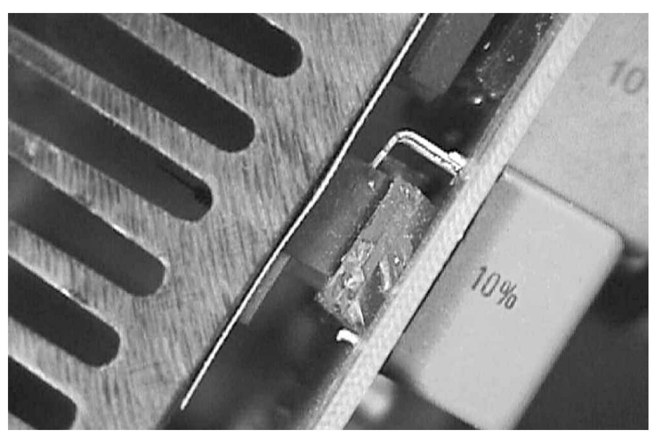

Figure 9. Spacer in Good Condition Holding Integrated Circuit Chip Against Heat Sink.

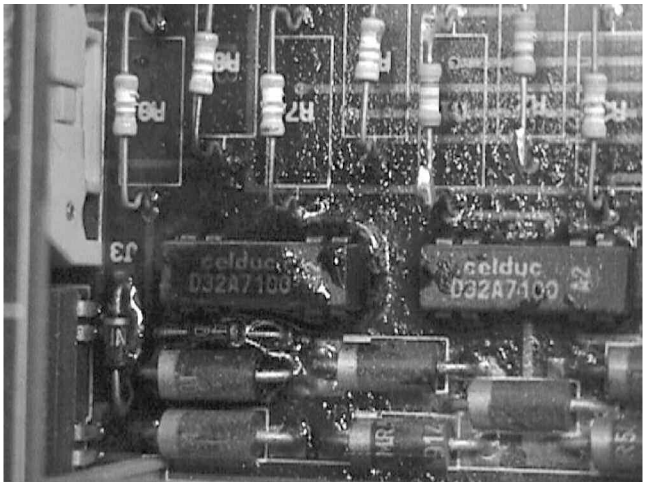

Figure 10. Melted Spacer Material from Power Supply Deposited on Nearby Circuits.

Even with a good PPM program, however, problems will eventually arise. This can be due to a number of factors. The process conditions may change, causing the machine to operate outside of its design envelope. An upset condition may damage internal components. In some cases, the problems actually arise due to the success of sustained operations. For example, if a turboexpander operates successfully for many years, the operators often forget how to start it up or shut it down properly, leading to damaged equipment.

Aging Problems

At some point, the control system itself becomes old and outdated. This can cause problems in many ways. Individual electrical components, which survived periodically high stresses over many years, may suddenly fail under otherwise "normal" conditions. Figure 11 shows a blown transistor on a radial power amplifier that blew out during normal machine operation, for no apparent reason. Figure 12 shows the backside of a circuit board that was operating normally and did not experience any failure. Notice that there is a large darkened area (near the center of the picture) that has been overheated. It is not known when or why this occurred, but it is reasonable to assume that this board will be somewhat more likely to suffer a sudden failure than a board that has not been subjected to overheating.

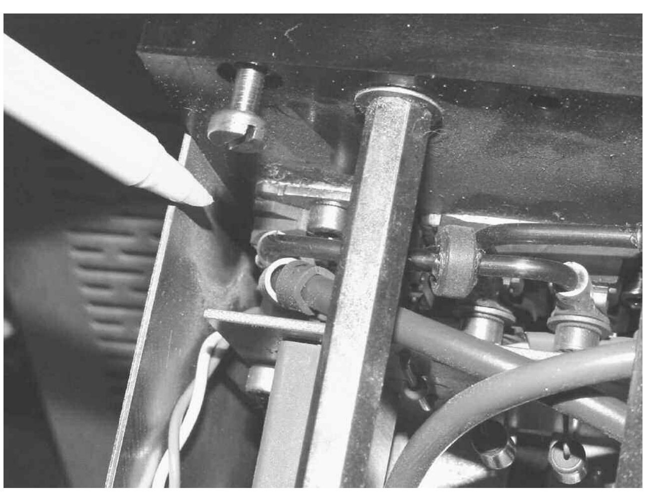

Figure 11. Blown Transistor Damaged During Normal Operation.

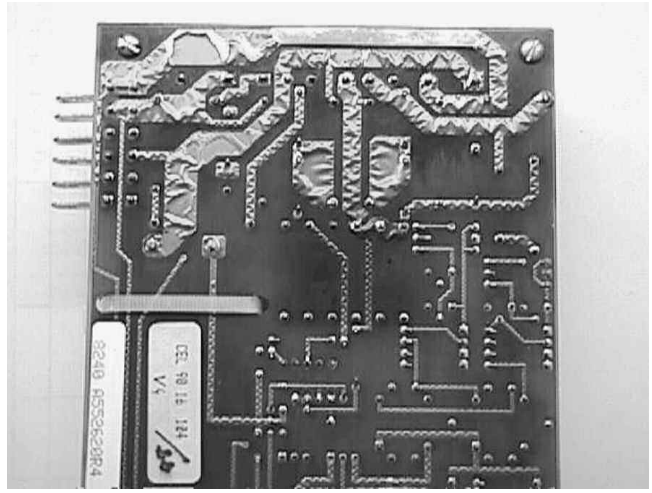

Figure 12. Overheated Circuit Board Still in Working Condition.

Oxidation and dirt built up over the years in card slots, terminal strips, and other areas may cause intermittent signal interruptions or false readings. Troubleshooting and repairs can be complicated by the fact that electrical technicians from the magnetic bearing supplier may not be trained on old, outdated equipment. Parts that were readily available at the time the system was new may no longer be available (note: it was highly publicized in 2002 that NASA was using an online auction site to obtain old microprocessor chips for the space shuttle, simply because they could not buy them new any more!).

PPM PROGRAM SUGGESTIONS

Many aspects of a typical PPM program for oil lubricated equipment also apply to machines using magnetic bearings. This paper will not attempt to recreate these items. In contrast, some interesting observations can be made about units with magnetic bearing systems that may be useful in improving traditional existing programs.

Predictive Monitoring

It seems obvious from the above pictures that the effects of elevated temperature are the enemy of the magnetic bearing control system. Virtually all magnetic bearing suppliers know this and install a high temperature alarm and shutdown of the control system to minimize the effects. The authors believe that this may not be enough for a critical system. While troubleshooting the overheated parts above, no data could be obtained regarding the temperature history of the control cabinet, except that plant personnel recalled many problems during the early years in which the temperature and humidity control for the building did not work correctly.

The authors suggest that cabinet temperature should be trended as a critical value, not only as an early warning sign of possible cooling system malfunctions, but also as an indicator of the potential life left in the critical components.

In fact, it would not be unreasonable to install temperature sensors on or near critical components and heat sinks. These could be relatively elaborate and expensive analog devices that are alarmed and trended, or they could be as simple as inexpensive temperature sensing labels that permanently change color when certain temperature levels are reached. These labels could be checked periodically and the maximum values recorded. New labels could then be installed if the previous period indicated over temperature had occurred. It should be noted that at least one major manufacturer offers analog trending capability for certain critical component temperatures in their latest digital control cabinets.

The short term goal of such actions would be to aid in monitoring and troubleshooting system components, but the long term database of such information could lead to extended runs between either planned maintenance or unexpected trips due to component failures.

A second predictive area that is done with some regularity involves clearance checks of the auxiliary bearing system. All industrial magnetic bearings incorporate some form of auxiliary bearing system (also called a “back up” or “catcher” bearing). This system provides support for the shaft in the event of a system failure or overload, as well as when the machine is at rest and delevitated.

To date, the lead author’s company has used two different types. The first is based around a ball bearing design that has no continuous lubrication fed to it (it is not normally spinning when the machine is in operation), but is instead prelubricated using a special process prior to installing the bearing in the system. The second type is based around a dry lubricated bushing. Either type can benefit from periodic clearance checks that are recorded and used to track changes in the measured clearance between the shaft and the auxiliary bearing.

It is of particular importance to check the clearance following an event in which the unit is known to have caused the shaft to contact the auxiliary bearings. If the control system is equipped with a counter to record these events, that is a good indicator. This information, coupled with visual inspections of the auxiliary bearings during machine overhauls, will help to arrive at a confident, rational decision regarding when a given number of “touchdowns” or a certain type of unplanned event has caused enough damage to replace the auxiliary bearings or if the damage is likely to be minor and thus continued operation is safe.

Preventive Maintenance

As shown in the pictures above, the magnetic bearing control systems can suffer from neglect during the period when everything is running great. This neglect is largely due to the fact that the control systems are frequently installed in “out of the way” locations within the plant, and thus are easy to forget about. This is simply human nature, like someone “intending” to clean out the attic or basement of their home, but never actually doing it! The solution here is simply to set up a plan and treat the magnetic bearing control system like the critical equipment that it is.

In order to establish the latest guidelines regarding preventive maintenance recommendations from the magnetic bearing manufacturer, the oldest magnetic bearing system (factory tested in 1991) used in a machine at the lead author’s company was chosen. The magnetic bearing supplier provided the following guidelines:

- *One year intervals:*
  - Replace air filters

- *Two year intervals:*
  - Replace batteries for uninterruptible power supply (UPS) system

- *Five year intervals:*
  - Replace set of thermo-contact relays in cabinet
  - Replace all cooling fans
  - Replace auxiliary bearings and damping ribbons
  - Replace high voltage power supply
  - Replace low voltage power supply

- *10 year intervals:*
  - Replace oscillator circuit board
  - Replace the battery test circuit board
  - Replace the chemical capacitor
  - Replace the three-phase bridge
  - Replace all radial amplifiers (total of eight)
  - Replace all axial amplifiers (total of two)
  - Replace set of fuses and lamps
  - Replace diagnosis counter (hour meter)
  - Replace ammeter

Further explanation is required on some of the recommendations. For instance, the recommendation that the auxiliary bearings (ball bearings in this case) be changed every five years means that the old bearings should be returned for factory inspection, recertification, and relubing. If the bearings pass inspection, they can then be returned to service or held as spares. Note that even if there have been no known incidents in which the auxiliary bearings are used, the OEM recommends the inspection and relubrication in case the bearings have become contaminated or the process fluid has adversely affected the lubricant.

The batteries listed are for the UPS. This system provides power to the magnetic bearings in the event of a power failure.

Note that the recommendations above are based on interval of time, not simply time alone. This means that on the tenth year of operation, the manufacturer recommends that *everything* on the one year, two year, five year, and 10 year list should be changed.

Looking at the 10 year list, it becomes clear that parts subject to the highest long term electrical loading like the power supplies and power amplifiers are on the list to be replaced. Obviously, it is expected that these parts will be in working order when the decision is made to replace them. This is the reason that better monitoring and control of the temperature of these parts is important. If a control system is running very near to full load and has had several high temperature excursions during its life, it may be that 10 years is far too long an interval for adequate protection from unexpected failures. Likewise, if a system is using a relatively small part of its capacity, and the cooling system has been trouble free, then 10 years may be far too conservative. The point is, without better information, there is nothing to base the decision on, and in that case following the OEMs recommendations is the best answer.

PROPOSED ISO-14839-2

As this paper is being written, the new proposed Part 2 of ISO/DIS 14839 (2002) covering vibration evaluation of rotating machinery equipped with active magnetic bearings is being circulated for review (and is thus subject to change). A brief summary of the proposal is included here in the interest of keeping the turbomachinery community informed of the work being done, and to give some insight into practical vibration guidelines for magnetic bearing equipment operating in the field. It also represents some degree of validation for the growing magnetic bearing industry, since international standards are now being written to cover these devices.

The standard proposes two criteria for vibration evaluation. The first criterion uses the same definitions as ISO 7919-1 (1996) for establishing four “zones” of vibration.

- Zone A represents the expected vibratory displacement of newly commissioned machines.
- Zone B represents a level of vibratory displacement that is considered acceptable for unrestricted long term operation.
- Zone C represents a level of vibratory displacement that is considered unacceptable for long term operation, but acceptable for a limited period until a suitable opportunity arises for corrective action.
- Zone D represents a vibratory displacement level believed to be sufficiently severe to cause damage to the machine.

It clearly points out that these values are not intended to serve as an acceptance specification on either the test stand or during the commissioning of the equipment. Rather, the proposed limits are meant to provide guidelines for ensuring that gross deficiency or unrealistic requirements are avoided, as well as providing guidance for condition monitoring, problem diagnosis, and for setting operational limits.

The current proposal lists:

- Zone A = Dmax less than 0.3 times Cmin
- Zone B = Dmax less than 0.4 times Cmin

- Zone C = Dmax less than 0.5 times Cmin
- Zone D = Dmax greater than 0.5 times Cmin

where *Dmax* is one of three different formulas (not given here) for arriving at the maximum distance that the shaft travels from the theoretical centerline of the bearing, and *Cmin* is the minimum value of a radial or axial clearance between the rotor and stator.

In words, this means that a magnetic bearing equipped machine would be acceptable for long term operation if the maximum motion of the shaft centerline never penetrates an imaginary circle centered on the middle of the bearing, having a radius of 40 percent of the minimum clearance to the auxiliary bearing. Note that these guidelines also apply to the axial motion, with measurements being linear instead of radial.

The point of all this is that the committee is trying to recognize that the typical active magnetic bearing is less stiff than the typical oil lubricated bearing, so transmitted forces are lower, and that there is no babbitt to fatigue, therefore a reasonable vibration criteria should be based on how close the shaft is to the nearest obstruction (almost always the auxiliary bearing), not on how high the vibration is. It is also worth mentioning that the *Dmax* value is not strictly vibration, but is also based on the actual location of the shaft in the bearing. This means that a machine with very low vibration levels might not be acceptable if the steady-state average position of the shaft is offset to one side of the clearance.

There may be a practical lesson for oil bearing users here as well. Lightly loaded oil bearings tend to have low eccentricity ratios (the shaft operates nearer to the middle of the bearing clearance) and have comparatively low stiffness values relative to heavily loaded bearings operating with high eccentricity ratios (the shaft is close to the babbitt). Therefore, a proper vibration limit for oil lubricated bearings should probably take into account *where* the vibration is taking place. It stands to reason that a given level of vibration is more acceptable when it takes place near the center of the bearing than when it occurs near the babbitt surface, since the cyclical bearing film pressure peaks will be lower when the shaft is centered compared to when it is close to the bearing surface.

The above guidelines for magnetic bearings constitute only one of the two criteria proposed. The second criterion applies to changes in the broadband vibration occurring under steady-state operating conditions. If changes from the normal magnitude exceed 25 percent of the upper boundary value for Zone B (higher or lower), then this is considered to be cause for concern, since a potentially serious fault may be indicated.

As a final comment on this topic, the proposed standard also states that guidelines for acceptable coil currents and voltages were considered, but not included at this time due to a lack of data. This seems to indicate that future editions will contain these guidelines if and when the data become available.

CONCLUSION

Magnetic bearings are currently being used on a relatively small, but growing, number of machines. The fact that an ISO standard is being written to address turbomachinery using magnetic bearings is a testament to their growing use in industry. This paper was written to provide guidance to both new and existing users of magnetic bearings, specifically in the area of improving long term reliability by examining conditions that have caused actual failures in the past. It is hoped that by sharing this information, additional dialog will be generated on this topic, and future installations will be even better.

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