MAGNETIC BEARING CONTROL SYSTEM FOR USE IN PHASE CONTROL OF HIGH-SPEED NEUTRON CHOPPERS

Kim T. Sundset, Tim Harris, and Shawn Gibson
Revolve Magnetic Bearings, Inc., An SKF Company, Calgary, Alberta, T2R 0B3, Canada
bearings@revolve.com, www.revolve.com

Chris. R. Rose, Ronald O. Nelson, Robert J. McQueeney
Los Alamos National Laboratory, LANSCE-12, Los Alamos, New Mexico, 87545, USA

ABSTRACT
Neutron choppers are used to vary the pulse widths and frequencies of neutron beams for use in material science. Similar to an electron beam used in an electron microscope, a tightly controlled neutron beam allows scientists to analyze the grain structure of a material at the atomic level. A Fermi-type neutron chopper produces a very narrow and precise energy beam utilizing a complex slit package that is positioned in line with the incident beam of neutrons. Magnetic bearings and a digital controller equipped with phase control provides high reliability and extremely precise control of the angular positioning of the slit package in the neutron beam at speeds up to 600 Hz (36,000 RPM). When the slit package is rotated at constant phase to the beam a precise frequency of neutrons is allowed to pass through. When not precisely aligned, curved boron slats imbedded in the slit package block the passage of neutrons. The combination of the curvature of the slats and the speed and accuracy of rotation allows for the precise control of the energy of neutrons that are allowed to pass through the neutron chopper and hit the target material that is being tested. All remaining neutrons are absorbed inside the Neutron Chopper[1].

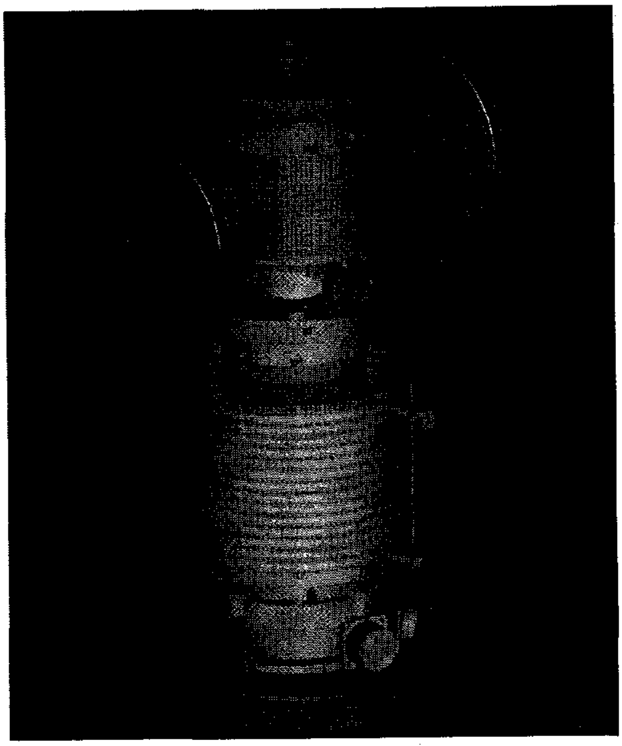

FIGURE 1: Fermi Type Neutron Chopper

INTRODUCTION
The purpose of a high-speed neutron chopper (HSNC) is to provide the means to select a fixed energy for the incident neutron beam that strikes a material sample under investigation. With such monochromation of the incident beam, the neutron-scattering instrument may perform inelastic studies, i.e., observe phenomena where the sample loses or gains energy from the incident neutron beam.

The slit package for the Fermi type neutron chopper, as shown in Figure 1 above, is several kilograms in mass and has a high speed of rotation (600 Hz) in order to interact effectively with neutrons. As a result, the chopper's moment-of-inertia and stored energy make it difficult to rapidly adjust the chopper frequency or phase. For some of the accelerator-based pulsed-spallation neutron sources, such as the one at Los Alamos National Laboratory, the proton pulses are phase locked to the local power grid which produces a pulse frequency that is modulated. For a phased-chopper spectrometer to work with these accelerators, the chopper must be forced to follow the varying power line frequency and phase[3]. Thus the problem becomes one of controlling chopper speeds while maintaining synchronization with the accelerator and the frequency and phase of the AC-power grid. Any signals that fall outside the allowable limits must be able to be detected and "vetoed" so that they do not obscure the test data. A single digital controller provides the magnetic bearing control, motor control, phase control, and the veto signal for the system producing a very efficient and highly reliable solution to the scientist's need for a high-resolution neutron beam.

MAGNETIC BEARING UTILIZATION

With a HSNC, which can operate up to 600 Hz (36,000 rpm), mechanical bearings are considered inadequate due to friction, heat, and general wear. With the utilization of magnetic bearings in the high-speed applications the scientist are becoming more aware of all the benefits of magnetic bearings and they are now being considered for all neutron chopper applications.

Magnetic bearing advantages in all neutron chopper applications include the following:

- Integration of bearing control and motor control including motor drive
- Integration of shutdowns with motor and bearing controller
- Digital phase control with collection of phase control statistics for performance evaluation
- Programmable Veto Window with BNC Veto-Out signal
- Interlock capabilities with auxiliary equipment with full alarm annunciation
- Local display of shutdown source as well as shutdown log
- MBScope™ software interface to view machine performance and alarm snapshots
- MBResearch™ interface to view real time analog signals of machine parameters
- Remote operation via RS-485 or by discrete input and outputs
- High machine reliability and bearing life
- Elimination of hydrocarbon and other mechanical bearing contaminates

The integration of magnetic bearing control with motor phase control allows for easier operation by the neutron scientists. Users can adjust the phase control parameters, running speed, as well as monitor the phase performance locally and remotely. In addition the controller has interlock capabilities with auxiliary systems such as uninterrupted power supply (UPS), vacuum, cooling, and remote emergency stop buttons, with full alarm annunciation. If there is a failure with another system, the neutron chopper system will shut down with the source of the shutdown identified. This makes it very simple for the user to configure a complete system as an integrated package.

Digital phase control utilizing a magnetic bearing controller has improved the phase locking performance by up to 50 times that of previous neutron chopper systems at speeds up to 600 Hz (36,000 RPM), allowing for more accurate alignment of the slit package in the neutron beam. The collection of phase control statistics allows users to rate performance, an important feature making the system much easier to use since there is no need for any external equipment. Statistics collected are phase accuracy, phase repeatability, and % of top-dead-center (TDC) pulses within a phase window.

Digital phase control also greatly increases the flexibility of the neutron chopper system for the users by the addition of features such as variable phase lag, Internal Reference Signal, TDC output, External Reference Input and Veto-out signal. Phase lag occurs via a time delay that can be adjusted to align the curvature precisely within the neutron beam. The Internal Reference Signal can enable the controller to act as the master signal which allows flexibility in the setup for users that do not want the system to be tied to the power grid. The TDC output can act as a master synchronization pulse for all other neutron chopper controllers in a beam line. The External Reference Input can accept a 50 or 60 Hz pulse train to allow synchronization to the electrical power grid. The veto signal allows the user to determine an adjustable window size in which to accept data. All TDC pulses falling outside the veto window can be rejected or "vetoed".

The utilization of magnetic bearings results in a higher reliability of the machine and bearing life over that of mechanical bearings. In addition, there is consistent steady drag resulting in improved phase control when compared to mechanical bearings which has changing drag over time that can cause a steady decline in the accuracy of the data produced. Magnetic bearings also solve the problem of grease and other hydrocarbons contaminating the beam line as is the case when using mechanical bearings. With the benefits of magnetic bearings and the functionality gained with integration of magnetic bearing control with motor phase control this magnetic bearing system is advantageous and affordable in both high speed and low speed neutron chopper applications.

SYSTEM REQUIREMENTS

The neutron chopper system operates in vacuum continuously at rated speeds from 60 Hz to 600 Hz (3,600 to 36,000 RPM), in speed intervals of 60 Hz (3,600 RPM). The operation must be extremely reliable at all speeds. It must allow for interchangeable slit packages (payloads) for flexibility in the experiments performed and must survive gamma radiation levels up to 2 x 10^6 rads over the course of its lifetime. The system must also be capable of phase locking to within an accuracy of ±0.054 degrees and repeatability specification of 0.108 degrees for each speed set point. For example, at 600 Hz (36,000 RPM) the phase accuracy requirement is ±0.25 μs and the repeatability is 0.5 μs[1].

INTEGRATION OF MAGNETIC BEARING CONTROL AND PHASE CONTROL

The controller used in this application is the MB350PC (Magnetic Bearing, 3 Amp, 50 Volt, Phase Control) Controller - a self-contained, fully digital, magnetic bearing and motor control system. It has been specifically designed for flexibility and ease of use, and to provide optimal performance. Features of the control system include:

- Integrated motor control with precision phase control capable of synchronizing to an external 60Hz source in 1 to 10 times speed increments
- Precision speed control that uses an internal speed reference or external analog input speed set point signal (0-10V or 4-20mA)
- A Veto-Out signal with an adjustable veto window width that allows data resulting from "bad" TDC pulses to be identified
- SISO (Single Input Single Output) control of 5 magnetic bearing axes
- Allows regular bias control or low bias control to reduce magnetic bearing losses
- 500W PFC (Power Factor Correcting) power supply and braking resistors to allow for quick stopping of the machine.
- Automatic power regeneration in the event of AC power loss or power supply failure
- Integrated alarming and shutdowns with the magnetic bearing controller, motor controller and auxiliary equipment contacts, and remote ESD button.
- 500 W auxiliary power supply that connects to the Controller to make 900W available to the motor amplifier.

These features provide the flexibility to customize the connection of the Controller to meet the specific application requirements.

MOTOR PHASE CONTROL

The magnetic bearing DSP electronics control the motor to synchronize the Once per Revolution pulse from the spindle to an external 60 Hz Reference pulse train. The rotation speed can be set between one and ten times the reference pulse to synchronize to the pulse train frequency. In addition, a time delay may be set between the synchronizing pulse and the once-per-revolution pulse for precise phase control[4].

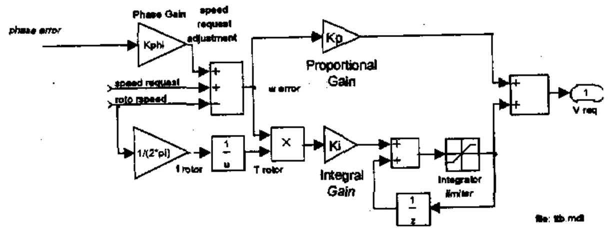

FIGURE 2: Phase Control Diagram

The phase control loop consists of two major parts: speed control (proportional-integral) and phase control (proportional). Ki and Kp -- respectively integral and proportional coefficients for speed control. Output of the phase control is added to the speed request. When Kphi is zero the compensator turns into a PI speed controller. A hardware counter is precisely clocked with a quartz-stabilized reference signal that is used as a time reference.

Phase error is measured as:

$$\Delta\varphi = \omega_r \times \Delta t_{tdc} = \omega_r \times (t_{tdcm} - t_{tdcr}),$$

where:

ω_r - request speed,

Δt_{tdc} - time delay between requested and actual (triggered) once per revolution pulse

t_{tdcm} - time when once per revolution pulse was triggered,

t_{tdcr} - time when once per revolution pulse was requested

DRIVE SPINDLE (MOTOR AND BEARINGS)

The neutron chopper drive spindle utilizes two 60-lb radial magnetic bearings and one 50-lb thrust magnetic bearing with a 90% efficient, 900-W, DC-brushless, motor. It operates up to 36,000 RPM in a medium vacuum of 100 mTorr and 2 x 10^6 rads of gamma radiation dosage levels. Features of the drive spindle include:

- Overhung design allows for easy accessibility to the top payload for quick interchangeability of slit packages. Interchanging slit packages allows for flexibility of customer tests requiring various energy levels of neutron beams. The design is such that minimal balancing is required upon assembling a new slit package.

- Revolve design of an integrated DC brushless, 900 W motor is utilized in the design of the Chopper system. The motor rotor is integral to the shaft providing a very efficient solution and allowing speeds to be achieved in excess of 36,000 RPM with phase control ability as described above.
- Extremely low loss bearing design for operation in vacuum environment.
- Complete success achieved on full speed drops with hybrid ball bearings. Exceeded five drops at 1,800,000 DN.

PERFORMANCE AND RESULTS

One of the Revolve SKF/LANL high-speed neutron choppers is being used successfully to chop beam for the LANL PHAROS neutron-scattering instrument. It provides superior neutron monochromation. Figure 3 shows the peaks of the passed neutrons.

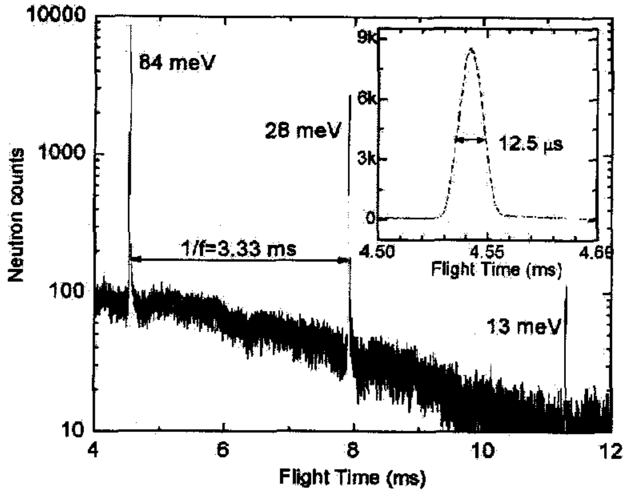

FIGURE 3: Neutron Spectra from the HSNC

Figure 3 shows a plot of neutron spectra from the high-speed neutron chopper taken in December 2001. The main figure shows neutrons counted in a detector placed just after the chopper. The chopper is placed at 18 meters from the neutron source, rotating at f=300 Hz, and is phased to transmit 84 meV neutrons (which arrive at the chopper 4.5 ms after the neutron pulse is created). Other transmissions occur every 1/f=3.33 ms with different incident energies. The inset shows the 84 meV transmission with a width of 12.5 microseconds (0.6 meV).

Jitter in the frequency and phase of the HSNC will cause a smearing to occur in the neutron energy. Figure 3 shows a clean gaussian shaped pulse. More jitter will smear this, and hence smear the incident energies of the neutrons, which in turn degrades neutron-scattering experimental results.

WHAT THE MAGNETIC BEARING SYSTEM HAS ALLOWED THE SCIENTISTS TO DO

One advantage of the present system is the ability to change payload housings and slit packages with relative ease. At present several high-speed neutron choppers with the digital magnetic bearing controller have been manufactured. Los Alamos has two choppers and three rotors, each with a different slit package designed to pass three different neutron energies, 100 meV, 300 meV and 1000 meV. These three rotors allow the instrument scientist to quickly reconfigure the chopper for a different energy.

SUMMARY

At present there are two Fermi neutron choppers installed and being used for material science experiments at Los Alamos National Laboratory. The magnetic bearing design has made it very easy for scientists, who are not familiar with magnetic bearing control, to use and operate the systems. Data is currently being collected that shows improved performance and reliability from the new Fermi choppers as a result of improved phase control using the MB350PC digital magnetic bearing controller.

REFERENCES

1. Technical Specification High-Speed Neutron Chopper, Los Alamos National Laboratory Lujan Center, October 23, 1998, Statement of Work No. 02061.
2. "What is Neutron Scattering And Why Is It Useful?", Allison Baldwin, Oak Ridge National Laboratory REVIEW, Numbers One and Two, 1998.
3. "Neutron Chopper Phasing For A Quasi-Periodic Pulsed Neutron Source", V. W. Bolie et al., p. 85-94, Nuclear Instruments and Methods in Physics Research A236 (1985), North-Holland, Amsterdam.
4. "Magnetic Bearing/Motor Controller MB350PC User's Guide", T. Harris, Revolve Magnetic Bearings Inc., 2001.