Chapter 10

Development Tools

Sharp tools suited to the task at hand can make any job easier. The development of a magnetic sensor assembly is no exception. This chapter will briefly describe some of the tools that can come in handy when designing magnetic sensors. Some of these are common to any well-equipped electronics laboratory, while others are unique to the magnetics world. This chapter will describe what kinds of equipment I have found useful in the past for this type of work.

10.1 Electronic Bench Equipment

For most sensor development projects, a well-equipped electronics lab can make development easier, faster and more straightforward. While one can spend large amounts of money on the highest-performance, leading-edge test equipment, it is also possible to get the measurement capabilities one needs for a modest price.

Power supplies

In the course of developing Hall-effect sensor assemblies, I have needed power supplies for three purposes:

- Powering sensors and related circuits
- Providing precision voltage and current references
- Driving coils to generate magnetic fields

These applications all place different demands on a power supply. Although it may be possible to get a single unit that can perform adequately in all of these tasks, it is usually better and less expensive to get several, more specialized units.

For powering sensors and related circuits, such as laboratory breadboards, the typical requirements of a power supply are that it be able to provide modest (< 500 mA) amounts of current over the operating voltage range of the sensor (0–30V). An important feature to look for is user-settable current limiting. While most good power supplies have internal current limiting designed to protect the power supply from output short-circuit conditions, this internal current limiting won't usually protect your circuits from the power supply if they are miswired or otherwise misbehave. The ability to set power supply current limits to some arbitrarily low and nondestructive value is extremely valuable in protecting your work as you debug it.

Multiple outputs are also a nice feature; being able to get two or three separate voltages out of the same box can greatly reduce benchtop clutter. Many power supplies also offer built-in digital or analog front-panel meters, so you can monitor the output voltage and current. The accuracy of these built-in meters tends to be limited, so for critical measurements you may want to do the monitoring with a separate voltmeter or ammeter.

A precision power supply is quite different from a general-purpose bench supply. Many of these units will have digital front-panel controls, and can often be controlled externally through a IEEE-488 GPIB port or serial port. They can be programmed to either supply a voltage and measure the current drawn, or to supply a current and measure the voltage, often with five or more digits of accuracy. In contrast to the meters built in to conventional bench supplies, the meters on precision power supplies generally are quite accurate. These units are commonly used in automatic test equipment (ATE) systems. Agilent (formerly Hewlett-Packard) and Keithley Instruments are two of the more well-known manufacturers of these devices.

The last application for power supplies is for driving coils or electromagnets to produce magnetic fields. These applications can require significant amounts of current (> 10A) at moderate voltages (50V). Needless to say, the exact requirements are crucially dependent on the magnet or coil to be driven. One common requirement, however, is that the power supply be able to go into a constant-current mode. Driving an electromagnet with a constant current as opposed to a constant voltage reduces the resultant magnetic field's temperature dependence as the coil resistance increases from heating.

Voltmeters and DMMs

My favored approach here is to get a few handheld digital multimeters (DMMs) of moderate resolution (3½ digits), and one or two high-resolution (5–6 digit resolution) bench-top units. It is worth having several handheld DMMs around because there will be times when you may need two or three (or even more) for a bench setup. For most measurements, a 3½ digit handheld DMM will provide sufficient measurement accuracy and resolution; the 6-digit bench DMM is for those rarer situations where higher accuracy is really needed.

Although it is possible to buy very inexpensive handheld DMMs from a number of sources, it is my opinion that it is usually worth spending a few extra dollars to get higher quality instruments, for several reasons. First, the better instruments tend to be more rugged and last longer. Additionally, it is usually easy to obtain calibration services for name-brand instruments. Aside from the general desirabilty of having instruments whose readings have some correlation with reality, calibration can become a major issue if you or your shop are subject to various quality systems (e.g., ISO9000).

Oscilloscope

Because most sensors detect mechanical motion, the resulting electrical outputs tend to vary slowly, at least by electronic standards. If speed and bandwidth were the only considerations for the selection of an oscilloscope, then just about any oscilloscope made since World War II would probably be adequate for most Hall-effect sensor development work. Small, no-frills analog oscilloscopes can be obtained for a few hundred dollars. One characteristic of many sensor applications, however, is that one often needs to look at events that occur either rarely or on a single-shot basis. In these cases, a digital storage oscilloscope (DSO) is much more useful than a traditional analog one. Fortunately, the prices on digital oscilloscopes have fallen dramatically in the past few years, and it is now possible to get a good entry-level scope with two input channels and 60 MHz of bandwidth for less than $1500.

Frequency Counter

When working with rotating targets, a frequency counter is often useful to accurately determine target speed (RPM). Increasingly, however, this function is incorporated into DMMs and digital oscilloscopes, so it may be unnecessary to buy a separate instrument to obtain this measurement capability.

Clamp-On Current Probes

If you are developing current sensors, some means of measuring large currents is necessary. Most handheld DMMs only offer ranges up to about 10A. Additionally, to measure current with a DMM, you need to break into the circuit carrying the current. To measure larger currents noninvasively, clamp-on current probes can be used. These devices come in two fundamental varieties; AC and DC. AC current probes are based on inductive sensing principles, and will only measure AC current, while DC current probes can be used to measure both AC and DC currents. A DC clamp-on current probe works much like the current sensors described in Chapter 7; the main difference is that the magnetic path is set up so it can be readily opened and closed around a conductor. This allows one to make current measurements without having to break the current path. Many current probes don't have an integral display, but need to be connected to a DMM to be used.

Solderless Breadboard

One final and very useful piece of electronic equipment is the solderless breadboard. This device consists of a plastic block with lots of holes into which you can insert components such as resistors and DIP ICs. You then temporarily wire the components together by poking wires into nearby holes. Solderless breadboards allow you to quickly build prototype circuits and allow for easy changes and debugging. Breadboards are available in several sizes and configurations. Some of them also provide power supplies.

It should be pointed out, however, that breadboards are intended for prototyping circuits; any circuit you expect to keep around for a while should probably be constructed with other, more permanent techniques. Other than lack of permanence, circuits constructed on breadboards also have two other major limitations. The first is that the breadboards are designed to accommodate through-hole components. While it is possible to buy adapter bards to make surface-mount parts fit into a breadboard, this can be a nuisance. For designs using surface-mount parts you are usually better off designing circuit boards for your prototyping work.

The second major limitation of solderless breadboards is that circuits constructed on them typically have lots of parasitic capacitance and inductance. Although most Hall-effect sensor circuits will operate at audio frequencies (10 Hz–20 kHz), these parasitics can have adverse effects on other components that may have much higher frequency responses. For this reason, circuits built on solderless breadboards will often have somewhat different performance characteristics than the final circuit will when built on a printed circuit board.

Because of their utility and low cost, and despite their limitations, it is usually worth getting a few solderless breadboards to have around the lab.

10.2 Magnetic Instrumentation

While the equipment described in the last section can be found in nearly any electronics lab, some more specialized items can be useful when developing magnetic sensors.

Gaussmeter

A gaussmeter measures magnetic flux density (B) at a given point in space. Most gaussmeters employ Hall-effect sensor elements as the magnetic probe. In its simplest form, a gaussmeter is a linear Hall-effect sensor with a meter readout. Indeed, it is possible to build a simple gaussmeter from a linear Hall-effect sensor IC, a small amount of interface electronics, and a DMM, but the result would not provide anywhere near the capabilities of a modern gaussmeter. A few of the features to look for in a gaussmeter are:

- Range – How small a field can it measure, and how large a field can it measure?
- Accuracy – To what degree does the reading reflect reality?
- Interface options – In addition to a front-panel display, can it communicate with PCs or other instruments?

Range is important because there are times when you will want to measure fields of a few gauss, and others where you will want to measure fields of several kilogauss. Low ranges are often important in sensor work. Even though most Hall-effect sensor ICs aren't useful for discriminating field differences much below 1 gauss, you will typically want an instrument with an order of magnitude finer resolution than what you need to measure.

The need for accuracy requires little if any elaboration. Inaccurate instruments can make your life vastly more difficult. Accurate instruments, regularly calibrated, can make development work go more smoothly, by reducing one potential source of errors. Note that accuracy is a key specification for gaussmeters and is often the only difference between two instrument models of differing price.

While interface options may not seem that important, they enable one to hook the gaussmeter to a PC and automate many simple tasks. Popular interface standards include RS-232, IEEE-488, and analog outputs.

Fluxmeter

A fluxmeter measures changes in magnetic flux, as detected through a Helmholtz or similar coil arrangement. Functionally, a fluxmeter consists of a pickup coil and an electronic integrator, as shown in Figure 10-1. A change in total flux through the pickup coil induces a small voltage, which is then integrated over time. By integrating the voltage developed by the coil, which itself is proportional to the derivative of the flux passing through the coil, a fluxmeter can measure net changes in that flux. A fluxmeter is therefore different from a gaussmeter in two major ways. First, the fluxmeter measures total flux (ϕ) over an area, where the gaussmeter measures flux density (B) at a single, small, point in space. The second major difference is that, while a gaussmeter can resolve a zero flux condition (to some degree of accuracy), the fluxmeter is a completely relative instrument; measurements are made relative to an arbitrary "zeroed" condition.

This ability to integrate flux over a wide area makes fluxmeters especially useful for characterizing magnets. The major problem encountered when using a gaussmeter for magnet characterization is that the reading obtained is extremely sensitive to the positional relationship between the magnet under test and the measuring probe. While this sensitivity can be reduced by properly fixturing the magnet and probe, it still can be a significant source of error. The other problem with using a gaussmeter for magnet characterization is the issue of what is really being measured. A gaussmeter only measures flux density at a single point in space; it has very little to say about the magnet material characteristics as a whole. By using a fluxmeter, however, it is possible to derive useful information about a material's overall degree of magnetization. Some microprocessor-controlled fluxmeters have options to enter the volume of the magnet under test, so the meter can directly report magnetic properties in a manner independent of magnet size. Because fluxmeter measurements can be performed easily, they are especially useful for performing incoming inspection and other quality control tasks.

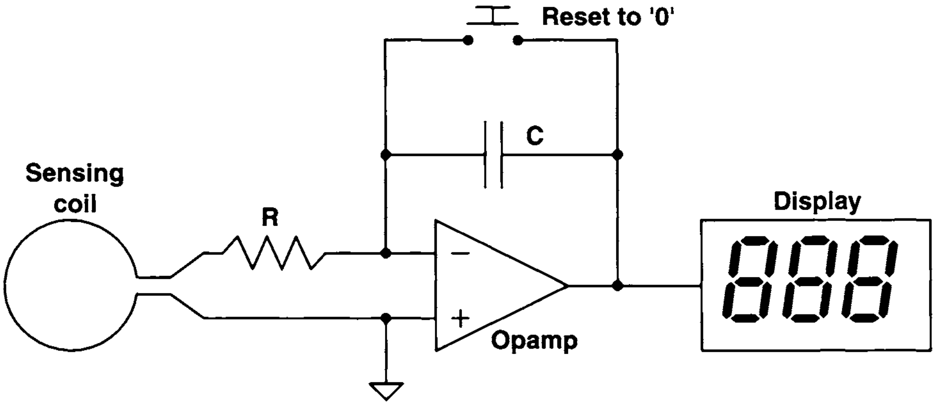

Figure 10-1: Functional block diagram of fluxmeter.

Calibrated Hall-Effect ICs

A calibrated linear Hall-effect IC can be considered a poor man's gaussmeter probe. The principal value of these devices is that, because they can be obtained in the same packages one will ultimately use for sensors in the finished assembly, they can be readily substituted (mechanically) for the ultimately desired IC. This allows one to obtain a measured magnetic response curve from a prototype. Because these devices are much less expensive than gaussmeter probes, they can be viewed as disposable items, and can economically be incorporated into prototype assemblies. Hall-effect IC manufacturers often make these devices available to customers as an aid in developing sensor assemblies.

Polarity probe

It is often useful to be able to distinguish the north pole from the south pole of a magnet. A handheld polarity probe can be used for this purpose. These devices can be bought ready-made, or can be easily built from an Allegro Microsystems UGN3235 dual-output Hall-effect switch and a pair of different colored LEDs, as shown in Figure 10-2.

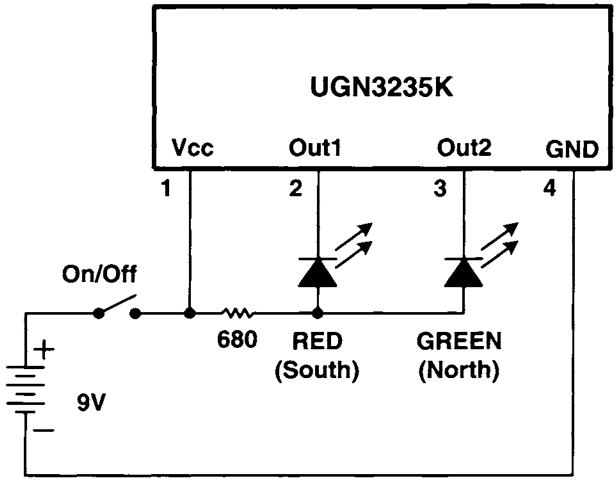

Figure 10-2: Schematic for simple magnetic polarity indicator.

Magnetic View Film

At one point or another in your scientific education you may recall seeing or performing a science experiment in which iron filings are sprinkled on a piece of paper held over a magnet. The filings line up in a way that indicates the magnet's poles and field lines. One drawback of using this method for visualizing magnet pole position is that loose iron filings tend to be messy. The mess-factor, however, has been eliminated by a green plastic film that contains captive ferrous particles. When this film is placed over a magnet, the particles line up accordingly and clearly indicate pole arrangement. This film is especially useful when working with ring magnets, as it allows one to readily see the pole count and position.

Magnetizers and Magnet Conditioners

The ability to magnetize and demagnetize magnets is a useful capability, from both development and production standpoints. The principal tools used to perform these tasks are magnetizers and magnet conditioners.

A simplified schematic of a capacitive-discharge magnetizer is shown in Figure 10-3. This circuit has two operating modes. The first is a "charge" mode in which the capacitor is connected to a charger circuit, which is typically a switch-mode power supply. When the capacitor is charged to a desired voltage level, the switch is then thrown over to "magnetize" mode. The charge stored in the capacitor results in a very high current pulse (often several thousand amperes) that is delivered to the windings in the magnetization fixture. This pulse results in a brief but intense magnetic field that is used to permanently magnetize materials inserted into the fixture. Because the LC circuit formed by the capacitor and magnetizing fixture may oscillate negative, a "flyback" diode may be used in the circuit to protect the capacitor from reverse voltage conditions. Solid-state devices such as SCRs or TRIACs are often used to switch the capacitor to the magnetizing fixture because of their ability to handle very high voltages and currents.

Depending on the value of capacitance, the maximum operating voltage, and the design of the magnetizing fixture, fields up to 50,000–60,000 Oersteds can be developed for a few milliseconds. A field of this magnitude is capable of magnetizing virtually all presently available magnet materials to complete saturation.

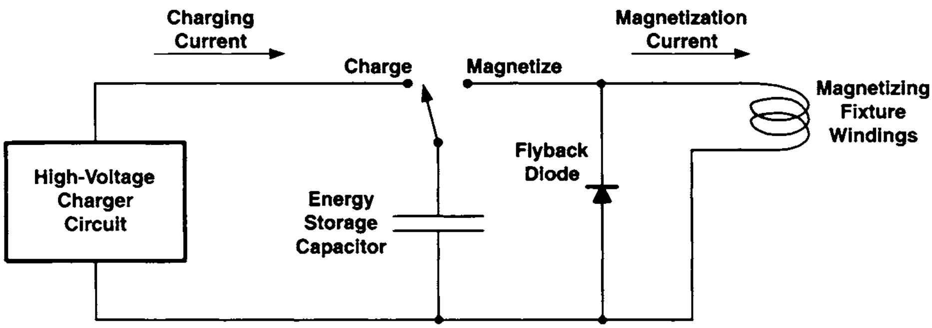

Figure 10-3: Capacitive discharge magnetizer—simplified schematic.

A magnet conditioner is similar to a capacitive discharge magnetizer except that the capacitive discharge is typically allowed to "ring" both positive and negative a number of cycles before it decays to zero. This results in a magnetizing field that alternates polarity, with a reduction in strength on each successive polarity reversal. Applying this kind of damped sinusoidal pulse to a magnet tends to demagnetize it. Partially demagnetizing certain types of magnet materials can be useful because it can reduce their sensitivity to further, unintentional demagnetization as a result of shock and temperature variations.

Because magnetizers and magnet conditioners operate at very high voltage and current levels (typically hundreds of volts and thousands of amperes) , one should not view these kinds of devices as "do-it-yourself" projects. Despite the apparent simplicity of a capacitive-discharge magnetizer, the design of a unit that performs in a safe and reliable manner requires significant amounts of expertise and experience with high-energy electronics and should not be attempted by those without suitable backgrounds. In almost all cases, the best approach to obtaining a magnetizer or magnet conditioning system is to buy one from a reputable manufacturer. When using such a system, follow the manufacturer's instructions for equipment use and maintenance, and exercise due caution when working with these devices.

Helmholtz Coil

It is occasionally useful to be able to generate well-controlled magnetic fields of up to a few hundred gauss for various purposes, principally testing ICs and small sensor assemblies. A small Helmholtz coil can often be used with a power supply for this purpose. An illustration of a Helmholtz coil is shown in Figure 10-4.

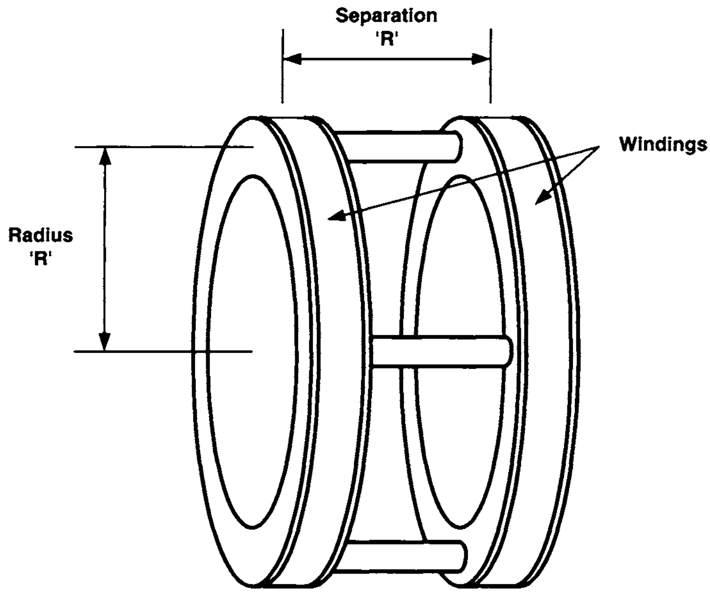

Figure 10-4: Helmholtz coil.

A Helmholtz coil consists of two relatively narrow circular coils that are spaced apart by their radius. The primary feature of a Helmholtz coil is that it produces a highly uniform field over a wide region located between the two windings. The magnetic field developed by an ideal Helmholtz coil, in which the winding cross-section of the two coils is zero, is given by:

$$B = \frac{\mu_0 N I}{r\left(\frac{5}{4}\right)^{3/2}} \qquad \textbf{(Equation 10-1)}$$

where N is the number of turns on each sub-coil, I is the current through each coil, and r is both the coil radius and separation.

In addition to generating magnetic fields, Helmholtz coils can be used to measure magnetic fields. A Helmholtz coil is often used as the magnetic sensing coil for a flux-meter.

10.3 Mechanical Tools

One aspect of magnetic sensor development that might come as a surprise to an electronic engineer new to the field is the mechanical-ness of the endeavor. While most EEs are familiar with DVMs, scopes, and other electronic test equipment, tools for mechanical positioning and measurement often cause a bit of culture shock. Nevertheless, when designing sensors that measure mechanical properties, you need some way of generating those mechanical properties. Here are some examples of tools I have found useful.

Optical Bench

An optical bench is a rigid table with threaded holes drilled and tapped into its top surface on a regularly spaced grid. Various fixtures and devices can then be easily and securely screwed down to the table surface. Optical benches can be used when developing sensors to hold sensors and targets and to build up temporary test stands. Small portable optical benches can be obtained from numerous sources. If a high degree of absolute accuracy isn't needed, however, and a good machine shop is available, it is also possible to get one made relatively inexpensively from a piece of steel or aluminum tool plate. An optical bench allows one to rapidly build (and modify) stable test set-ups on which to perform experiments and test prototypes. A small bench, with a good assortment of hex-drive cap screws and small fixtures, can make many measurement tasks much faster and easier to perform, and is much safer and more pleasant to work with than fixtures improvised from c-clamps and double-sided sticky tape!

Linear Positioning Slides

A linear positioning slide consists of a small table running on a linear track containing ball or roller bearings, and provided with some means to accurately set displacement. This device allows you to move the table back and forth by small, precisely controlled amounts. One application of linear slides is for creating precise, repeatable airgaps between sensors and targets. While smaller units may use a micrometer thimble for positioning, larger ones may use a precision leadscrew and ballnut to drive the table slide assembly. Nearly all linear slides have holes provided for mounting to an optical bench or other assembly.

Rotary Table

Like a micrometer slide, a rotary table provides fine control of positioning, but for angular motion. In a typical rotary table, a control knob is used to rotate a worm gear. The worm gear engages the threads of a mating spur gear mounted beneath the table surface. When the worm gear turns, it causes the table to rotate a small amount. By using this arrangement, it is possible to obtain high ratios between rotations of the control knob and rotation of the table, with reduction ratios of 90:1 and 180:1 common. These high ratios make it possible to accurately rotate a target by as little as a few hundredths of a degree. One disadvantage, however, of rotary tables is that they are not usually designed to be rotated quickly and attempting to drive one at high speed can damage the worm gear drive assembly. Figure 10-5 shows an example of a small rotary table.

Figure 10-5: Example of small (4") manual rotary positioning table.

Calipers and Micrometers

A good set of calipers and micrometers are also worth obtaining for one's tool kit. These measuring instruments allow one to easily make dimensional measurements down to 0.001" or better accuracy. Many of these devices come equipped with digital readouts, which make using them extremely simple, compared to the old-style dial and vernier-reading instruments. No toolbox in a sensor development lab should be without a good set of calipers and micrometers.

Machine Tools

Machine tools such as lathes and milling machines can be invaluable when developing sensor products. First, they allow you to rapidly implement small sensor housings and fixtures to try out your ideas. A second application is for modifying housings and fixtures that you buy from an outside source. The ability to accurately cut a slot, drill a hole, or shave a few thousandths off a tight fit can often save you a trip back to your outside machine shop and several days of time. Because most of the machining operations you are likely to want to do to a sensor are relatively small scale, miniature machine tools are often more than adequate for these purposes, and offer the additional benefits of not taking up a lot of space and being relatively inexpensive. Depending on your organization's capital expenditure guidelines, you may even be able to hide many small machine tools and accessories in the budget as generic "tools," thus avoiding the ugly scenario that often occurs when senior management thinks that their engineering staff is setting up their own machine shop.

Another application for machine tools is as temporary sensor test stands. While it is possible to build custom fixturing to mount and spin the target and to hold the sensor at a specified airgap, I have found that miniature machine tools can often be used to perform this function, at least for smaller-diameter targets. Using a tool such as a lathe or milling machine as a test stand can provide several significant features and advantages. The first is that good machine tools have minimal runout and can maintain a tightly controlled sensor-to-target airgap over the course of an entire rotation, assuming of course that the target is concentric. A second advantage provided by some tools is variable speed control. This makes it easy to vary test speed by the turn of a knob. Yet another feature of machine tools is that they normally incorporate precision linear tables for positioning work-pieces and cutting tools, and can accurately position targets and sensor assemblies. Finally, since machine tools are designed to hold and position variously shaped workplaces, the associated clamping and mounting accessories also allow one to set up a given test with a minimal amount of custom fixturing. Figure 10-6 shows an example of a miniature lathe with variable speed control, holding a target and sensor. The cross-slide allows two axes of position control for the sensor.

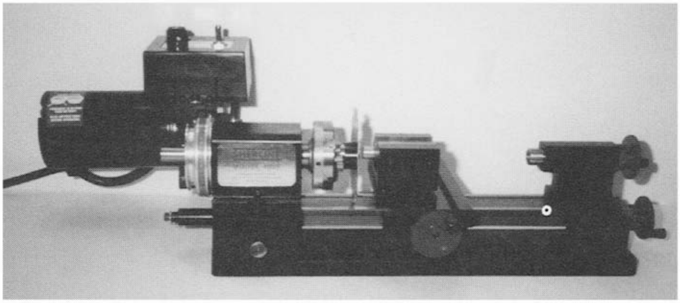

Figure 10-6: Example of miniature lathe holding target and sensor.

Because machine tools, even the small ones, can develop enough speed and torque to cause serious injury if misused, always follow the manufacturer's instructions and exercise due caution (e.g., wearing safety glasses, keeping fingers away from moving parts, etc.) when operating these devices.

Environmental Chamber

An environmental chamber provides a convenient way to subject sensor assemblies to both hot and cold environments, to see how and if they work at temperature extremes. A good environmental chamber has a programmable controller that allows target temperatures to be set. In many cases the controller also allows a user to enter temperature profiles, which specify a sequence of conditions the oven will automatically generate.

In most environmental chambers, heat is generated by resistive heating elements. Chambers are typically cooled in one of two ways. Larger (and more expensive) environmental chambers have self-contained refrigeration systems to provide cold conditions, while smaller units often rely on external supplies of liquid nitrogen (LN_2) or liquid carbon dioxide (CO_2) for cooling. Both materials have their advantages and disadvantages. LN_2 is more effective at developing low temperatures than CO_2. LN_2's big disadvantage is its limited shelf-life; it is stored cold ($\approx -196°C$) in a Dewar flask and spontaneously boils away over time. On the other hand, liquid CO_2 is stored under pressure at room temperature in a gas cylinder, and can be stored indefinitely, barring valve leakage. The CO_2 in the tank is not actually cold; it cools when it exits the vessel and boils away. When using either a CO_2 or LN_2-charged environmental chamber, it is important to ensure that the area has adequate ventilation to prevent buildup of these gasses to hazardous levels.

If one uses an environmental chamber frequently, it may be worth buying one with an integral refrigeration unit, as this will eliminate the cost, handling, and storage issues associated with either LN_2 or liquid CO_2.

10.4 Magnetic Simulation Software

Although the fundamental equations describing magnetic fields are straightforward to express, they are not as straightforward to solve except in a very few idealized cases. Closed-form analytic solutions may be either difficult or impossible to find except for the most simple magnetic systems. A magnetic system does not need to become very complex before it becomes practically impossible to find closed-form solutions. For this reason a number of approximation techniques have been developed, but they may not yield satisfactory results for complex systems.

Computer simulation offers one solution to the problem of predicting the performance of a magnetic system without having to actually build it. Several computational techniques have been developed for this purpose, with finite-element analysis (FEA) and boundary-element analysis (BEA) the most commonly implemented. In either case, the geometry of the system, the properties of the materials used, and the characteristics of any "sources" (such as electric currents in coils) are known, modern magnetic simulation software can provide a good estimate of how a magnetic system will behave under a variety of conditions.

The first step in building a simulation model is to define the geometry of the system. A short time ago, one was limited to building two-dimensional approximations, and having to make numerous assumptions about how the behavior of the two-dimensional model would extrapolate into three-dimensional reality. Because of advances in both simulation algorithms and computer speed and memory, it is now possible to directly model three-dimensional systems. Figure 10-7 shows an example of a 3-D model built in Ansoft's MAXWELL simulator.

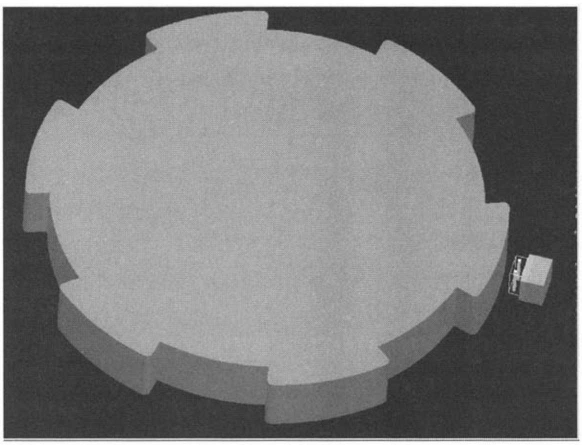

Figure 10-7: 3-D geometric model of geartooth sensor (courtesy of Ansoft, Inc.).

After one defines the model's geometry, the next step is to define the characteristics of the various materials used. Accurate modeling of nonlinear behaviors, such as saturation, is essential to obtaining good results. Improvements in fundamental simulation algorithms have also led to improvements in the area of materials modeling as well.

Once geometry and materials have been defined, the next step is to define sources and boundary conditions. In the case of a static (DC steady-state) magnetic simulation, the two major sources of interest are permanent magnets and electrical currents. In the case of permanent magnets, the magnetization is often defined when one defines an object as being made from a particular material. The direction of magnetization, however, must still be defined. In the case of electrical current, both magnitude and direction also need to be defined. Boundary conditions define how the simulator should behave at the spatial edges of the simulation. Several options are usually available for defining boundary conditions; selecting the proper set is dependent both on the system being modeled and the algorithms used by the simulator.

After geometry, materials, and sources have been defined, the software can begin solving the problem. For the finite element method, the first step is to subdivide the geometry you defined into a collection of smaller subunits, often terahedra or "bricks." This process is commonly called *meshing*. Figure 10-8 shows an example of a mesh. A problem must be meshed for a finite element solution because the method works by defining analytic solutions for the fields within each subunit, and then iteratively solving for a set of solutions that simultaneously satisfy all the relationships among the subunits. Mathematically, this requires solving large sets of simultaneous equations, and is why these types of simulation programs typically require large amounts of memory and a fast processor.

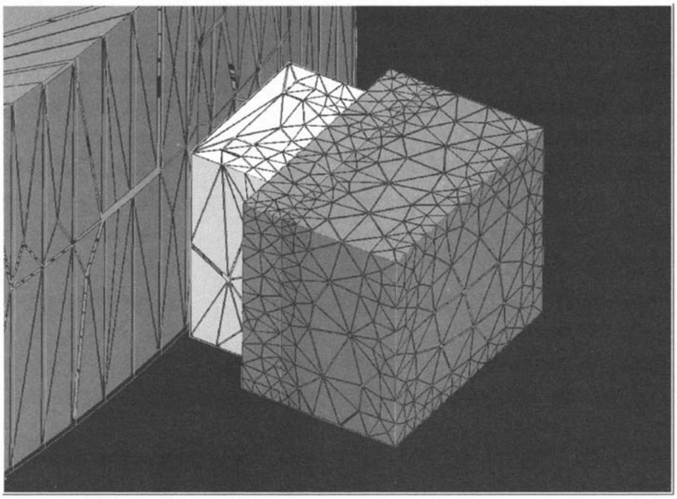

Figure 10-8: Example of finite element mesh (courtesy of Ansoft Inc.).

Finally, after the problem is solved, the results need to be viewed. Presenting the data in the form of raw numbers does not tend to be particularly useful, especially for large problems. For this reason most magnetic simulation packages include some kind of postprocessor, which allows the user to plot data in a number of ways. Some of the more common and useful plots that can be generated by these postprocessors are:

- 2-D plots, magnetic quantity versus position
- Contour maps
- Color-scale maps
- Vector plots

Figure 10-9 shows an example of a vector plot of flux density for the geartooth sensor model.

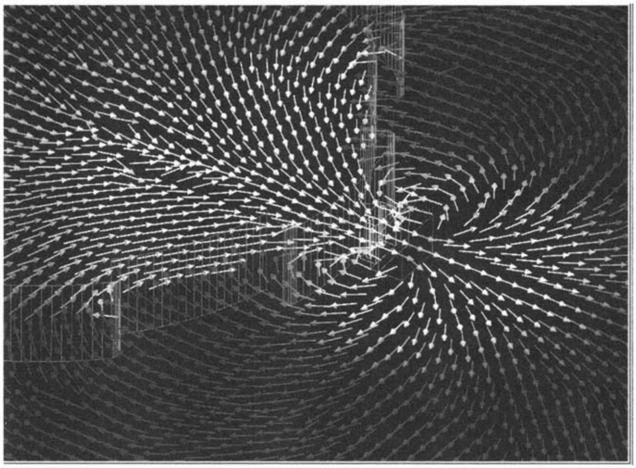

Figure 10-9: Vector plot of magnetic flux density (courtesy of Ansoft Inc.).

Although magnetic simulation tools do not eliminate the need to actually build a sensor and evaluate it, they can vastly speed the process of getting to a design worth prototyping and testing. For the relatively simple magnetic systems used with most Hall-effect sensor assemblies, three-dimensional simulation tools can provide a high degree of accuracy. Because it is much faster to try alternatives out on the computer than in the lab, a larger number of design alternatives can be evaluated, resulting in better product designs. The ability to quickly ask "what if" also can result in much more robust designs, because you can do things such as vary material characteristics and mechanical tolerances to explore design sensitivity issues. The use of magnetic simulation tools should be considered by anyone serious about designing high-quality Hall-effect sensor assemblies.