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PERFORMANCE OF FIELD MEASURING PROBES FOR SSC MAGNETS*

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ABSTRACT

Several years of experience have been acquired on the operation of probes ("moles") constructed for the measurement of the multipole components of the magnetic fields of SSC magnets. The field is measured by rotating coils contained in a 2.4-m long tube that is pulled through the aperture of the magnet by an external device—the transporter. In addition to the measuring coils, the tube contains motors for rotating the coil and a system for sensing local vertical using gravity sensors to provide an absolute reference for the field measurements.

We describe the steps that must be taken in order to ensure accurate, repeatable measurements; the design changes that have been motivated by difficulties encountered (noise, vibration, variations in temperature); and other performance issues. The mechanical interface between the probe and the beam tube of the magnet is also described.

MAGNETIC MEASURING SYSTEM

Components

The magnetic field in the aperture of an SSC magnet is determined by measuring the voltages induced on a number of rotating windings. These voltages are then Fourier analyzed to obtain the multipole coefficients. The system at BNL measures the voltages at 128 positions over one complete rotation of the coil. The field angles are determined relative to an absolute reference, the direction of the gravitational field. The part of the magnetic measurement system that is inserted into the aperture of the magnet (the "mole") is made up of the following components:

- three or more coil windings
- a hollow, cylindrical, coil-form made of epoxy-fiberglass or ceramic
- slip rings to bring out the electrical signals
- an electric or air motor for rotating the windings that is connected to the coil-form through gear reducers, torsional flex joints, and viscous dampers
- bearing supports
- precision and coarse-resolution gravity sensors mounted on a rigid, but rotatable, platform

- a precision optical encoder, mounted to the gravity sensor platform, for determining the angular position of the coil-form relative to the platform
- an air or electric motor for rotating the gravity sensor platform and encoder
- a tachometer for the gravity sensor drive
- a metal (brass) shell that encloses all the elements listed above
- electrical connectors (and, in the case of air motors, connectors for the air hoses).

External to the mole itself are:

- the mole control chassis and its remote interfaces
- cables for carrying the electrical and air signals ("tethers")
- the mole transporter which moves the mole through the magnet under computer control, the transporter control system, and its connecting cables
- a digital volt meter for each winding
- for cold measurements, a warm bore tube to maintain the mole at the desired temperature
- a temperature controller and heater cable for the warm bore tube
- a computer for controlling the equipment, performing the measurements, and storing the results.

Construction, Assembly and Calibration

Coil and Gravity Sensor Motors. In order to avoid damage and excessive wear, it is important that the motor, gear reducer and other mechanical parts of the mole should be operated only within the desired speed range. After assembly, each motor is tuned by finding the voltage values that give the desired fixed speed or speeds. The nominal rotation period of the coils is 3.5 ± 0.1 s (17.14 ± 0.5 rpm). The gravity sensor platform has three nominal rotation speeds as well as a pulse mode in order to allow the platform and encoder to be accurately zeroed with respect to gravity under program control.

Gravity Sensors. The mole incorporates electrolytic gravity sensors (Figure 1) in which the resistance of a conducting fluid in a curved glass tube is sensed and converted into an angle relative to gravity. The sensor has three terminals and acts as a potentiometer. Two sensors (one serves as a back-up) have a resolution of about 2 millidegrees and a range of $\pm 2^\circ$. The third sensor has a resolution of about 30 millidegrees and a range of $\pm 60^\circ$.

Each gravity sensor is adjusted and then fixed to the platform so as to minimize its sensitivity to a tilt of the longitudinal axis of the platform. The sensors are then rotated to specified angles using an indexing head, and a linear fit of angle vs. sensor output is produced for each sensor.

An angle of 0° is defined as a potentiometric voltage of 0 across the primary gravity sensor.

Coil Windings. The principal winding for obtaining the harmonics is the *tangential* winding and has a small opening angle (Figure 2). Other windings are provided to measure the fundamental component of the field and are wound on the same coil-form as the tangential winding. For example, to measure a dipole field, two dipole bucking windings are provided. The digitized voltages from these two windings are analyzed by the computer and digitally combined so as to produce a dipole component of the same phase and amplitude as that sensed by the tangential winding. This combined signal is then subtracted from the digitized voltages of the tangential

Figure 1. The high resolution electrolytic gravity sensor acts as a potentiometer whose setting is determined by the position of the sensor relative to vertical.

Figure 2. The coil form and three typical windings.

winding. The process is called "digital bucking." For the measurement of quadrupole fields, the coil-form has two bucking windings sensitive to the quadrupole field plus a dipole winding for removing the dipole component that is present when the coil-form is not collinear with the magnetic axis.

The amplitude of the field is not adjusted in the mole calibration procedure. Instead, the measured opening angle, radius, and number of turns of each coil is used to convert the voltage measurements into a field amplitude. For air moles, a dipole field of about 1.37 T can be applied, so it is possible to check the agreement with an NMR measurement of the same field.

The angle of the field is calibrated by determining an offset angle for each winding. This offset angle is the angle of the dipole field as measured by a given winding in the reference dipole magnet. This procedure assumes that: 1) the dipole component of the field produced by the reference dipole is precisely vertical, 2) the position of the index pulse from the encoder relative to vertical (gravity) is correctly reported by the primary gravity sensor, and 3) all 128 encoder positions used for acquiring field measurements during a single rotation are precisely spaced relative to the index pulse.

DIFFICULTIES AND SOLUTIONS

Vibration

Rhythmic vibration of the gravity sensor platform causes the liquid in the sensor to develop standing waves, and the resulting reading deviates actual angular position of the platform. New, larger gravity sensors are being incorporated in the moles that contain an electrolyte with a higher viscosity.

When the mole is calibrated in the reference dipole, it is placed in a supporting tube. It was observed that this support tube would vibrate when the coil motor was turned on. The support tube was stiffened up and the mole support modified to reduce these vibrations.

During the measurement of magnets at cryogenic temperatures, warm nitrogen gas flows through the bore tube. It was found necessary to shut off the gas during the time that a measurement was being acquired in order to eliminate vibrations produced by the gas flow.

Temperature

The gravity sensor reading is temperature dependent. To keep the sensor at a constant temperature during measurements, a small heater on the platform is used to maintain the temperature at $\sim 32 \pm 0.5$ °C.

This heater is sufficient for measurement of magnets at ambient temperature. For the cold measurements, a warm bore tube is inserted in the magnet. Both a single-wall and a double-walled bore tube have been tried with the double-walled giving more satisfactory results. The warm bore tube has an electric heater arranged in four strips along the length of the tube, spaced 90° apart. The current flow is such as to cancel the torque on the tube when the magnet is powered. The cancellation is not perfect however, so it has been found necessary to turn off the heaters during the time the measurement is being taken.

In the double-wall design, an insulating vacuum exists between the inner and outer tubes. This vacuum space is filled with 15 layers of superinsulation. The stainless-steel heater strips are mounted on the outer surface of the inner tube. Thermocouples are located in the vacuum space to monitor and regulate the temperature.

Magnetic Field Gradients

To verify that the gravity sensor readings do not change significantly in a dipole field, gravity sensors were rigidly mounted and inserted into a SSC dipole which was then ramped from 0 to 6600 A. No significant field dependence was observed. A magnetic field *gradient*, however, strongly affects the gravity sensor readings. The dependence is a strong function of the magnitude of the field gradient, so at low field gradients (< 65 T/m), the effect is negligible, but as the quadrupole current is increased, the deviation from the expected reading increases as $I^{-4.5}$. The

electrolytic fluid in the gravity sensors is, apparently, paramagnetic, and moves when subjected to magnetic field gradients, thus producing an incorrect reading.

Impact Forces

When the calibration of a mole is rechecked by placing it in the reference dipole, the reported phase angle will sometimes be shown to be different from 0.0° by as much as 0.1° . The shifts never occur gradually, but instead appear suddenly. The shift has been observed to alternate in sign.

The most likely sources of calibration shifts are 1) the encoder, along with the shaft and couplings connecting it to the coil form and the encoder connection to the gravity sensor platform, and 2) the gravity sensors themselves or the method used to affix them rigidly to the gravity sensor platform.

It is known that application of any dc voltage to a gravity sensor will plate out material on the metal pads inside the sensor and cause the readings to shift. However, shifts have now been observed in moles where the gravity sensor itself is protected by capacitors from ever having a dc voltage applied to it.

Even though moles are handled carefully, they can not be entirely protected from mechanical shock. To investigate the effects of impact forces on the mole, one mole was repeatedly struck, lightly but firmly, with a hammer in the region of the gravity sensor platform. This caused the phase angle to shift by $\sim 0.05^\circ$, and it did not return to the original value.

The shifts may therefore principally result from jarring, mechanical shock, and bending of the mole when moving it from place to place, inserting it into a magnet, and pulling it through the magnet.

Some moles (FA3 and RA1), while showing shifts initially, are not observed to change subsequently over periods of months (two and three months, respectively).

To prevent errors from calibration shifts, a short permanent magnet that can be precisely leveled will be used. Before the mole enters or exits a magnet, it will pass through the permanent magnet where a measurement will be taken to verify that the phase angle calibration has not changed.

FUTURE WORK

Field Gradients

For short quadrupole magnets, it may be possible simply to locate an electrolytic sensor beyond the influence of the field. Otherwise, it will be necessary to develop or use a new type of gravity sensor. For example, a pendulum with some optical means of determining the pendulum's angle relative to some reference.

Calibration Shifts

In order to investigate the sudden small shifts in the measured phase angle of the reference dipole, two mole subsystems will be constructed. One will examine the output of the small Teledyne-Gurley optical encoder used with the moles relative to that of a larger (and presumably more stable) BEI encoder on the same shaft. The other will investigate the effects of shock and movement on the gravity sensors. Each subsystem will be portable and will be subjected to the same kinds of impact forces that these devices would be expected to encounter when used in a mole.

CONCLUSIONS

The moles that have been developed are capable of highly precise measurements of the multipole components of the magnetic fields of SSC magnets. Small shifts in the reference phase angle are observed to occur. A permanent magnet will be used to detect these shifts to insure reliable absolute phase angle measurements. Other difficulties resulting from rhythmic vibration of the mole and temperature fluctuations have been largely overcome.

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