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AN-108

APPLICATION NOTE

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COMPENSATION OF EARTH'S FIELD WITH A THREE-AXIS HELMHOLTZ COIL

INTRODUCTION

A three-axis Helmholtz coil assembly, a bipolar power supply (BOP) and a three-axis magnetometer can be used to dynamically cancel the Earth's magnetic field in a control volume at the center of the coil assembly. The magnetometer sensor, which is located in the Helmholtz coil assembly near the control volume, is used as a null detector in a negative feedback loop that drives the Helmholtz coils.

The sensor measures the difference between the Earth's field and the opposing Helmholtz coil field. This difference signal is applied to the input of the BOP that is driving the Helmholtz coil. If the difference signal indicates that the ambient field is greater than the Helmholtz coil field, the BOP increases the magnitude of the Helmholtz coil field. Likewise, if the difference signal indicates that the ambient field is less than the Helmholtz coil field, the BOP reduces the magnitude of the Helmholtz coil field. Eventually a steady state condition is reached where the difference between the two fields is very small, in fact near zero.

How close to zero the difference field becomes depends on the forward gain of the feedback loop. Such a system can usually attenuate the 50 µT to 60 µT (500 mG to 600 mG) Earth's magnetic field to under a few nT (1 nT = 0.01 mG = 1 gamma).

This system automatically attenuates any changes in the ambient Earth's field as well as local disturbances that produce a uniform change in the control volume.

The following sections provide a more detailed description of how the system works, including the mathematics behind it.

SYSTEM TOPOLOGY

Figure 1 is an overview of the closed loop system described in the introduction.

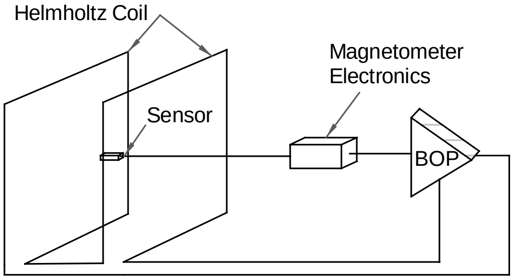

Figure 1 Feedback System Topology

The sensor is placed at the edge of the control volume and inside the Helmholtz coil. Normally the control volume is in the middle of the Helmholtz coil. The size of the control volume depends on the size of the Helmholtz coil and the desired zero field error. A typical control volume for a 4 meter (side length) square Helmholtz coil might be a 40 cm diameter sphere about its center.

The magnetometer electronics unit excites the sensor and processes its output. The magnetometer output is an analog signal that is proportional to the field detected by the sensor. The output of the magnetometer drives the BOP which in turn drives the Helmholtz coil.

Fluxgate magnetometers are particularly suited for this application. These magnetometers are rugged, reliable, relatively inexpensive and have the sensitivity and dynamic range needed to achieve a very good null in the control volume.

CONTROL SYSTEM OPERATION

Figure 2 is the block diagram for the feedback control system.

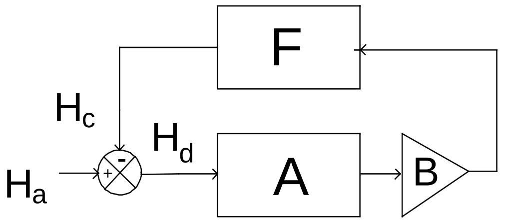

Figure 2 Feedback Control System Block Diagram

The symbols are defined below.

H_c = Helmholtz coil field (nT).

H_a = Ambient Earth's field (nT).

H_d = Difference (residual) field (nT).

A = Magnetometer transfer function (V/nT).

B = BOP transfer function (A/V).

F = Helmholtz coil transfer function (nT/A).

The following equation gives the ratio of the difference field to the ambient Earth's field.

$$\frac{H_d}{H_a} = \frac{1}{1 + A \cdot B \cdot F}$$

This ratio is a direct measure of the ambient field attenuation that can be expected.

Although *A, B* and *F* are functions of frequency, at dc or low frequencies they are essentially constant. Typical values for these parameters are:

A = 1 V/nT.

B = 0.6 A/V.

F = 50,000 nT/A.

Thus a system having these parameter values would attenuate the ambient field by a ratio of 1:30,000. In the presence of an ambient field of 60 µT, the field in the control volume would be on the order of 2 nT. The higher the value of the *ABF* product, the higher the attenuation factor.

This system will even attenuate low frequency uniform fields. The upper frequency depends on the frequency response of the magnetometer and BOP as well as the electrical properties of the coil system.

Even though the sensor is offset from the control volume, the attenuation factor described above will be achieved. The Helmholtz coil field is fairly uniform over a large volume so the difference between the field at the center of the coil and the sensor will be small. A bias signal can be added to the magnetometer sensor field to trim the control volume field to the desired zero field level.

AN ALTERNATIVE APPROACH

The Earth's field compensation system described above relies on a high sensitivity analog magnetometer to measure the difference field near the control volume. This approach has the advantage of continuous compensation of the Earth's field and other sources that produce uniform magnetic disturbances in the control volume.

There is another approach. A high resolution three-axis digital magnetometer, such as MEDA's FM300, can be used to sense the difference field. The FM300 has an RS232 serial output that can be connected to a conventional PC serial port for the acquisition of magnetic field data. Commercial power supplies, including the BOP, can be purchased with an RS232 or IEEE-488 interface for transmitting data and control information to the power supply.

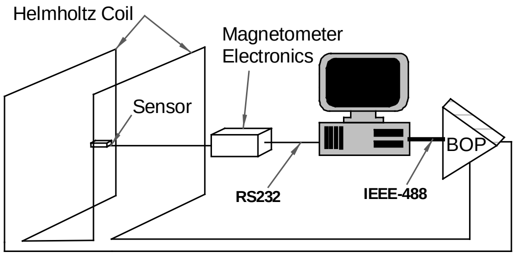

Figure 3 A High Resolution Magnetometer Approach

Figure 3 illustrates how this alternative system could be configured. A typical operational sequence of events might be:

1. Turn off the compensating field.
2. Read the ambient magnetic field measured by the digital magnetometer.
3. Compute the BOP value that is needed to cancel the ambient field.
4. Transmit the computed values to the BOP over the IEEE-488 buss and turn on the compensating field.

5. Read the difference field measured by the digital magnetometer.
6. Adjust the Helmholtz coil compensating field to achieve a lower difference field.
7. Repeat steps 5 and 6 until the difference field is within some prescribed limits.

Once the initial ambient field has been compensated (cancelled), the computer must periodically sample the difference field and trim the Helmholtz coil field as necessary to keep the control volume field within the desired limits.

A BOP with an IEEE-488 or serial interface has a finite resolution which limits the level of compensation that can be achieved using this approach. Commercially available BOPs, such as those manufactured by Kepco, have a 12-bit resolution. If the field to be compensated is 50 µT, then the step size for the compensating field will be about 25 nT.

One advantage of this approach is that it is relatively simple to set up. The Helmholtz coils, three-axis digital magnetometer and BOP are off-the-shelf items as are the computer and the IEEE-488 interface card. Some mechanical design is required to locate and secure the sensor inside the coil. Also, a computer program to control the operation would have to be developed, but it could be a rather simple one.

A disadvantage of this approach is that it is much slower to react to ambient field changes than the analog approach described earlier. The iterative process of repeatedly reading the magnetometer output, computing the correction field and transmitting the data to the BOP, until the desired limits are reached, takes time. Fortunately, ambient field changes are relatively slow. Sampling the difference field every few seconds or even once a minute is probably adequate for most situations.

Another disadvantage of this method is that the computer program monitoring and controlling the system must be continuously operating in the background in order to respond to ambient field changes in a timely manner. If the computer is being used for other tasks, this background operation might be a significant burden. Modern multitasking operating systems such as Microsoft Windows 95, Windows 98 and Windows NT 4.0 can usually handle the relatively low computer demands of this alternate approach without a problem.

A HYBRID SYSTEM

A third approach, which overcomes the BOP digital interface resolution limitation, is to drive the BOP analog input using a high resolution (e.g., 16-bit) digital-to-analog converter (DAC). Multichannel DAC plug-in boards are available for PCs at a reasonable cost. The hybrid system equipment configuration is the same as that shown in Fig. 3 with the IEEE-488 connection to the BOP replaced by a cable carrying the DAC output signal.

The cost of the DAC board is usually less than the cost of the IEEE-488 interface card that plugs into the BOP, but the hybrid system requires some additional DAC to BOP interface design and assembly. The cost to develop the operating computer program is about the same.

The Hybrid system can be extended by replacing the digital magnetometer with an analog one and using a high resolution analog-to-digital (ADC) converter PC plug-in board. The cost of the ADC board will be offset by the smaller cost of the analog magnetometer, but the cost to develop the operating program will increase.

GENERATING PRECISON FIELDS

Often the reason for building a three-axis Helmholtz coil system is to have the ability to set the field level within the control volume to some known value. Maybe the user is calibrating magnetic field sensors or trying to simulate Earth's field at specific locations around the world or testing the magnetic properties of a spacecraft. Both of the systems described above can be used for this purpose.

Analog Magnetometer Approach

Known magnetic fields can be generated in a high sensitivity analog magnetometer based system by biasing the magnetometer signal. The difference field value presented to the BOP input is the sum of the actual control volume difference signal and the bias signal. The BOP will adjust the Helmholtz coil field until it equals this sum. The result will be a field in the control volume that corresponds to the bias value.

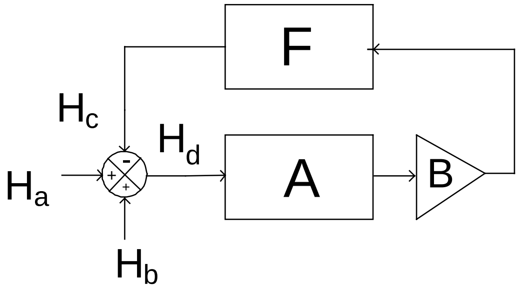

Figure 4 Control Loop with Bias Input

H_b in Fig. 4 is the bias field. The negative feedback control loop will drive H_d towards zero by adjusting H_c. The steady state value of H_c will be approximately equal to $-(H_a + H_b)$, and the net field in the control volume will be close to $-H_b$. The following equation can be used to compute the control volume field.

$$(H_a - H_c) = -H_b\left(\frac{A \cdot B \cdot F}{1 + A \cdot B \cdot F}\right) + \frac{H_a}{1 + A \cdot B \cdot F}$$

Using the typical values for *A, B* and *F* given above, the net field in the control volume is

$$-0.999967 H_b + H_a/30{,}000$$

The ambient Earth's field is attenuated to the same level as it would have been without the bias, and the field within the control volume is within 0.003% of the bias field value.

A variable current source driving a solenoid wound around the sensor is one way to generate the bias field.

Digital Magnetometer Approach

In the system described above that used the digital magnetometer and a computer to control the Earth's field compensation system, the objective was to create a control volume in which the magnetic field was close to zero. This approach can be extended to generating known fields other than zero in the control volume. This is done by setting the field limits for the control volume to bound the desired field value. The accuracy of the field will depend on the accuracy and resolution of the digital magnetometer and the BOP.

The same limitations described earlier also apply with respect to the generation of the known field. If the local ambient field is changing rapidly, the system may not be able to adequately keep up with the changes. The result will be a noise signal that rides on top of the generated field. This is still a good approach for applications that do not require a high degree of precision or stability.

MAGNETOMETER PROPERTIES

The magnetometer characteristics determine the overall performance of the Earth's field compensation system. The purpose of the system determines which characteristics to emphasize.

Zero Offset Errors

The most important magnetometer property is its zero field stability. In the closed loop configurations described above, the system will try to drive the magnetometer output to its zero field value. Although the initial magnetometer zero field output can be corrected, changes caused by magnetometer drift will cause the field in the control volume to change.

Sensor Alignment Errors

A three-axis fluxgate magnetometer measures the three vector components of a magnetic field with three fluxgate sensors that are aligned at 90 degrees to one another and to a reference orthogonal (right hand) coordinate system. The sensor alignment errors indicate how well these sensors satisfy this prescribed configuration. Any misalignment will cause a coupling between the three feedback loops that form a complete Earth's field compensation system.

The high sensitivity analog magnetometer configuration will automatically correct for these errors as long as the errors are small (under a few degrees). Angular alignment errors are more difficult to accommodate in the digital magnetometer system configuration. Each time a correction is made in one axis, it will cause a change in the other two axes. This increases the length of time required to iterate to a prescribed limit.

Analog Magnetometer Sensitivity

The analog magnetometer should have sufficient sensitivity so that

1. The *ABF* product in the feedback loop equation is much greater than 1 and,
2. The error caused by BOP zero offset is insignificant.

Of the three transfer functions in the feedback loop, the magnetometer sensitivity is the most important. By keeping its value high, the errors associated with the BOP and the Helmholtz coil become less important. For example, the BOP zero offset referred to the sensor input is

$$H_{off} = \frac{V_{off}}{A}$$

where V_{off} is the BOP offset voltage and H_{off} is the equivalent field offset in the control volume.

If A equals 1 V/nT, then a 1 V BOP zero offset will only produce a 1 nT equivalent field offset in the control volume. On the other hand, a 1 mV/nT magnetometer sensitivity will result in an equivalent field offset of 1000 nT for the same BOP zero offset. Also, to maintain the same level of Earth's field attenuation, any reduction in magnetometer sensitivity must be made up by changes in the BOP and/or Helmholtz coil transfer functions.

Digital Magnetometer Resolution

The lowest resolution component in the digital magnetometer based system will determine the degree of Earth's field attenuation that can be achieved. Commercially available BOPs, with a maximum resolution of 12 bits when controlled over a digital interface, are the usual limiting components. The magnetometer resolution should be at least twice the BOP's resolution (13 bits or better with a 12-bit BOP).

OPEN LOOP SYSTEMS

A closed loop Earth's field compensation system automatically corrects for changes in the ambient field, but an open loop system is an acceptable approach for less demanding applications.

In an open loop system there is no control magnetometer. The nominal ambient field is cancelled by applying fixed voltages to the input of the BOP. The voltages are trimmed until the magnetic field in the control volume is within the desired limits. Earth's field changes and local disturbances will not be attenuated in the control volume, therefore the control volume field must be measured from time to time and adjusted to keep it within bounds.

There are several methods that can be used to initially set the compensation fields and then trim them as needed. Figure 5 illustrates one technique.

In this example, a simple interface circuit uses the BOP reference voltages and resistors to set the nominal Earth's field compensation. R3 is chosen to provide a coarse compensation field. R6 provides a fine adjustment of the field.

Also illustrated is a technique for using a computer to trim the compensation field and applying known fields. R1, R2 and R5 are determined based on the desired zero trim and field range.

Two 12-bit DACs under the control of the PC

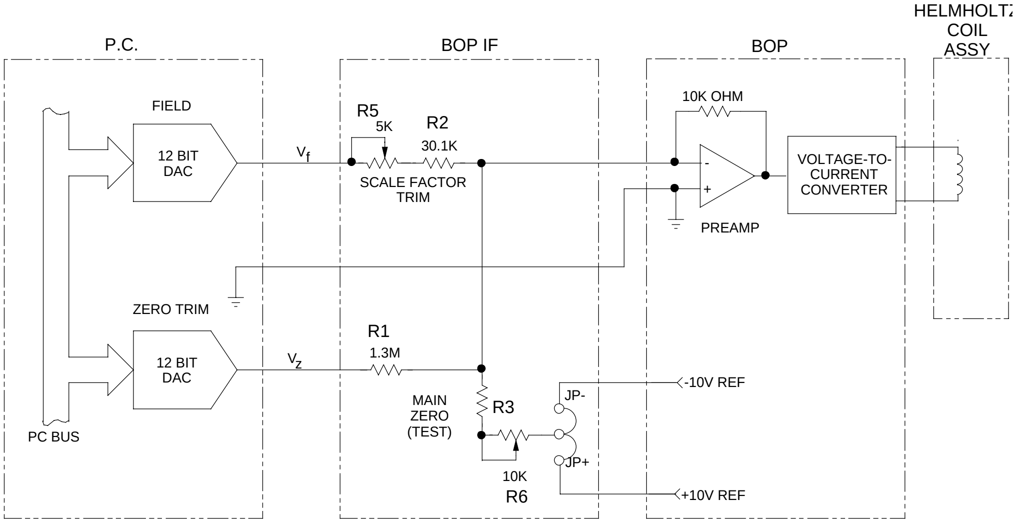

Figure 5 Example of One Axis of an Open Loop System

generate the control voltages. 16-bit DACs could be used to achieve greater field resolution.

A magnetometer is needed to set the initial ambient magnetic field compensation and the scale factors for the field application circuit. This same magnetometer can be used from time to time to trim the field in the control volume if it has gone out of established bounds.

BUILD OR BUY

This is the age old question when considering how to satisfy a need. Commercial turn-key systems are available on the market today. The cost of a turn-key system might be considered high (from $50,000 to $125,000), but the buyer does not have to deal with the problems of purchasing components from various vendors and then trying to integrate the system and develop the operating software.

On the other hand, building your own system means you have control over its quality and features. If you have the appropriately qualified technical staff, this may be the best way to go.

MEDA Turn-Key Systems

MEDA offers 1, 2 and 4 meter (side length) square three-axis Helmholtz coil systems with closed or open loop Earth's field compensation and precision field generation.

The MEDA closed loop system uses the negative feedback high gain analog magnetometer approach. It is the system of choice for applications that require very good attenuation of Earth's field and local disturbances.

The open loop system does not use a magnetometer to nullify Earth's field. This is done manually by the user. The open loop system also does not automatically correct for ambient field changes. The open loop system is less expensive than the closed loop system and is more appropriate for applications that can tolerate small changes (several hundred nanotesla) in the control volume field.

Building Your Own System

If the decision is to build your own system, then the tables below will be helpful. The first table lists the major common components that you will need to build a closed loop three-axis system and their approximate cost. The second table lists the additional components needed to build a low cost digital magnetometer based system. The third table lists the additional components required to build the more expensive high sensitivity analog magnetometer based system.

Table 1 Common System Components

Component	Qty.	Vendor	Total Cost
2 Meter 3-Axis Coil Assembly	1	Various	$15,000
BOP	3	Kepco	$7,500
Rack	1	Various	$500
		Total	**$23,000**

Table 2 Additional Components for Digital Magnetometer Based System

Component	Qty.	Vendor	Total Cost
3-Axis Digital Magnetometer	1	MEDA	$3,500
Computer	1	Various	$1,500
IEEE-488 IF for BOP	3	Various	$2,200
		Total	**$7,200**

Table 3 Additional Components for High Sensitivity Analog Magnetometer Based System

Component	Qty.	Vendor	Cost
Three-Axis Coil Control Magnetometer	1	Schonstedt Instrument Company	$25,000

You must add to these costs the costs to assemble and integrate the hardware and to develop the software needed to operate the system.

Other useful equipment to have include:

1. A multilayer magnetic shield for periodically checking the zero field output of the control magnetometer.
2. A shield demagnetizer for cleaning the magnetic shield.
3. Spare system components in the event of equipment failure.