Magnetometers & ASSOCIATED TECHNIQUES

Gavin Cheeseman gives an insight into this fascinating topic with a project next month.

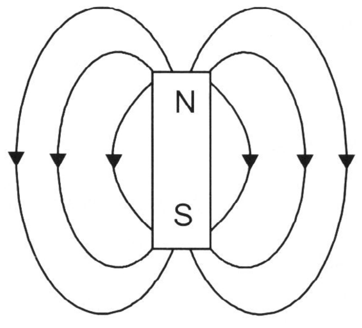

Figure 1. Conceptual illustration of the magnetic lines of force around a permanent bar magnet.

Introduction

In this article we look at a variety of different ways to measure magnetic fields and investigate various applications for magnetic sensors. A wide variety of measurement and sensing techniques are in use providing different levels of sensitivity and accuracy. These considerations, together with cost and complexity, determine which method is employed in any given application. The intention is not to give an in-depth theoretical analysis but to provide the reader with an overview of the kind of techniques in common use. The study of magnetism is a complex subject and readers requiring further information regarding magnetic theory are referred to standard text books on the subject.

Units of Measurement

There are a variety of different parameters to consider when measuring magnetic fields. Firstly the field has direction. If you move a compass close to a bar magnet, the magnet will deflect the compass needle. The orientation of the needle depends on the position of the compass relative to the magnet. Figure 1 provides a conceptual illustration of the lines of magnetic force around a bar magnet. The arrows show the apparent direction of the magnetic field. The compass needle will tend to point away from the north pole of the magnet (marked 'N') and toward the south pole ('S').

Further parameters relate to the 'strength' of the magnetic field. The magnetic flux density is effectively a measure of the 'amount' of magnetism per unit area or the density of the flux lines (analogous to contours on a map). The SI unit of magnetic flux density is the Tesla (symbol 'T'). Another common unit used when measuring magnetic flux density in cgs units is the Gauss (symbol 'G'). Sometimes magnetic field strength is also quoted. This is usually measured in A/m (amps/metre). An alternative (gaussian) unit is the oersted (symbol Oe). There are also a variety of other units in use.

Basic Techniques

Probably the simplest form of magnetometer is a coil of wire. Exposing the coil to an alternating magnetic field results in an alternating current being induced in the wire. This effect may easily be demonstrated using the arrangement shown in Figure 2. As the position of the permanent magnet changes with reference to the coil a current is induced in the coil windings. This current may be displayed on a centre zero moving coil meter. The polarity of the current induced in the coil is determined by the direction of movement. The speed at which the magnet moves affects the current level induced in the coil. Moving the magnet more rapidly produces a faster change in flux density and results in greater deflection

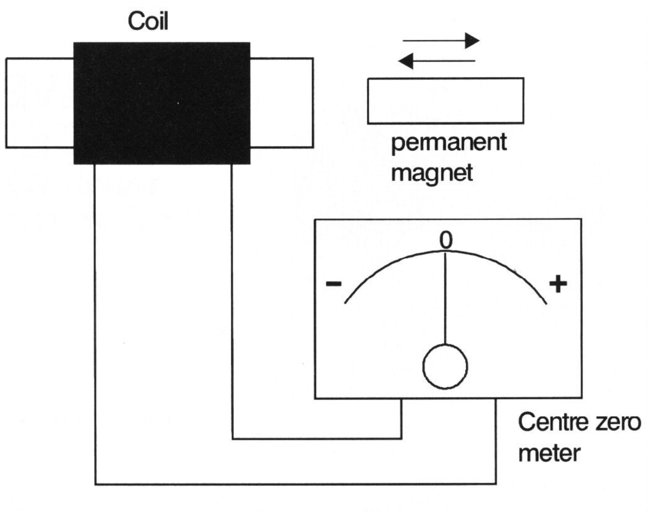

Figure 2. Simple arrangement to illustrate how a magnetic field induces current flow in a conductor.

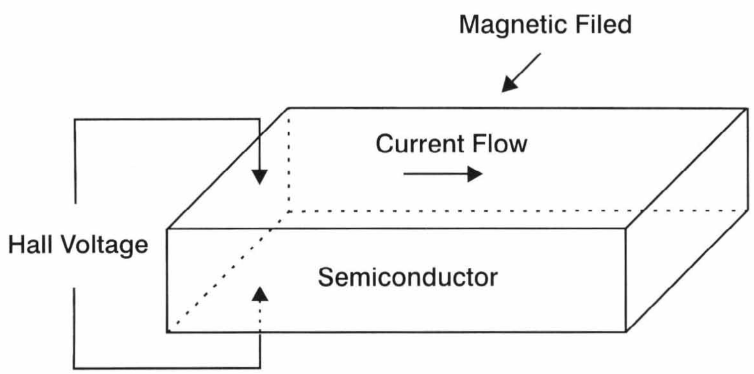

Figure 3. Simplified illustration showing the functionality of a Hall effect sensing element.

of the meter. The tendency for a coil of wire to react in this way when exposed to a changing magnetic field is often put to good use in audio frequency transducers such as microphones and pick up coils, and in fact forms the basis of AC transformers. The magnitude of the induced current is partially determined by the frequency and intensity of the varying magnetic flux and partially by the coil dimensions. This type of fixed-coil detector is suitable for measuring alternating magnetic fields such as those produced by power lines and other rapid changes in magnetic flux.

In order to measure a stable (non-alternating) field, such as that produced by a stationary permanent magnet, it is necessary to move the coil in the field. As the coil moves through the magnetic field, current is induced in the windings as illustrated above. If the coil is continuously rotated at a known speed, the current flow will be relative to the magnetic flux density. This type of sensor, although very simple in concept, is capable of providing accurate readings with good sensitivity when properly arranged. However, because a relatively large coil is often required to provide good sensitivity, these units can be quite bulky.

Hall Effect Sensors

Another type of detector makes use of a phenomenon known as the Hall effect as illustrated in Figure 3. This effect is produced when current flowing in a conductive material is influenced by an external transverse magnetic field. As a result, a voltage proportional to the magnetic flux density is set up in the material. Hall effect devices typically make use of semiconducting material as the conductive medium. Integrated sensors using Hall effect technology are readily available. An example is the UGN3503U IC (Maplin code GX09K). This is a 3 pin device comprising an internal Hall effect sensing element, an amplifier and a buffer all on one chip. The device provides an output voltage proportional to magnetic flux density. Hall effect switches are also available providing a magnetically controlled switched output. These devices are ideal for use at medium to high magnetic flux densities and find many applications particularly in industrial control. They offer the advantage that they do not normally require alignment and are pretty much ready to use as supplied. In the example shown in Figure 4, the Hall effect sensor is used to sense the movement of gear teeth. This setup is only suitable for use with gears made from ferrous materials. A small permanent magnet is attached to the rear of the Hall effect IC. The presence of ferrous metal in proximity to the magnet affects the flux density. Therefore each time a gear tooth passes the Hall effect device there is a variation in output voltage from the sensor. The output pulses can be shaped and counted providing an accurate method of measuring the rotational speed of the gear wheel. This general principle may be adapted to a whole range of proximity detection applications. The maximum frequency that the sensors will respond to varies considerably but is typically in the range of a few kHz.

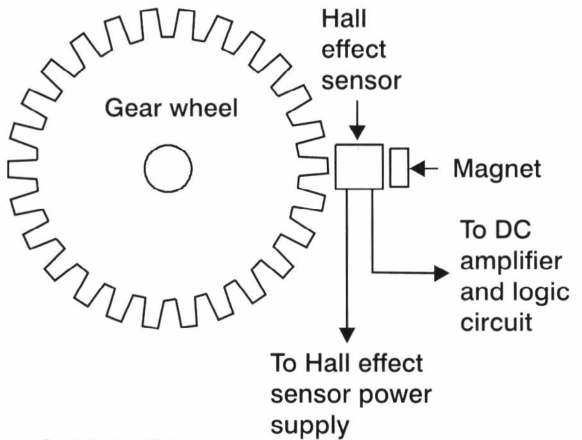

Figure 4. Using a Hall effect sensor to detect the movement of ferrous gear teeth.

A further application of Hall effect devices is in current sensing. As the magnetic field around a current carrying conductor is directly related to the current level, the sensors may be used to monitor relative current in an electrical system without the need to break the circuit. This technique has the advantage of providing good electrical isolation and therefore does not significantly load the circuit being measured. Applications in this respect include over current sensing in power supply systems and relative power measurement.

Magnetoresistive Sensors

Another type of magnetic sensing element is the magnetoresistor. As the name implies, these devices exhibit a change in resistance dependant on the magnetic flux density. This is a field that is rapidly changing and it is quite possible that the use of magnetoresistive sensors will become considerably more common place in the future. In their basic form, the devices produce a relatively small resistance change for a

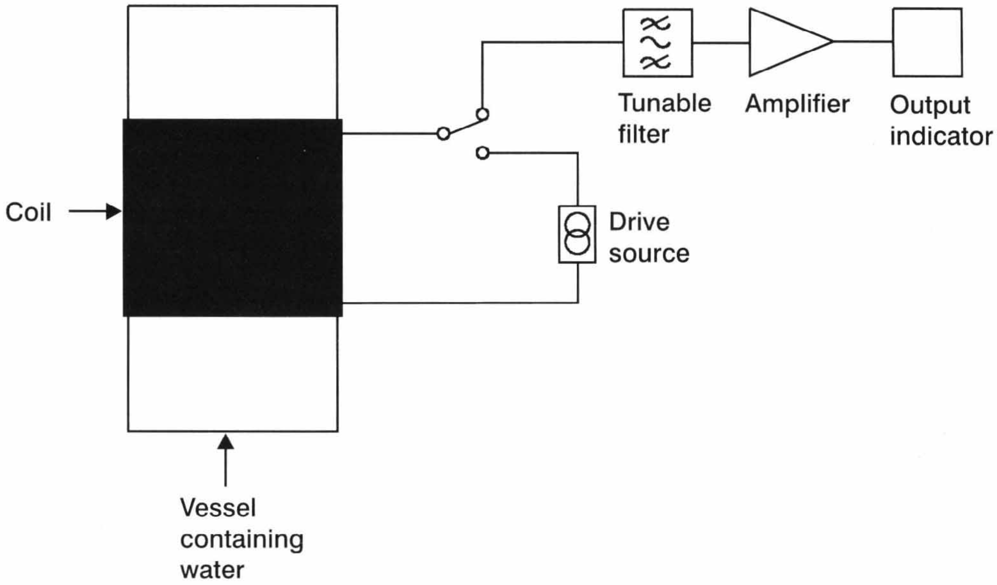

Figure 5. Simplified conceptual illustration of a proton magnetometer.

relatively large change in the magnetic field. Therefore, as with Hall effect devices, careful design techniques are required in order to obtain optimum performance. In recent years, magnetoresistive materials that exhibit a much larger change in resistance have been produced but this is still a developing field. Applications of magnetoresistors are similar to those discussed for Hall effect devices. In addition they find applications in navigational equipment such as electronic compasses.

Nuclear Magnetic Resonance

Magnetometers based on a phenomenon known as Nuclear Magnetic Resonance (NMR) provide a method of measuring the absolute value of a magnetic field and are capable of high accuracy and sensitivity. These devices operate on a totally different principle to those mentioned so far, utilising the resonance produced in specific atomic nuclei when acted upon by an external magnetic field. Often radio frequencies are used to initially excite the atomic nuclei.

The proton magnetometer operates by detecting resonance set up in the nuclei of hydrogen atoms (protons). The system may consist of a coil arrangement located around a vessel containing water. A current is passed through the coil, creating a strong magnetic field that affects the orientation of the protons in the water. As a result, there is a tendency for the protons to become aligned in one direction determined by the magnetic field. When the current is switched off the magnetic field collapses. At this point, if an external magnetic field is present, the protons become re-aligned under the influence of the external field. However, because the protons are spinning, this re-alignment is not instantaneous. Instead, the protons precess to the new orientation (governed by the laws of quantum physics). The frequency at which this precession occurs is directly related to the magnetic flux density allowing accurate magnetic field measurements to be made. A second coil may he used to detect the field produced by the precessing protons or alternatively the drive coil may be switched so as to drive detector circuitry. Figure 5 shows a simplified conceptual illustration of a proton magnetometer. The output from the device may be presented in a number of ways ranging from a directly audible tone to a computer interface. The arrangement used is very much dependant on the intended application.

Unlike most of the other sensors discussed, magnetometers based on NMR do not allow measurement of the direction of the magnetic field. Although initially, this may appear to limit the usefulness of the technology, this is not necessarily the case. In some applications, for example, where it is required to measure small changes in flux density the sensitivity of the system often outweighs the limitations. There is also the great advantage that the data from the device are output as a frequency rather than a voltage or current level and as a result it is possible to achieve a high degree of accuracy.

The Fluxgate Magnetometer

Yet another method of measuring magnetic fields is the Fluxgate magnetometer. Once again this is capable of providing very good sensitivity as well as directional data. The device finds uses in a wide range of applications in the laboratory and in navigational aids such as compasses.

The heart of the device is a series of coils wound onto ferromagnetic core material. A single toroidal core may be used. The characteristics of the core material are fundamental to the correct operation of the device. A simplified example of a possible coil arrangement is shown in Figure 6. An alternating signal is applied to the drive coil such that an alternating magnetic field is set up in the core. The amplitude and frequency of the drive signal is such that the core is in the region of saturation on signal peaks (as the signal voltage increases this no longer results in a corresponding increase in magnetic flux), during the part of the cycle that the core is saturated, the drive current increases considerably. A second coil wound around the outside of the toroidal former acts as a pick-up coil. When the core is exposed to an external magnetic field, an imbalance occurs. This imbalance results in current pulses being induced in the pick-up coil of an amplitude relative to the magnetic flux density. Suitable circuitry is required to separate out and process the relevant pulses in order to provide a meaningful reading.

The above arrangement is a typical example and there are a number of vari-

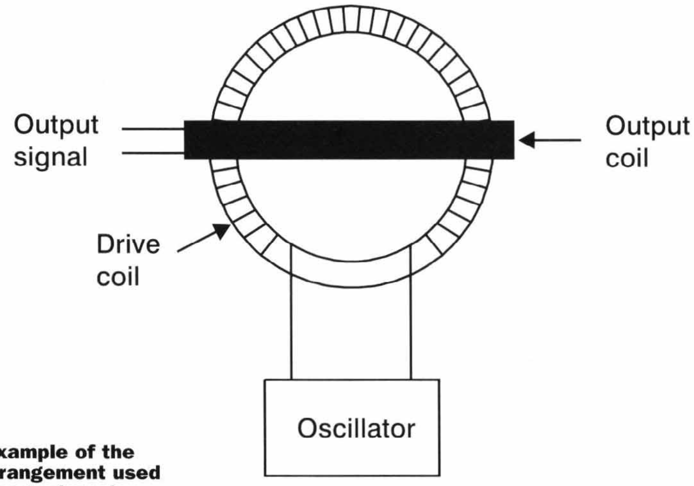

Figure 6. An example of the type of coil arrangement used in a fluxgate magnetometer.

ations. For example, rods may be used in place of the toroidal core.

SQUIDs

The SQUID or Superconducting Quantum Interference device is one of the most sensitive magnetic sensor technologies, capable of measuring very small changes in magnetic flux. The device requires very low temperatures (a few degrees above absolute zero) to operate and can be complex and costly to implement. Therefore the use of this type of sensor is usually confined to specialised applications.

Applications

Applications for magnetic sensors and associated technologies are becoming considerably more diverse as time moves on. In addition to some of the more standard applications such as proximity sensing there are also a host of more unusual uses. For example Magnetic Resonance Imaging (MRI) uses Nuclear Magnetic Resonance techniques to build up an image. Equipment operating on this principle is sometimes used in a medical environment to provide images of internal parts of the human body such as the brain.

Magnetometers can also be used to detect large ferrous objects or mineral deposits deep in the ground. It is possible to do this by detecting small localised variations in the earth's magnetic field. By taking readings at different positions, it is possible to determine the position of buried objects with a relatively high degree of accuracy. Such variations can be small, so use of a sensitive detector is essential. Magnetometers used in this application are often based on the Fluxgate or NMR principles. As mentioned previously, proton magnetometers produce an output which varies in frequency with magnetic flux density. This is convenient as the outputs from two sensors positioned a short distance apart can be combined to produce a series of mixing products. One of the mixing products is equal to the difference between the two detector frequencies. If the magnetic flux density is equal at both sensors, the difference between the two frequencies is negligible; however, a variation in the magnetic field caused by a ferrous metal object below one of the detector coils will result in a notable difference between the output frequencies of the two sensors. When the outputs are mixed, the difference manifests itself as a low frequency modulation of the output signal that when amplified may be audible as a warble. The frequency of the difference signal will be determined by the degree of variation in magnetic flux density between the two sensors.

Another common use for magnetometer technology is in research into the earth's magnetic field. The earth's magnetic field is not stable as some may expect but is subject to continuous variation. There are a number of reasons for this including the effects of the 'solar wind' a stream of high energy charged particles emitted by the sun. It is solar emissions that are responsible for the atmospheric phenomenon known as the northern lights or aurora borealis at high northern latitudes and the aurora australis in the southern hemisphere The sun is in a constant state of flux and particle output varies depending on solar conditions and on periodic effects such as the 11 year sunspot cycle. Emissions from the sun are not only responsible for creating spectacular atmospheric light shows. Study of these phenomena are of increasing importance as a solar storm may result in a serious threat to satellite and terrestrial communications and disruption of navigational systems In addition, many conventional short wave broadcast and communications circuits actually rely on ionisation of specific layers in the upper atmosphere (the ionosphere) to propagate the radio signals around the world. The condition of these ionised layers is heavily dependant on solar conditions. Monitoring various parameters of the earth's magnetic field provides an important source of data in studying the effect of solar particle emissions on the earth's atmosphere.

Changes in the earth's magnetic field can also result from changes inside the earth which can be of interest to geologists. The magnetic poles do not correspond with the physical north and south poles but are continuously drifting (see Figure 7). For example the magnetic north pole is currently somewhere in northern Canada. This has important implications for navigation. It is also interesting to note that the Earth's magnetic and geographic poles are actually opposite, so the magnetic south pole is closest to the geographic north pole and so on.

Control and Proximity Sensing Applications

As mentioned earlier, magnetic sensors such as Hall effect devices may he applied to a whole range of control applications both in industry and the domestic environment. We looked at the use of a Hall effect sensor for detecting the movement of teeth on gear wheels. This arrangement can be easily adapted to suit a range of practical cir-

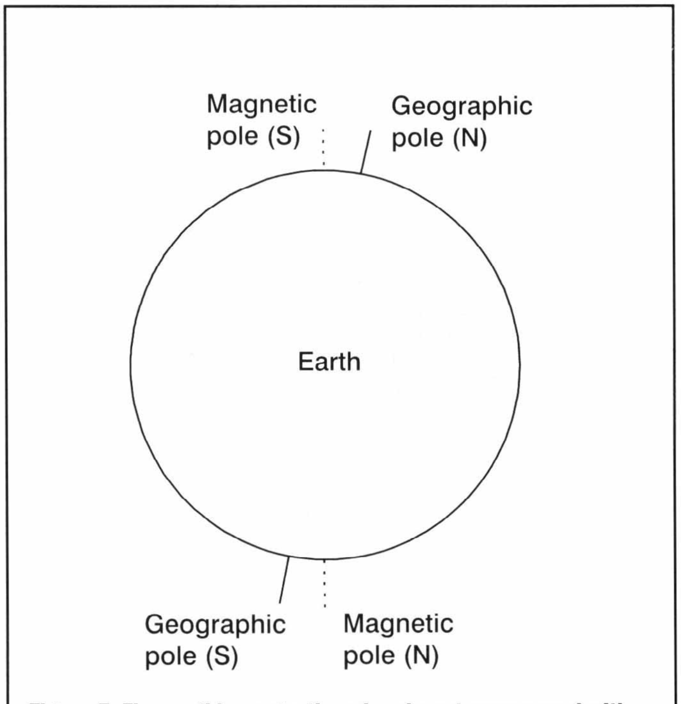

Figure 7. The earth's magnetic poles do not correspond with the geographic poles and are continuously drifting.

cumstances. For example, to measure the movement of non-ferrous or non metallic objects a small magnet may be attached to the object.

Hall effect devices can be used in electromusic applications such as keyboards to indicate when a key is pressed. This gives the musician more control than a simple set of contacts. A linear Hall effect device will produce an output voltage proportional to the relative position of the key. This information can be processed so as to detect how rapidly the key is depressed and used to adjust the characteristics of the envelope produced by the instrument. A similar application is in volume pedals, where the output from a Hall effect sensor can be used to determine the gain of a voltage controlled amplifier. The arrangement must be such that when the pedal is operated, the position of an internal magnet is varied relative to the Hall effect sensor. This type of system can effectively be used in place of mechanical potentiometers which often become noisy after a period of use due to dust deposition and wear to the resistor track.

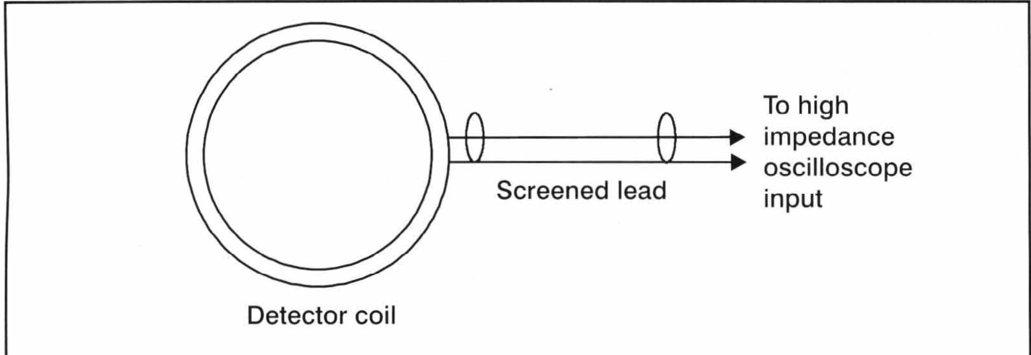

Figure 8. A simple 'near field probe' for detecting alternating fields.

AC Fields

Of recent years there has been considerable interest in alternating magnetic fields produced by power lines and many pieces of electrical equipment. Alternating fields can adversely affect the operation of electrical apparatus. There has also been much discussion relating to the effects of alternating fields on the human body. Many biological processes involve chemical reactions in which electrical charges play an important role. Electrically charged particles are heavily influenced by magnetic fields and one area of possible concern is that intense alternating magnetic fields may significantly affect biological activity in the body.

The level of alternating fields in the average home can be relatively high. This is not surprising when you consider that many pieces of equipment operate from the AC mains supply which is alternating at a Frequency of 50Hz. Also some appliances contain internal oscillators operating at higher frequencies.

A simple coil based detector or 'near field probe' (see Figure 8) is useful is detecting relative levels of AC fields. This can be as simple as a few turns of wire wound into a loop and connected via coaxial cable to the input of an oscilloscope. A portable unit with a similar coil arrangement connected to the input of a small audio amplifier can also be useful when detecting mains cable runs in walls etc.

Next Month

This time we have looked briefly at a variety of different sensor technologies and magnetic measurement techniques. Next month we will look at the practical aspects of magnetometer design and there will be some experimental circuits.