The Design of High Reliability Magnetic Bearing Systems for Helium Cooled Reactor Machinery

M. Swann, N. Davies¹, R. Gao², Z. Guo², R. Jayawant¹, R. Leung¹, R. Shultz¹

Waukesha Magnetic Bearings
20 Technology Way, West Greenwich, RI 02817 USA
phone: +1 401 385 3703, mswann@waukbearing.com

¹ Waukesha Magnetic Bearings, Unit K Downlands Business Park, Lyons Way, Worthing, W. Sussex BN14 9LA, UK

² Waukesha Magnetic Bearings, No. 11 Wei Wen Road, Suzhou Industrial Park, P R China 215122

Abstract – The requirements for magnetic bearing equipped machinery used in high temperature, helium cooled, graphite moderated reactor applications present a set of design considerations that are unlike most other applications of magnetic bearing technology in large industrial rotating equipment, for example as used in the oil and gas or other power generation applications. In particular, the bearings are typically immersed directly in the process gas in order to take advantage of the design simplicity that comes about from the elimination of ancillary lubrication and cooling systems for bearings and seals. Such duty means that the bearings will usually see high temperatures and pressures in service and will also typically be subject to graphite particulate and attendant radioactive contamination over time. In addition, unlike most industrial applications, seismic loading events become of paramount importance for the magnetic bearings system, both for actuators and controls. The auxiliary bearing design requirements, in particular, become especially demanding when one considers that the whole mechanical structure of the magnetic bearing system is located inside an inaccessible pressure vessel that should be rarely, if ever, disassembled over the service life of the power plant. Lastly, many machinery designs for gas cooled nuclear power plants utilize vertical orientation. This circumstance presents its own unique requirements for the machinery dynamics and bearing loads.

Based on the authors’ experience with machine design and supply on several helium cooled reactor projects including Ft. St. Vrain (US), GT-MHR (Russia), PBMR (South Africa), GTHTR (Japan), and most recently HTR-PM (China), this paper addresses many of the design considerations for such machinery and how the application of magnetic bearings directly affects machinery reliability and availability, operability, and maintainability. Remote inspection and diagnostics are a key focus of this paper.

INTRODUCTION

The magnetic bearing industry has evolved to serve a wide range of industrial applications from high volume vacuum pumps for the semiconductor industry with relatively standardized specifications to some highly specialized applications in the oil & gas sector with very demanding specifications. Application to gas cooled reactor machinery is more akin to the latter but with some very unique requirements for reliability and safety. The specification and design of these bearings accordingly becomes significant to the nuclear power plant system design basis. In particular, remote observability and diagnostics becomes of vital importance in order to gain long term reliability and availability while completely
eliminating any maintenance requirements for many years.

Like many aspects of nuclear power plant design, certain technology choices have an important effect on the overall viability of the power plant. The bearings for the machinery may have significant influence on the overall plant efficiency, maintainability and cost of maintenance, reliability and availability, personnel radiation exposure, and plant safety. Of course, thermodynamic and practical machinery considerations will largely govern some of the primary machine decisions like single vs. multi-shaft designs, and horizontal vs. vertical orientation. Flow losses in the piping connected to the reactor are an example of the thermodynamic considerations; building support structure is also important in the consideration of the machinery orientation. Another primary consideration is whether the machine design will be hermetic or non-hermetic using dynamic shaft seals, employing external buffer gas supplies, internal or external cooling provisions or not. Implicit in these decisions is the choice between ‘wet’ and ‘dry’ bearings that affect whether there will be an external lubrication system or not. In turn, this choice impacts considerations of the fire protection provisions.

Active magnetic bearings (AMBs) have been employed in all recent helium cooled reactor designs as the only mature dry bearing technology after problems with wet bearings contributed directly with operating difficulties at the early AVR and THTR helium reactors in Germany where oil lubrication was used, as well as the HTGR at Ft. St. Vrain in the United States where water lubricated bearings were used. This history dates back thirty years. Speaking of the HTGR at Ft. St. Vrain after a series of at least 14 failures of the circulator systems leading to several lubricant ingress events and large down times”, Brey [1] concluded that “successful circulator operation requires nearly flawless performance of a complex circulator auxiliary system which includes ... valves and instruments while supporting components such as pumps, compressors, heat exchangers, and vessels, ...overall plant performance has been impaired”. Speaking of the AVR after a turbine oil fire, Ziermann and Engel [2], reported that “it must be emphasized that the reliability of a primary gas circulator in gas cooled reactors absolutely depends on the effectiveness of the buffer helium system (used to keep oil confined to the oil reservoirs)”. With regard to the THTR, Glahe and Stolzl [3], stated following an incident where radioactive gas escaped after graphite fuel balls stuck in the fuel inlet “that further development work on the circulators is currently being continued for the only reason that active magnetic bearings permit vertical arrangement of the circulators...without requiring the operation of an extremely complicated and expensive oil system...The costs of the oil and gas seal systems are about twice as high as the costs of the (six) circulators themselves”. All three of these reactors were prematurely shutdown and decommissioned in large part because of these and related issues that can be traced directly to inadequate design decisions including the bearings.

Moreover, as indicated in [3], the precedent for equipping all such helium reactor machinery with magnetic bearings became well established and has led all the recent helium cooled reactor designs to consider and specify magnetic bearings for the primary coolant loop machinery. This population includes the direct cycle designs for PBMR in South Africa, GT-MHR in Russia, GT HTR in Japan, and the indirect cycle design for HTR-PM by INET in China. The magnetic bearing systems of these designs must provide acceptable levels of reliability and availability while minimizing maintenance. This is accomplished through proper design which includes the exploitation of provisions for remote observability and diagnostics.

Figures 1, 2, and 3 contained herein, respectively show the machine design arrangements with magnetic bearings for the PBMR fuel ball blower, the HTR-PM fuel ball blower, and the HTR-PM circulator.

![Fig. 1: PBMR Fuel Ball Blower.](image)
II. BEARING ENVIRONMENT & COOLING

Eliminating liquid lubricants still leaves the choice of whether to fully exploit the advantages of magnetic bearings and employ hermetic designs with no dynamic seals of any kind. Doing so ensures the simplest machine designs and therefore intrinsically promises the highest reliability because the ancillary supports systems for bearings and seals are eliminated or reduced along with the associated pressure vessel penetrations. The elimination of shaft seals means that the bearing compartments operate near to system pressure and the bearings are immersed in the primary coolant. A general arrangement of the PBMR fuel ball blower is provided in Figure 1 clearly showing the overall design simplicity achieved.

For direct cycle designs the temperature of the bearing compartments may approach reactor discharge temperature depending upon heat exchanger/recuperator arrangements. In addition to operating temperature considerations there is also the matter of ‘soakback’ from reactor residual heat generation and conduction into the structure of the bearing compartment. These considerations dictate that some form of active bearing cooling is required. This is usually provided from temperature reduced primary coolant introduced into the bearing compartment and distributed in an advantageous manner through the bearing in order to dissipate heat via forced convection. A schematic of the bearing cooling provisions for the HTR-PM circulators at the non-drive end is given in Figure 3. The design temperature of the bearing compartment is 100°C for the upper compartment and 140°C for the lower; the inlet temperature of the cooling gas is 65°C in each case.

Complicating the bearing environmental requirements is the possible presence of high concentrations of graphite particulates suspended in the gas stream especially for pebble bed type fuel elements. Over time these particles may become lodged into bearing crevasses and cavities posing a risk of radiation exposure to plant maintenance personnel when the machinery is eventually decommissioned and disposed of, or in the unlikely event that periodic maintenance is required. For such circumstances it is preferable that all bearing surfaces be smooth and without cavities where the graphite particulate may become lodged. Figure 4 displays examples of ‘sealed’ magnetic bearing designs and ‘canned’ magnetic bearing designs. The latter clearly is superior in terms of ability for easy decontamination but the presence of the canning structure carries size and bandwidth (dynamic response) penalties that must be addressed in the overall system design for machinery performance, especially rotordynamics.
Graphite particulate also may have a large impact on the operation and reliability of auxiliary bearings which, depending on their design, may be much more prone to adverse effects than the magnetic bearings because the auxiliary bearings are intrinsically contact type bearings whereas the magnetic bearings are not. For this reason alone, bushing type auxiliary bearings, Figure 5, are preferred with few or no moving parts that may become fouled, thereby leading to a compromised operating ability with the buildup of contaminants over time. Obviously, this becomes more problematic where the particles are relatively large in size, have a high hardness and exist in high concentrations. A fine dispersion of soft graphite, on the other hand, may be beneficial for lubrication of the bearings.

III. SEISMIC DESIGN CONSIDERATIONS

Unlike most other industrial applications, seismic loading events become of paramount importance for the magnetic bearings systems used in high temperature gas cooled reactor applications. This presents a set of design considerations for magnetic bearing system actuators and their control systems.

In general, the seismic events can be classified as Operating Basis Earthquake (OBE, SL-1) and Safe Shutdown Earthquake (SSE, SL-2), following the commonly recognized standards by the International Atomic Energy Agency (IAEA) and Nuclear Regulatory Commission (NRC). All safety-related equipment must prove its seismic adequacy to withstand the effects of the earthquake by ensuring the safe operation of machines under design basis operating events (OBE, SL-1) and the safe shutdown under the maximum design earthquake events (SSE, SL-2).

One of the indicators to define the seismic conditions for the design basis operating event and safe shutdown is by the magnitudes of Peak Ground Accelerations (PGA). Typically, the maximum values of PGA’s magnitudes in X, Y, Z coordinates can be defined as the seismic conditions corresponding to the two events.

The importance of the response spectrum approach in the seismic design of safety related equipments is well known to earthquake design engineers. The response spectrum would show the influence of various parameters such as site geographical conditions and the level of peak ground accelerations. The seismic design response spectrum is often obtained by a statistical analysis of a large number of actual earthquake ground motions and response spectra. For example, the studies completed in [4], [5], and [6] provided a foundation for the AEC Design Response Spectra in its Regulatory Guide 1.60 (1973), which was also adopted by ASME in [8] and IEEE in [9]. The response spectrum describing the local site geographical conditions becomes the design basis of machines for its application.

When considering the design of magnetic bearing systems for nuclear power reactors, distinction should be made between large earthquake loads and other short term loading events. In the event of complete failure of the magnetic bearing system, a signal is generated by
the control system requesting a system shutdown. In contrast, in the event of certain magnetic bearing system transient overloads without magnetic bearing system failure, the auxiliary bearings accept the momentary overload and allow the magnetic bearings to regain control of the rotor. Normal operation then continues. The nature and duration of these overloads needs to be defined. The OBE or SL-1 is one such event but SSE or SL-2 is not. In the case of a SL-2 event, the rotor may experience a complete rundown on the auxiliary bearings as part of the controlled shutdown sequence.

The control logic for seismic loading considerations can be summarized as:
- During a SL-1 event the rotor may momentarily contact the auxiliary bearings. The magnetic bearing system will not initiate a shutdown during a SL-1 event.
- During a SL-2 event the rotor may rundown on the auxiliary bearings. The magnetic bearing system will undergo a controlled shutdown during a SL-2 event.

Seismic qualified design of the magnetic bearing systems is comprised of the relevant static and dynamic analyses including the transient simulation analysis when the rotor is supported on magnetic bearings and/or auxiliary bearings during seismic as well as other short term overloading events.

IV. VERTICAL MACHINERY ORIENTATION

Reactor and plant layout considerations often demonstrate the advantages of vertical orientation of the rotating machinery, e.g. the helium circulator for HTR-PM in Figure 3. Vertically oriented machinery presents special considerations.

With horizontal machines the primary radial magnetic bearing load is often the gravity load. Obviously, the gravity load for the radial bearings of a vertical machine is zero, but the sizing of the radial magnetic bearings must still be carefully considered. With the vertical orientation, the loading for the radial bearings includes the dynamic load due to imbalance, side loads induced by aerodynamic effects, and dynamic loads from environmental effects, such as seismic loading. The radial bearing size is determined based on these loads, as well as the stiffness and damping characteristics required for the application. The required bearing stiffness to control the amplitude of rotor motion often governs the bearing sizing.

For rotor vertical orientation, the axial magnetic bearing sizing must accommodate the gravity load and other loading effects. These other loading effects include pressure loads, loads induced by machine aerodynamics, and loads induced by environmental effects, such as seismic loading.

With regard to the auxiliary bearings, the vertical orientation changes the sizing criteria for the radial and axial bearings. The radial auxiliary bearing sizing must accommodate whirl loads, aerodynamic side loads, and dynamic loads due to environmental vibrations, i.e. excitation of the machine support structure including seismic loads. The worst case seismic loading will cause overloading of the magnetic bearings, and the resulting contact with the auxiliary bearing will be an impact type loading; this often becomes a significant design criterion.

The axial auxiliary bearings loading consists of the gravity load, pressure and aerodynamic loads, and loads induced by environmental effects, in this case the seismic loading. During each auxiliary bearing full landing event, the drop through the working air gap clearance of the bearing induces an impact load. Also, the worst case seismic loading will cause overloading of the magnetic bearings, and the resulting contact with the auxiliary bearing will be an impact type loading. Again, this often becomes a significant design criterion for a successful auxiliary bearing design.

Unlike fluid film bearings, vertical rotor orientation does not cause any significant rotordynamic stability concerns with magnetic bearings. Whirl instability may occur in fluid film bearings because of the absence of a gravity load that provides a consistent eccentricity in the fluid film bearing. This problem does not occur at all with magnetic bearings: the linear rotordynamic characteristic of the magnetic bearing is not dependent on the static loading condition. Even with a static loading of zero, the magnetic bearing maintains a stable operating characteristic.

V. AMB SYSTEM NUCLEAR QUALIFICATION

The mechanical components of the magnetic bearing system are qualified for seismic service by stress and deflection analyses of the mechanical components to establish that the integrity of the design is maintained during the seismic events. This is often done with a static equivalent analysis method, a well recognized method for qualifying
mechanical components for seismic and shock environments.

Considering that the magnetic bearing control cabinet is placed away from the machine, the challenging issue for nuclear qualification of this unit is its performance during the seismic events. The control cabinet should maintain structural integrity and properly perform its specified functions before, during and after the design basis operating event and the safe shutdown event. This requirement may involve special mounting design for the control cabinet, to attenuate the transmission of seismic loading from the ground to the equipment. The seismic qualification test of controls shall be then carried out to demonstrate the seismic mounting design is fit for purpose. The testing of the equipment should be implemented in compliance with [9].

VI. RELIABILITY, AVAILABILITY & LIFE

VLA General Reliability Considerations

Few applications of magnetic bearings demand more system level reliability than nuclear power. A single failure mode in the magnetic bearing system has the potential to take down the entire plant leading to a loss in power production. As in other systems, there are two fundamental approaches to the attainment of high reliability: (1) ultra high reliability of individual components, especially those that comprise a single point failure, and (2) built in redundancy that may be implemented either by manual or automatic means. The choice between these two approaches is usually governed by considerations of allowable failure rates vs. the costs involved in implementation.

Fortunately, the intrinsic reliability of the components that comprise a magnetic bearing system is high and the factors limiting the service life of these same components, especially those located inside the machine structure and pressure vessels are few. With proper design, long lives may be attained without any appreciable attention by plant operators. Obviously, the environmental conditions discussed above like bearing compartment pressure and temperature may have an effect on service life thereby underlining the importance of good design of the components themselves, the materials used and the cooling provisions. Exposure to long periods of immersion in helium by bearing designs of the authors’ company (e.g. the PBMR fuel ball blower in Figure 1) has shown no quantifiable degradation in the condition of these components as long as fundamental protection from the environment is afforded. Notably, this includes the proper selection of electrical resins for the impregnation of the bearing windings and position sensors for the high pressure, high temperature helium environment.

Some of the designs for large turbine generators of direct cycle plants (e.g. PBMR) utilized fully redundant AMB systems with fully redundant controls serving magnet structures in the machines that are also fully redundant. However, for compact machine design with good rotodynamic behavior, non-redundant magnet cores (or bearing “magnets”) will generally be utilized with a level of redundancy applied to the position, temperature, and speed sensors. Position sensors may employ voting (e.g., 2 out of 3 logic) or, more simply, two complete sensor systems with the capability to manually switch over to the inactive sensor from the control cabinet. There is an obvious impact here on the number of electrical penetrations required as described below. In addition, unless the position sensors are collocated, there is a need to change the servo control software to accommodate the axial change in location of the redundant sensor along the rotor length.

The selection of auxiliary bearing materials and associated lubricants has a fundamental effect on their long term life and operability. The inertness and lack of any oxygen or water in the helium environment, coupled with the potential presence of hard particulates in the gas, present a significant challenge to the lubrication of the auxiliary bearings rendering most designs employing rolling elements to be challenged by the long term exposure and the need to provide a low risk of failure when their operability is required following a machine event. This indicates that contacting surfaces will usually need to be protected by dry lubricated bushings and thrust washers that have been specially selected for the inert and difficult environment.

For power plant equipment that is considered as safety related, an Equipment Qualification (EQ) program is usually employed. A key aspect of EQ as described in [10] is the aging to be simulated before the demonstration of the capability to perform the safety function at the end of the qualified equipment life. This aging depends on the environmental service conditions (normal and accident) and on the operational cycles and points
to challenges particularly with auxiliary bearings during the OBE because of fouling and contamination issues that may accrue over time.

**VI.B AMB Controller Reliability Considerations**

The use of magnetic bearing controllers that provide quick recovery from a single point failure may be of the ‘A+B’ type where two complete and independent control systems are utilized, or ‘n+1’ where one additional “channel” is provided that may be brought into operation to replace an operating channel after fault detection. A channel is usually associated with one of the control axes of the machine. For example, a machine with two radial bearings and one axial bearing will have five channels controlling five degrees of freedom of motion: two for each radial bearing and one for the axial bearing. The switch over to the redundant controller or channel may be either automatic or manual. The A+B arrangement has been used reliably in several AMB applications. Automatic switchover of the n+1 arrangement is also possible but making this truly ‘bumpless’ without auxiliary bearing contact is very challenging. Hence, where redundancy is specified, A+B systems are usually employed and the auxiliary bearing system must be capable of accepting the extra duty of momentary contact without inducing undesirable rotor behavior. There are often some challenges here.

**VI.C Reliability & Pressure Vessel Penetrator Considerations**

For both cost and reliability concerns, the number of pressure vessel penetrations needs to be minimized and there are special considerations for the arrangement of penetrators used. Generally, separate penetrators are employed for the electric motor connections and the magnetic bearing connections.

As an example, for the HTR-PM circulator project, the wires for the magnetic bearings are arranged to go through two penetrators. There is one penetrator for the large cross section magnet wires and another penetrator for the small cross section sensor wires in each circulator. There are 28 pins in the bearing magnet wires penetrator with no spare pins. There are no critical issues with the allocation of pins. To minimize the amount of the potential electromagnetic interference arising from the electrical connection to the bearing magnet, the two connections for a magnet are allocated adjacent pins. This reduces the area enclosed by the wires and hence the magnetic flux produced.

There are 164 pins in the sensor signal penetrator for each HTR-PM circulator in Figure 3. The count is high in order to satisfy redundancy requirements. For the signal penetrator, noise is an important factor and the allocation of pins is critical for the performance of the bearing. These pins are physically grouped into position sensor, speed sensor, temperature sensor and flux sensor, in the order of lowest to highest noise level. The temperature sensor and flux sensor are located adjacent to the magnet coil which is a very noisy environment. Therefore, the temperature sensors and flux sensors are in an adjacent area in the penetrator. The position sensor pins are at the far end of the penetrator relative to the noisy temperature and flux sensors. Spare penetrator pins are allocated between sensor groups to provide extra spacing between noisy and clean signals. Both sets of redundant sensors are routed through the penetrator so that if the need arises, a swap over of connections can be done in a safe, non-radioactive area.

The penetrators for the HTR-PM fuel ball blower, Figure 2, are for individual bearing parts. This arrangement allows different parts of the bearing to be disassembled without removing wires from the penetrator. For the impeller end of the machine, there are three penetrators. One penetrator is for the radial magnet connections. The second penetrator is for the axial magnet and flux sensors connections. The third penetrator is for the position, speed and temperature sensors connections. Similarly, on the motor end of the machine, there are penetrators for the bearing magnets and the three sensor group connections.

**VI.D Remote Inspection and Diagnostics of Magnetic Bearing Machine Components**

As indicated earlier, condition monitoring of magnetic bearing supported equipment is of particular concern when the equipment is located within the primary coolant loop inside a pressure vessel. In this case the costs associated with a visual inspection of the equipment are significant and such magnetic bearing supported equipment may be equipped with a diversity of diagnostic capability to assess and predict the ability of the machine to continue in operation. Even where machinery is outside of the primary loop, condition monitoring can help ensure that unplanned downtime is eliminated.

Except for auxiliary bearings, the service life of magnetic bearing components is very long, often
measured in decades, and the assessment of their condition is readily accomplished. The electrical windings of the magnetic bearing themselves will have a service life dictated by the quality of the electrical insulation system design and implementation. The commonality of these windings with those that have been used in motors and generators opens up the realm of standard electrical tests that have been used in such equipment for decades, e.g. megger, hi pot, and surge testing techniques. Generally, the full spectrum of these tests will require access to the magnetic bearing controller side cable lead ends in the safe, non-radioactive area where the controllers are located.

The operation and maintenance of the rotor-bearing systems for helium service is readily assisted by using the innate intelligence of the magnetic bearing system. This intelligence stems partly from rotor position and vibration information that is used to control the rotor with the electromagnetic forces of the bearings. There is a whole body of work demonstrating the usefulness of vibration information in diagnosing rotating machinery condition and this information is available for display and monitoring from remote via the magnetic bearing controller.

Vibration information is augmented from the AMB controller by information related to the bearing loads as well as fundamental information regarding the rotor-bearing system stability. The bearing load information is characterized via bearing currents or bearing magnetic flux measurements that may be viewed and analyzed from remote. The rotor-bearing system stability data is enabled via the ability to measure transfer functions of rotor displacement for force (or voltage) disturbances across a broad frequency band by voltage signals injected into the controller from remote using the controller internal spectrum analyzer functionality. The API and ISO specifications on magnetic bearings, [11] and [12], respectively, recognize the significance of such transfer functions. Mechanical bearings have no comparable capabilities without a large amount of added complex features and external instrumentation. Third generation magnetic bearing technology provides the capability for internal spectrum analyzer functionality and remote connection via TCP/IP thereby adding a whole new dimension to the magnetic bearing system measurement capability. This is particularly relevant to gas cooled nuclear power plant machinery. All of this bearing current, flux, and transfer function information is available remotely from the AMB controller in order to assist in monitoring and diagnosing rotating machinery condition.

As examples, a waterfall plot from a current sensor with its frequency content taken in a machine rundown is shown in Figure 6. Figure 7 shows elimination of the rotor response of a machine at the rigid body mode from remote. Figure 8 shows the before and after vibration response of a machine following implementation of the authors’ company vibration attenuation algorithm from remote. These capabilities can be used for initial commissioning and subsequent maintenance troubleshooting. It can also be used to retune the machine after many years of operation where necessary. For example, changing impeller clearances may cause a change in cross-coupled impeller forces that start to degrade the stability of the rotor. Figure 9 shows an example of a stability plot before and after re-tuning. Increasing impeller seal clearances are a significant indicator of machine health and they may be measured by changes in the rotor ‘plant’ with magnetic bearings. The plots represented by Figures 6-9 and many more are available from the magnetic bearing controller.

![Fig. 6: Waterfall plot of machine shutdown showing bearing current frequency content.](image)

![Fig. 7: Remote tuning to eliminate machine response at rigid body mode.](image)
the machine or remote. By stepping a machinery engineer through the commissioning process in a structured sequence, Automated Commissioning enables a magnetic bearing system to be brought into operation without the presence of a magnetic bearing specialist. Being computer driven, Automated Commissioning is also faster compared to existing hands on commissioning procedures, and it collects and archives all necessary results, providing a baseline for scheduled maintenance.

For the first machine of a new design using magnetic bearings, tuning will be based on rotordynamic analysis, and this tuning will need to be verified by measurements on the real machine. The System Dynamics tool automates the collection and presentation of the performance data necessary to verify this theoretical tuning. Since the data collection can be controlled remotely, the specialist engineers responsible for rotordynamic analysis and design never need to visit the machine on site.

The System Dynamics tool also adjusts the controller parameters automatically to achieve predefined performance targets. The targets and criteria are saved in configuration files so they can be reused later in the lifecycle of this machine and speed up the tuning of the magnetic bearing controller. The tools use transfer function, spectrum analysis and harmonic (order) analysis functions built into the magnetic bearing controllers; therefore, specialist test equipment is not required to complete the tuning of the magnetic bearing.

Throughout the operating life of the machine, with this added functionality the end users will have the benefit of automated re-commissioning tasks after maintenance, independent of the magnetic bearing supplier or the machine builder. Furthermore, the plant operator can schedule routine measurements using the System Dynamics tools to measure and detect long term degradation in machine performance, and plan maintenance at the most appropriate time. Such degradation can be related to changes in the bearing vibration or current measurements, or changes in the basic rotor-bearing system stability as measured by changes in the transfer function measurements.

VI.E Auxiliary Bearing Reliability and Observability

Unlike the other internal magnetic bearing system components, the auxiliary bearings are expendable contact type devices and have finite service lives. Full use of their service life, i.e.
failure, means there is no longer any ability to provide further protection to the machine against internal rub damage between rotating and stationary components. Accordingly, auxiliary bearing failure may be accompanied by damage to the magnetic bearing system and/or internals of the rotating machine and therefore must be avoided beforehand in order to enable a replacement or take other preventative measures. Remote observability is thus very important.

The employment of bushings such as in Figure 5 where wear is the only real failure mode provides a superior capability for remote observability of the service condition because electronic clearance checking, both laterally and axially, may be performed using the magnetic bearing controller. This may be done by commanding rotor traverses in the bearing clearance while the rotor is levitated but not rotating. These traverses may be along the magnetic bearing control axes or preferably around the full circumference of the bushing thereby producing a complete profile of the bushing wear patterns. Such checks should be performed after any substantial contact event and before each restart of the machine.

The importance of such checks has been recognized in the magnetic bearing standards, [11] and [12]. For example, the auxiliary bearing language in [11] requires a means to detect auxiliary bearing contacts during machine operation and necessitates that the “operability” or service condition of the auxiliary bearings be observable without machine disassembly. Obviously, the impracticality of accessibility of machinery components inside a nuclear pressure vessel underscores the importance of such remote observability.

The way in which different auxiliary bearing designs fail is important in the determination of the risk of premature failure as well as the capability for remote assessment of the service life. Because of the uncertainty of the auxiliary bearing service life, and its shortness in terms of the ability to withstand more than a few full speed drop downs (or “landings”), the best way to address bearing failures is through statistical analysis that provides quantitative insight into the probability of obtaining the full design life. The Weibull statistical distribution is one means to accomplish this: it is the most widely recognized and employed tool by which to quantify life data and predict component reliability, [13]. The Weibull β shape or slope parameter characterizes the manner in which failure occurs while the η characteristic life parameter provides the time for which 63.2% of the population will fail (a standard Weibull measure). The two parameter Weibull cumulative distribution function (CDF), Abernathy (2000), provides the probability of auxiliary bearing failure, $F(t)$, up to life time parameter $t$, in this case the number of cycles or full rotor drops:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$  \hspace{1cm} (eq. 1)

Both Weibull parameters are important in life studies but $\beta$ is important here because it characterizes the risk in the early life of the auxiliary bearing system. The value of $\beta$ identifies whether the failure mode is predominantly of the infant mortality, random or wear-out type mode; these failure mode characteristics are captured by $\beta<1$, $\beta = 1.0$ and $\beta >1.0$, respectively. Complex auxiliary bearing designs with multiple failure modes will have separate CDF characteristics for each mode but with good design only one will predominate.

Differences in the numerical value of $\beta$ are apparent as differences in the slope of the CDF characteristic, Figure 10 where three different plots for $\beta = 0.5$, $\beta = 1.0$ and $\beta = 3.0$ of the dominate failure mode are shown for all three designs. Rather than the API minimum (which can be interpreted as $\eta =2$) $\eta =10$ is chosen as a reasonable characteristic life target for magnetic bearing equipped, high speed machines contained within a nuclear pressure vessel. The CDF characteristic of secondary failure modes will appear to the right of those shown in Figure 10.
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Fig. 10: Weibull plot showing desirability of wear failure modes for auxiliary bearings.

Referring to Figure 10 the plot with $\beta = 0.5$ obviously carries the higher risk as measured by its ordinate intercept with any service below the characteristic life. For example, at the API minimum of 2 cycles, the ordinate intercept is at CDF = 37% (compared to CDF = 19% and 37%) for the $\beta = 1.0$ and 3.0 values respectively therefore quantifying a high risk of premature failure for the two designs with $\beta \leq 1$ (assuming $\eta = 10$ for all three). Such differences in $\beta$ values may readily make up for differences in $\eta$ of individual designs leading to the general conclusion that wear out type failure modes such as found in bushings are favored for magnetic bearing applications in high value rotating machinery where investment protection is of vital importance. Moreover, since wear is remotely observable via clearance checking as discussed earlier, such designs have a clear superiority over other types that do not fail via wear, i.e. types employing moving parts that suffer from impact (yielding or rupture) or overheating, failure modes usually characterized by $\beta \approx 1$ because they happen randomly.

The positive observability effect on the CDF of wear measurements may be assessed statistically with reference to the expression for the median of the Weibull distribution, $T$:

$$T = \eta \ln 2^{(1/\beta)}$$ (eq. 2)

The values of $\beta$ and $\eta$ for a particular design may be extracted from rotor drop testing using conventional Weibull rank regression. However, this procedure requires testing until auxiliary bearing failure and therefore should only be conducted with dummy rotors. With knowledge of the apparent value of $\beta$ and $\eta$ for a given design, and recognizing that $\beta$ is a constant and the tendency is always to underestimate the value of $\eta$ for reasons of conservatism, the apparent new value of $\eta$ may be recalculated after each rotor drop using $\eta = T/\ln(2)^{(1/\beta)}$ where $T$ is the apparent median number of cycles to failure based on measured wear incurred since last the last drop. Generally, the effect of this measurement is to move the Weibull CDF to the right on the cycle plot reflecting the attainment and use of greater life. This capability does not exist for designs with infantile or random failure modes $(\beta \leq 1)$ that cannot be evaluated via clearance checks.

VII. SUMMARY AND CONCLUSIONS

The design of AMB systems for helium cooled reactor service follows many standard principles that have been applied in other demanding applications over the past thirty years. What is different is that as electronic components have become more reliable, AMB controller capability has increased and better understanding of auxiliary bearing characteristics, and best practices from a range of demanding applications have been adopted, very high reliability has been achieved. This meets the requirements of fourth generation nuclear power plant design. The innate intelligence now being fully exploited in the third generation AMB technology now available augments the fundamental virtues of high reliability and availability with remote observability and diagnostics not available in previous generations of AMB technology.

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