Design and qualification testing of active magnetic bearings for high-temperature gas-cooled reactors

Zenglin GUO*, Guohui ZHOU**, Richard R. SHULTZ***, Minlong QIAN** and Liang ZHU****
*Waukesha Magnetic Bearings
No.11 Wei Wen Road, Suzhou Industrial Park, Suzhou 215122, China
E-mail: zguo@waukbearing.com
**Shanghai Blower Works Co., Ltd.
No.3000 Gong He Xin Road, Shanghai 200072, China
***Waukesha Magnetic Bearings
99 Mechanic Street, Pawcatuck, CT 06379, USA
****INET of Tsinghua University
Haidian District, Beijing 100084, China

Abstract
Active magnetic bearings have been utilized in all recent high-temperature helium-cooled reactor designs as the only mature dry bearing technology to provide high reliability and availability of operations for these highly demanding applications. High reliability and availability is accomplished through proper design of the magnetic bearings, auxiliary bearings, and control and monitoring systems, as well as the exploitation of provisions for remote observability and diagnostics. Designing magnetic bearings into HTR fluid machines such as primary helium circulators and fuel ball blowers eliminates bearing lubricant contamination and also eliminates the ancillary equipment associated with the sealing systems for bearing lubricant. Recently a helium circulator and a fuel ball blower supported with magnetic bearings were tested separately and fully qualified for HTR plant operation. The magnetic bearings and auxiliary bearing systems were fully tested in a helium environment inside the machines. The current paper addresses the unique attributes in the design of magnetic bearing systems and the qualification testing performed for the HTR-PM fuel ball blower.

Keywords : Active Magnetic Bearing, HTR, Nuclear Power Plant, Helium, Fuel Ball Blower, Testing

1. Introduction

High-temperature gas-cooled reactors (HTR) are one of the major technology options for the next generation of nuclear energy development and receive extensive attention worldwide, due to their inherent safety, simplicity of system and high power-generation efficiency (Locatelli et al, 2013; Zhang et al, 2016). Active magnetic bearings (AMBs) have been utilized in all recent high-temperature helium-cooled reactor designs, including PBMR (South Africa), GT-MHR (Russia), GTHTR (Japan), and most recently, the HTR-PM (China), as the only mature dry bearing technology to provide high reliability and availability of operations for HTR nuclear power plants.

Use of AMBs for high-temperature helium-cooled reactor designs emerged 30 years ago as a result of wet bearings contributing directly to operating difficulties at the early AVR and THTR 2 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. Discussing 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 long down times, Brey (1987) concluded, “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, …”. After a turbine oil fire at the AVR reactor, Ziermann and Engel (1987), reported, “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)”. Following an incident where radioactive gas escaped after graphite fuel balls stuck in the fuel inlet of the THTR, Glahe and Stolzl (1988) stated, “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”. The prematurely shutdown and decommissioning of all three of these reactors was due in large part to issues that could be traced directly to inadequate design decisions involving the bearings.

As indicated by Glahe and Stolzl (1988), a precedent for equipping helium reactor machinery with magnetic bearings was established and has led all recent helium cooled reactor designs to consider and specify magnetic bearings for the primary coolant loop machinery. Designing magnetic bearings into the HTR fluid machinery eliminates bearing lubricant contamination and also eliminates the ancillary equipment associated with the sealing systems for bearing lubricant. The magnetic bearings are typically immersed directly in the process gas. Such duty means that the bearings will usually see high temperatures and pressures in service and be subject to attendant radioactive contamination over time. Despite these harsh conditions, the magnetic bearing systems must provide acceptable levels of reliability and availability while minimizing maintenance. This is accomplished through proper design of the magnetic bearings, auxiliary bearings, and control and monitoring systems, as well as the exploitation of provisions for remote observability and diagnostics.

The current paper addresses the unique attributes in the design of magnetic bearing system for HTR-PM fuel ball blowers and the qualification testing performed on these machines.

2. Magnetic bearing system design

In highly demanding applications such as HTR fluid machines, magnetic bearings are typically immersed directly in the process gas, in this case helium, in order to maximize design simplicity. In addition, specific considerations are given to the use of sealed or canned AMB technology, the bearing environment and cooling system design, the auxiliary bearing technology, and nuclear qualifications.

2.1 Design simplicity

A key benefit of applying magnetic bearing technology is the elimination of liquid lubricants. The capabilities of magnetic bearings can be fully exploited by employing hermetic designs with no dynamic seals of any kind. Doing so ensures the simplest machine design and intrinsically promises the highest reliability, as the ancillary support systems for bearings and seals are eliminated or reduced, along with the associated pressure vessel penetrations. With the elimination of shaft seals, the bearing compartments operate near system pressure and the bearings are immersed in the process gas. A general arrangement of the HTR-PM fuel ball blower with magnetic bearings is shown in Figure 1, which clearly shows the overall design simplicity achieved.

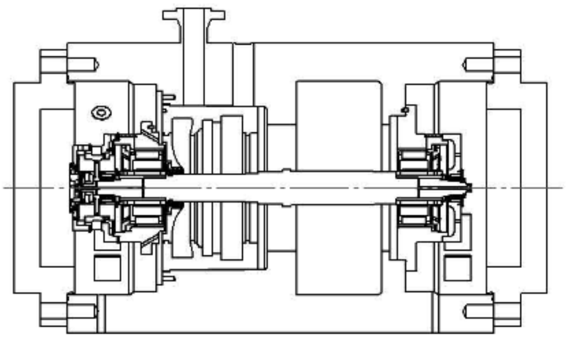

Fig. 1 HTR-PM fuel ball blower

2.2 Bearing environment and cooling system

In HTR fluid machines, the possibility of high concentrations of graphite particulates suspended in the gas stream especially in pebble bed fuel elements, complicates the bearing environmental requirements. Over time these particles may become lodged in bearing crevasses and cavities, posing a risk of radiation exposure for 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 graphite particulates could become lodged. ‘Sealed’ and ‘canned’ magnetic bearing designs (Figure 2) can address this challenge. The canned design is superior for 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. For each application, the customized cooling system is designed accordingly to fulfill the cooling requirement. In addition, qualification and selection of materials for long-term exposure to a radioactive environment shall be addressed in the design of magnetic bearing systems for such applications.

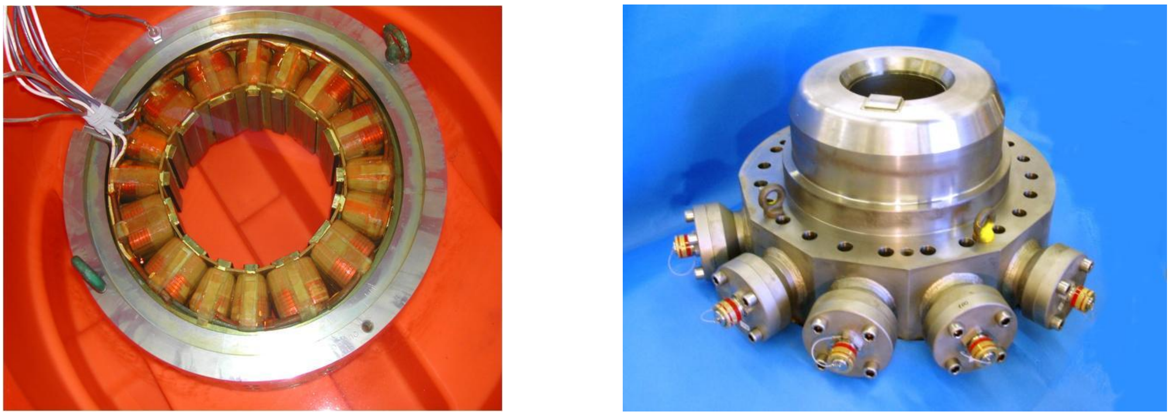

Fig. 2 Sealed (left) and canned (right) magnetic bearings

2.3 Auxiliary bearing design

Auxiliary bearings provide protection to AMB machines by preventing the rotor from contacting the stator parts during a landing event or at standstill conditions. Bushing type auxiliary bearings (Figure 3) are the most resistant design to particle fouling, an essential characteristic considering the bearing environment encountered in HTR applications. They also provide maximum reliability in the unlikely event that the rotor drops onto the auxiliary bearings due to loss of power or bearing overload. With no moving parts, bushing type designs have the highest inherent robustness. For extended coastdown times, however, auxiliary bearings with rolling elements may be required to maintain acceptable bearing temperatures.

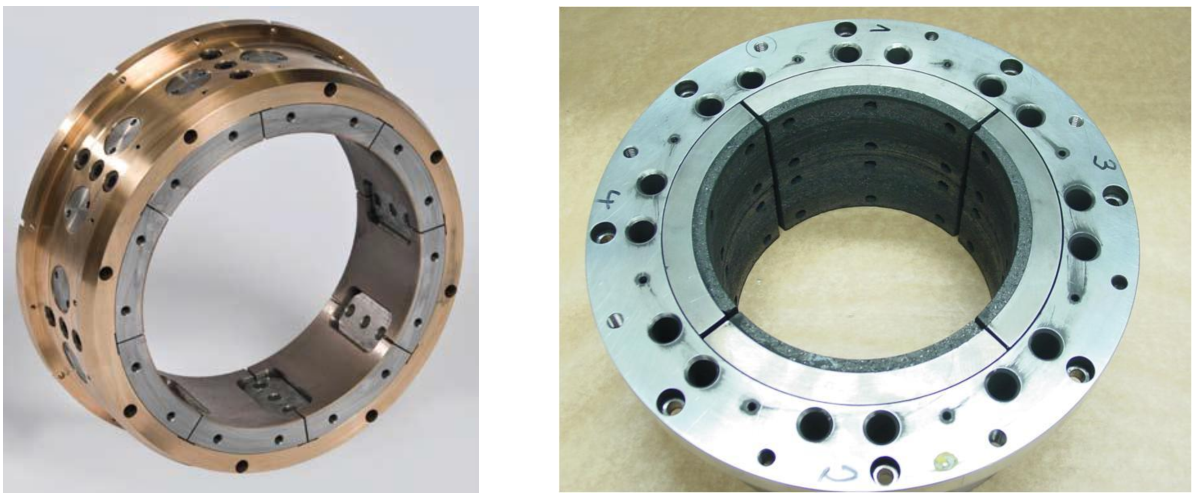

Fig. 3 Bushing type auxiliary bearings

2.4 AMB system seismic qualifications

Unlike most industrial applications, seismic loading events are of paramount concern for magnetic bearing systems used in high-temperature gas-cooled reactor applications (US NRC, 1973). This presents a unique set of design considerations for magnetic bearing system actuators and their control systems.

In general, seismic events can be classified as Operating Basis Earthquake (OBE, SL-1) and Safe Shutdown Earthquake (SSE, SL-2) in following the commonly recognized standards of 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 earthquake by ensuring the safe operation of machines under design basis operating events (OBE, SL-1) and the safe shutdown of machines under maximum design earthquake events (SSE, SL-2).

In the design of magnetic bearing systems for nuclear power reactors, a distinction should be made between large earthquake loads and other short-term loading events (Newmark et al, 1973; Vestroni, 2010). In the event of a complete failure of a magnetic bearing system, a signal is generated by the control system requesting a system shutdown. 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. Typically, an OBE or SL-1 is a short-term loading event, while in the case of an SSE or SL-2 event, the rotor may experience a complete rundown on the auxiliary bearings as part of the controlled shutdown sequence. The nature and duration of these overloads needs to be defined.

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

Mechanical components of the magnetic bearing system are qualified for seismic service through stress and deflection analyses, establishing that the integrity of the design will be maintained during seismic events (ASME, 2000). Static equivalent analysis method is a well recognized method for qualifying mechanical components for seismic and shock environments.

Nuclear qualification of the magnetic bearing control cabinet is based on its performance during the seismic events (IEEE, 2004). The control cabinet should maintain structural integrity and properly perform its specified functions before, during and after the OBE and SSE events. Since the control cabinet is typically installed away from the machine, this requirement may involve a special mounting design for the cabinet, to attenuate the transmission of seismic loading from the ground to the equipment. The seismic qualification test of controls is carried out to demonstrate the mounting design is fit for purpose.

3. Reliability design

Equipment for nuclear power plants demands a high level of reliability. A single failure mode in the magnetic bearing system has the potential to take down an entire plant, leading to a loss in power production. As in other systems, there are two fundamental approaches to the attainment of high reliability: ultra high reliability of individual components, especially those that comprise a single point failure; and built-in redundancy that may be implemented either manually or automatically. The choice between these two approaches is usually governed by considerations of allowable failure rates versus the costs of implementation.

3.1 Reliability considerations in the design

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’ type, where one additional “channel” is provided that may be brought into operation to replace an operating channel after fault detection.

From both a cost and reliability perspective, the number of pressure vessel penetrations needs to be minimized and special consideration is given to the arrangement of the penetrators used. Generally, separate penetrators are employed for the electric motor connections and the magnetic bearing connections. For the HTR-PM project, the wires for the magnetic bearings were arranged to go through two penetrators: one penetrator for the large cross section magnet wires and another penetrator for the small cross section sensor wires.

For auxiliary bearings, the selection of materials and associated lubricants has a fundamental effect on life and operability. The inertness and lack of any oxygen or water in the helium environment of HTR applications, coupled with the potential presence of hard particulates in the gas, present a significant challenge to the lubrication of auxiliary bearings, rendering most rolling element designs inadequate. To provide a low risk of failure following a machine event, the auxiliary bearings' contact surfaces will usually need to be protected by dry lubricated bushings and thrust washers that have been specially selected for long-term exposure in the inert and difficult environment.

3.2 Remote inspection and diagnostics

The condition monitoring of magnetic bearing-supported equipment is of particular concern when the equipment is located inside a pressure vessel. In nuclear power plants, the safety concerns and costs related to worker exposure during visual inspection of equipment are significant. Therefore, the equipment may be supplied with various diagnostic capabilities to assess and predict machine operability.

The operation and maintenance of rotor-bearing systems for helium service are readily assisted by the innate intelligence of the magnetic bearing system. This intelligence stems in part from rotor position and vibration information that is used to control the rotor with the electromagnetic forces of the bearings. There is a large body of work demonstrating the usefulness of vibration information in diagnosing rotating machinery condition; with a magnetic bearing system, this vibration information can be displayed and monitored remotely via the magnetic bearing controller.

Vibration information is augmented by information related to the bearing loads and rotor-bearing system stability. Bearing loads are characterized via bearing currents or bearing magnetic flux measurements. Rotor-bearing system stability data is obtained by measuring transfer functions of rotor displacement for force (or voltage) disturbances across a broad frequency via signals injected into the servo control loop. The API (2014) and ISO (2002/2004/2006/2012) specifications on magnetic bearings recognize the significance of such transfer functions. Mechanical bearings have no comparable capabilities without the addition of many complex features and external instrumentation.

As with all AMB functionalities, this internal transfer function analyzer can be configured via a web server interface. Internal transfer function analyzer functionality and remote connection via TCP/IP add a new dimension to magnetic bearing system measurement and are particularly relevant to gas-cooled nuclear power plant machinery. All of the 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.

Condition monitoring capabilities of AMB systems also include evaluation of auxiliary bearing condition. AMB onboard functions such as automatic clearance checks and trip data storage buffers are used to assess the auxiliary bearing condition after landing or contact events. After any unusual events, personnel can quickly determine whether the auxiliary bearings are fit for purpose for more landing events.

Where data is accessible through a data communications interface, the data would normally be captured by the plant data systems to allow trending and correlation of bearing behavior with power plant operating conditions. To facilitate remote diagnostics and diagnostics by on-site personnel, the magnetic bearing controller may be equipped with external tools which allow automation of routine and complex tasks in both the commissioning phase and when conducting diagnostics on an operational machine for health monitoring purposes. This Automated Commissioning capability requires training of plant staff as well as availability of the necessary communication network infrastructure.

Automated Commissioning is a suite of programs that automates the procedures followed by skilled magnetic bearing commissioning engineers. These programs run on an external computer that communicates with the magnetic bearing controller via TCP/IP networking; the computer can be near the machine or located remotely. 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 than existing hands-on commissioning procedures, and it collects and archives all necessary results, providing a baseline for scheduled maintenance.

Throughout the operating life of the machine, this added functionality provides end users with 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 then 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.

4. Qualification testing

The HTR-PM fuel ball blower machine and HTR-PM helium circulator machine with magnetic bearing systems have both successfully completed qualification testing with helium gas.

The HTR-PM fuel ball blower machine is a horizontal motor-driven compressor with a 240 kg rotor that is fully levitated with two radial magnetic bearings and one axial magnetic bearing. The qualification testing included running the machine with helium gas to ensure the cooling and thermal conditions of the machine were stable at the maximum speed condition. The bearing temperatures, vibration levels and bearing dynamic loads were all as expected. The vibration levels were measured and trended using the on board monitoring capabilities of the magnetic bearing system.

Auxiliary bearing testing was also conducted during the qualification. With the blower machine operating at maximum speed, the magnetic bearings were delevitated, causing a landing onto the auxiliary bearings. The coastdown curve of the landing event followed the expected decreasing speed trend due to the braking effect of the aerodynamic section of the machine. A specified number of full-speed landings were performed on the blower machine and subsequently an even higher number of full-speed landings were successfully conducted on a circulator machine. After each landing the built-in monitoring function of the AMB controller was used to assess the condition of the auxiliary bearings. In each case the built-in function predicted the auxiliary bearings were in excellent condition and fit for purpose for more landings.

5. Conclusions

The design of AMB systems for helium-cooled reactor service follows many standard principles that have been applied in other demanding AMB applications over the past 30 years, but specific design considerations are also implemented to provide the highest reliability and availability for these high-performance fluid machines.

Magnetic bearings and auxiliary bearing systems have been fully tested in a helium environment in HTR-PM fuel ball blower machines and successfully qualified.

References

American Petroleum Institute, API Standard 617: Axial and centrifugal compressors and expander-compressors, 8th edition (2014).

ASME, QME-1-2000, Qualification of active mechanical equipment used in nuclear power plants (2000).

Brey, H. L., Ft. St. Vrain performance, Gas-cooled reactors and their applications, IAEA-TECDOC-436 (1987), pp.61-69.

Glahe, E. and Stolzl, D., Circulator performance during THTR trial and post-commissioning operation, Gas-cooled reactor coolant circulator and blower technology, IWGGCR/17 (1988), pp.39-27.

IEEE, Std 344-2004, IEEE recommended practice for seismic qualification of class 1E equipment for nuclear power generating stations (2004).

International Standards Organization, ISO 14839-1/2/3/4: Mechanical vibration – Vibration of rotating machinery equipped with active magnetic bearings (2002/2004/2006/2012).

Locatelli, G., Mancini, M., and Todeschini, N., Generation IV nuclear reactors: Current status and future prospects Energy Policy, Vol. 61, No.10 (2013), pp.1503-1520.

Newmark, N. M., Blume, J. A., and Kapur, K. K., Design response spectra for nuclear power plants, ASCE Structural Engineering Meeting, San Francisco (1973).

US NRC, Regulatory Guide 1.60, Design response spectra for seismic design of nuclear power plants (1973).

Vestroni, F. and Lucarelli, V., Design requirements for seismic safety of NPP, International Technical Meeting on Seismic Safety of NPP, Tivoli, Italy (2010).

Zhang, Z., Dong, Y., and Li, F., The Shandong Shidao Bay 200 MWe high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant: an engineering and technological innovation, Engineering, Vol. 2, No.1 (2016), pp.112-118.

Ziermann, E., AVR experience, Gas-cooled reactors and their application, IAEA-TECDOC-436 (1987), pp.71-97.