MAGNETIC MEASUREMENTS

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Summary

Magnetic fields have played an important role in human history since the discovery of the lodestone in prehistoric times. Devices based on magnetic fields are used to navigate, generate electricity, convert electrical energy into mechanical energy, control spacecraft attitude, and perform many other tasks that make life easier. This article reviews the various techniques used to accurately measure the weak magnetic fields produced by the brain and the strong magnetic fields generated by superconducting magnets. The measurement devices are divided into two categories: vector and scalar. Instruments that measure the magnetic-field vector magnitude and direction include the extremely sensitive superconducting quantum interference device (SQUID) magnetometer used to measure small changes in magnetic field; the rugged and reliable fluxgate magnetometer, which finds application in general-purpose weak magnetic-field measurements; and the Hall-effect magnetometer that can measure the very high fields produced by magnets. Also included in this category are new sensors based on anisotropic magnetoresistance (AMR) and magnetostriction (fiber-optic magnetometers).

Scalar magnetometers, which only measure the magnitude of the magnetic field, are called nuclear magnetic resonance (NMR) magnetometers, since their operating principle depends on electron or proton resonance phenomena. Included in this category are the proton precession, helium, and alkaline-vapor magnetometers. These NMR magnetometers serve as primary standards for the measurement of magnetic fields. The article concludes with a discussion of tools that can be used to generate magnetic fields and calibrate magnetic field devices.

1. Introduction

The magnetic field is a fundamental property of the earth, the sun, and many planets in our solar system and indeed in the universe. Humans use magnetic fields to navigate, to control spacecraft attitude, to produce rotary and linear motion, to generate electrical power, to heal, to view the biological activities within the human body, to move objects, to hold notes on refrigerator doors, to latch cabinet doors, to measure car speed, to detect buried objects, to detect the presence of vehicles, to propel projectiles, to convert sound into electric currents, to convert electric currents into sound, to deflect electrons in a cathode ray tube, to store information, and so on and so forth. There is also strong evidence that animals use the earth's magnetic field to navigate.

A moving electric charge produces magnetic fields, whether it is electrons flowing in a wire (electric currents), ions flowing in a fluid, electrons moving around the nucleus of an atom, or a spinning proton. Like gravity, a magnetic field causes action at a distance since its influence extends beyond the source producing it. The magnetic field is a vector quantity, that is, it has two properties: magnitude and direction. Magnetic-field measuring instruments measure one or both of these properties.

Throughout this article we will refer to all magnetic-field measuring instruments as magnetometers, even though "gaussmeter" is often used to describe these devices as well. Table 1 lists the characteristics of several types of magnetometer. Modern practical magnetometers can be divided into two classes: the vector types and the scalar types. The vector magnetometer, as its name implies, measures both the direction and magnitude of the magnetic-field vector. Scalar magnetometers measure only the magnitude of the magnetic field.

Type	Field range	Frequency range	Characteristics
Fluxgate	100 pT–200 μT	DC–2 kHz	Low power, rugged, wide-operating temperature range, and small size.
Induction coil	1 fT–1 T	0.01 Hz–1 MHz	Low power, large field range, wide frequency range, and rugged.
SQUID	1 pT–100 μT	DC–10 Hz	Highest sensitivity, but requires cryogenic apparatus.
AMR	5 nT–200 μT	DC–10 kHz	Medium power, rugged, small size, and low cost.

Fiber optic	100 pT–100 μT	DC–10 Hz	Under development
Hall effect	10 μT–50 T	DC–1 MHz	Very small size and low cost. Good for measuring high fields in small spaces.
NMR	20 μT–100 μT 10 pT resolution	DC–5 Hz	Highest absolute accuracy. Usable as a calibration system standard.

Table 1. Typical magnetometer characteristics

Vector magnetometers use one or more sensor elements to measure the three components of the magnetic-field vector. The sensor element has a well-defined sensitive axis. It responds to the projection of the magnetic-field vector along this axis (see Figure 1). When the sensor's sensitive axis is aligned with the field, its output is at a maximum.

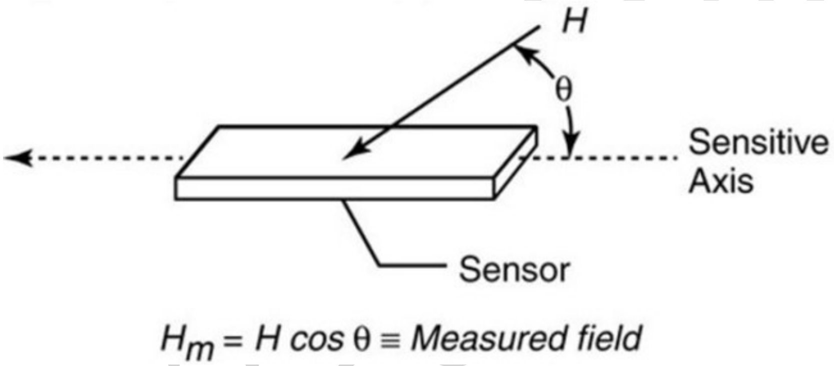

Figure 1. A vector magnetometer sensor measures the projection of the magnetic-field vector onto its sensitive axis

A single sensor can be used to measure the magnetic-field vector by rotating it until the sensor is aligned with the vector. The sensor-output magnitude indicates the field strength, and the sensor orientation indicates the vector direction. Some magnetometers use three sensors that are oriented at right angles to one another to measure simultaneously the three components of the magnetic-field vector. The three sensors form a reference coordinate system. The vector direction is determined by standard trigonometric calculations based on the values of the measured components. The vector magnitude is the root mean square of the three components.

Commercially available vector instruments include the induction coil, fluxgate, Hall effect, magnetoresistive, and SQUID magnetometers. The fiber-optic magnetometer also measures the magnetic-field vector, but it has not yet left the laboratory.

Scalar magnetometers use atomic resonance to measure the magnitude of a magnetic field and are usually referred to as nuclear magnetic-resonance (NMR) magnetometers. Their designs are based on the Zeeman effect, which was discovered in 1901, and the principles of quantum mechanics. Zeeman found that the energy levels within an atom split into a hyperfine structure when subjected to a magnetic field. Resonance magnetometers stimulate atoms into the higher energy levels of this hyperfine structure and measure the frequency of the radiated energy while the atoms return to their preferred energy levels. The frequency of the radiated energy is given by the following equation:

$$f = \frac{\gamma \cdot H}{2\pi} \quad (1)$$

where γ is the gyromagnetic ratio of the electron or proton, H is the field, and f is called the Larmor frequency. Since the gyromagnetic ratio is very well known and frequency can be determined quite accurately, the magnetic-field magnitude can be measured to a very high degree of accuracy. The proton-precession magnetometer that is used for geophysical exploration is the best-known scalar instrument. Other scalar instruments include the helium and alkaline-vapor magnetometers.

A magnetic-field measurement is only as accurate as the instrument that is used to make the measurement. Effective use of these instruments requires an understanding of calibration techniques and measurement error sources. Instruments that measure voltage, resistance, or frequency derive their accuracy from a primary standard that is established by a national laboratory (in the United States it is the National Institute of Standards and Technology or NIST). There is no such primary standard for magnetic fields.

Calibrating magnetometers normally requires constructing a coil or set of coils through which a current is passed that produces a uniform magnetic field in a volume of space. The magnetometer being calibrated is placed in this uniform field and its response is measured as the field is varied. Solenoids and Helmholtz coils are the two most popular methods for generating a uniform magnetic field. The coil system dimensions and the coil currents determine the magnetic field. The field in the volume is measured directly or computed using accurate measurements of the coil system dimensions and the currents. An NMR magnetometer, which is the closest to a magnetic-field primary standard there is, can directly measure the field if the volume is large enough to accommodate its sensor. To determine the zero-field reading, a magnetometer is usually placed in a magnetic shield constructed of highly permeable material, such as Mumetal. A well designed and constructed shield will have a residual magnetic field of less than 2 nT.

The accuracy of the calibrating field is only one source of measurement error. Other sources include linearity, zero-field reading, and temperature stability. In vector magnetometers the alignment of the individual sensor elements to some reference coordinate system is an important error source. Corrections can be made for all these error sources to reduce overall uncertainty in the measurement.

Often overlooked is the influence the earth's magnetic field has on magnetic measurements. We are enveloped in a magnetic field that can vary in strength and direction from a horizontal field of 30 μT at the equator to a vertical field of 70 μT at the magnetic poles. Locally, the field appears uniform in strength and direction over great distances (hundreds of meters). It magnetizes ferromagnetic objects, producing local distortions in the uniformity of the field. In some cases this distortion is a benefit if the purpose of the field measurements is to locate the object. In other cases, such as determining magnetic north in a navigation system on a moving vehicle, this distortion can produce errors. The important issue is that the earth's magnetic field is a bias that must be taken into account when measuring weak (<100 μT) fields.

The following sections of this article describe the current state of and recent advances in magnetic-field measurement technology. First, basic information is provided about the nature of magnetic fields and their interaction with matter. This is followed by more detailed descriptions of the various technologies used in practical vector and scalar magnetometers. Finally, there is a discussion about calibration techniques and measurement-error sources.

2. Magnetic-Field Fundamentals

Although they have been observed and utilized since prehistoric times, it was not until the seventeenth century that a formal analysis of magnetic phenomena was undertaken: by William Gilbert, an English physician who published his findings in the now famous book *De Magnete*. Gilbert used a lodestone to map the magnetic field lines around magnetized objects. He was the first scientist to suggest that the earth was like a magnetized sphere with magnetic poles near the geodetic north and south poles.

Major breakthroughs in understanding magnetic fields were achieved in the late eighteenth and nineteenth centuries. In 1785 Charles Coulomb determined experimentally that the force of a magnetic pole was inversely proportional to the square of the distance from the pole. He also found that the pole was not exactly at the end of a magnet, but slightly in from the end. In 1820 Hans Oersted discovered that an electric current passing near a magnetic compass caused the compass needle to deflect. André Ampère found that two current-carrying wires when brought close together were attracted to or repelled one another depending on whether the currents were in the same or opposite direction. Ampère also determined that an electric current was accompanied by a magnetic field at right angles to the current. In 1820 Jean Biot and Félix Savart developed their famous Biot–Savart law that is used to compute the magnetic field produced by a current element. In 1831 Michael Faraday observed that there was a reciprocal relationship between electric and magnetic phenomena, which led to his law of induction. He was the first to explain magnetic fields acting at a distance using fictitious lines of force, which eventually led to the concept of field. Following up on Faraday's work, Heinrich Lenz in 1834 declared, "the direction of the induced current must be such as to oppose, by its own magnetic field, the action tending to induce the current"—a consequence of the conservation of energy law. Finally, James Clerk Maxwell in 1856 formulated his well-known set of equations that completely unified electromagnetic field theory.

Textbooks are available that provide detailed information about electromagnetic field theory. In this section we provide only a summary of the more important concepts that are pertinent to magnetic measurements.

In electric field theory we talk about an electric field arising from a distribution of independent positive and negative electric charge. In magnetic field theory we talk about a magnetic field arising from a distribution of moving charge (electric current). The magnetic field generated by an electric current element is at right angles to the current flow and its strength is inversely proportional to the distance from the current element.

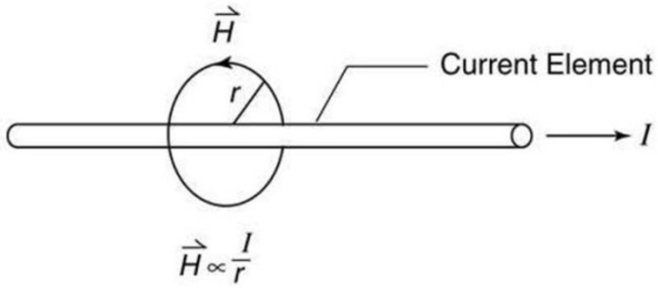

Figure 2. The magnetic-field vector is at right angles to the current element producing the field and its strength is inversely proportional to the distance from the current element

When electric current circulates about a loop it generates a magnetic field that can be conveniently characterized using the magnetic-dipole concept. Many magnetic phenomena can be visualized using this concept.

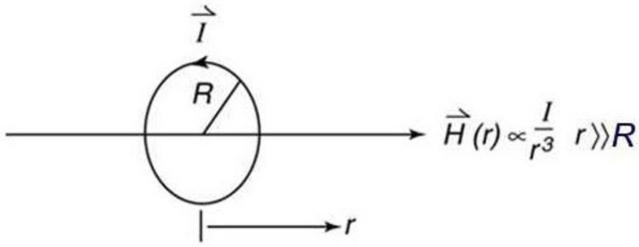

Figure 3. A current circulating in a loop produces a magnetic field that behaves like a magnetic dipole

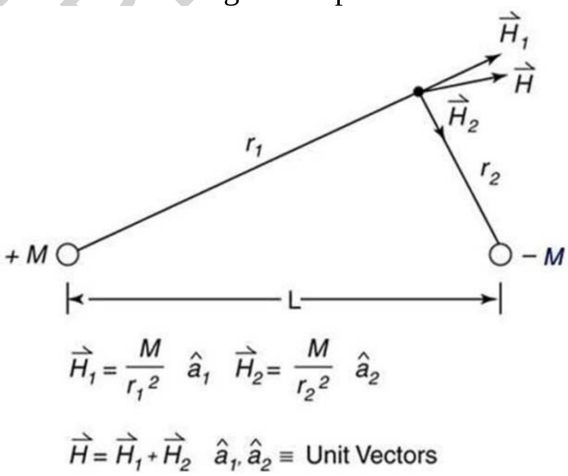

Figure 4. A magnetic dipole consists of two magnetic poles of equal strength and opposite polarity spaced some distance apart. The strength of the field generated by each pole is inversely proportional to the square of the distance from the pole.

The idea of a magnetic dipole was derived from the concept of an electric dipole. A magnetic dipole consists of a pair of magnetic charges—poles—of equal strength and opposite polarity, spaced some distance apart. Unlike electric charge, a magnetic charge has yet to be discovered and is merely a concept for visualizing magnetic-field phenomena.

The field produced by localized current distributions and magnetized objects is dipole in nature when measured at a distance that is greater than twice the longest dimensions. That is, the field strength is inversely proportional to the cube of the distance from the object or current source producing the field.

A vector called the magnetic dipole moment characterizes a magnetic dipole. The magnetic field that is generated by a magnetic dipole moment can be computed at a point in space using the following equation:

$$\vec{H} = \frac{3(\vec{m} \cdot \hat{a}_{\mathrm{r}})\hat{a}_{\mathrm{r}} - \vec{m}}{r^3} \qquad (2)$$

where $\hat{a}_{\mathrm{r}}$ is a unit vector along *r*, *r* is the distance between the magnetic-field source and the measurement point, and $\vec{m}$ is called the magnetic-dipole moment. Because most magnetized objects behave like dipoles when measured at a distance, this equation is a convenient way to estimate the magnetic field produced by the object. The magnetic field near a magnetized object is more complex and cannot be estimated using this equation.

The density of the aligned magnetic dipoles within an object determines its overall magnetic strength. This magnetic strength is called its magnetization and is defined as the vector sum of the magnetic-dipole moments per unit volume. The magnetization vector $\vec{M}$ is a material property that can be the result of self-contained internal dipoles—permanent magnetization—or the alignment of randomly oriented dipoles by the application of an external magnetic field—induced magnetization.

The behavior of ferromagnetic material is usually described in terms of the domain theory. Domains are regions of a material that are magnetized to saturation in some direction. In an unmagnetized object these domains are randomly oriented resulting in a zero-net magnetization. When a magnetic field is applied to the object these domains will experience torque that tries to align them with the applied field. This action induces a nonzero magnetization state in the object. When the object is removed from the field it may or may not return to the zero magnetization state. Any residual magnetization is normally referred to as permanent magnetization.

A magnet is an example of an object that has permanent magnetization, that is, its magnetization is a fixed property of the object and does not depend on an external magnetic field. Induced magnetization in an object is temporary, that is, it exists only while the object is in a magnetic field. When removed from the magnetic field, the induced magnetization disappears. Both kinds of magnetization can exist in an object. Both types of magnetization vectors may not have directions that coincide with the magnetic field, thus the resulting flux density may also have a different direction than the field.

Faraday, in developing magnetic-field theory, introduced the concept of flux lines. Flux lines are imaginary lines in space along which the strength of the magnetic-field vector is constant but its direction may vary. The density of these flux lines is a measure of the magnetic field strength within an area of space through which the lines pass. The following equation describes the relationship between flux density and magnetic field in a vacuum:

$$\vec{B} = \mu_0 \vec{H} \tag{3}$$

where $\vec{B}$ is magnetic flux density and μ_o is the permeability of free space.
Flux density is enhanced in matter by the object's magnetization vector. In matter flux density is given by the following equation:

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right) \tag{4}$$

Induced magnetization vector $\vec{M}$ depends on the magnetic properties of the object and is a function of the magnetic-field vector:

$$\vec{M} = \chi \vec{H} \tag{5}$$

where χ is called the material's magnetic susceptibility tensor. The magnetic properties of materials can be isotropic or anisotropic, that is, direction independent or direction dependent with respect to the object's body coordinates. The susceptibility tensor of an object with anisotropic magnetic properties is a three by three matrix. The susceptibility tensor of an object with isotropic magnetic properties becomes a scalar function and Eq. (5) becomes

$$\vec{B} = \mu_0 \left(1 + \chi \right) \vec{H} = \mu_0 \mu \vec{H} \tag{6}$$

where μ is called the relative permeability of the material. This equation assumes the object has no permanent magnetization. In this case the flux density and magnetic-field vectors are aligned. In a paramagnetic or diamagnetic material the magnitude of μ is close to one. Ferromagnetic materials can have a relative permeability in the hundreds of thousands. A magnetized object in a magnetic field will experience torque that tries to align its magnetic dipole moment vector, $\vec{m}$, with the magnetic-field vector, $\vec{H}$. The torque is given by the following expression:

$$\vec{T} = \vec{m} \times \vec{H} \tag{7}$$

Magnetic torque is what causes a pocket compass needle to align itself with the earth's magnetic field and the magnetic domains within a ferromagnetic material to align with an externally applied field.

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Biographical Sketch

Steven Macintyre graduated from George Washington University in Washington, D.C., USA, with a BS (Electronics) degree in 1965 and an MSE (Engineering Mechanics) degree in 1971. Early in his career he worked for the Schonstedt Instrument Company, developing fluxgate magnetometers for geophysical exploration, space research, and surveillance systems. He developed the first metal detection security system for screening passengers at airports. He also developed a magnetic compensation method for

magnetic anomaly detection (MAD) equipped aircraft, which resulted in a patent. He later joined ENSCO, Inc., where he developed instruments for the high-speed measurement of railroad track geometry parameters (curvature, crosslevel, profile, and gauge). In 1979, while with ENSCO, he developed a current-amplification technique and algorithms for designing optimized, broadband, low-noise, induction-coil sensors in the 0.1 Hz to 100 kHz range. This technique is currently used in the magnetotelluric method of geophysical exploration, in detecting the magnetic signatures of ships and submarines, and in measuring the sub-rf electromagnetic environment. He is currently President of MEDA, which he founded in 1980 with the mission of providing engineering consulting services to government and industry in the design and development of state-of-the-art, high-sensitivity, magnetic-field sensors and magnetometers in the DC to 500 kHz frequency range. Various government organizations have utilized his unique magnetic sensor-design expertise to solve problems in the detection of very low-level magnetic signals for both military and intelligence applications.