Induction Basics

by Carl Moreland

Some hobbies, such as collecting stamps or coins, are educational, while other hobbies, like building models, tend to exercise creativity. Metal detecting is clearly on the side of educational, providing you take the time to learn about the items you find, and the context in which they are found.

Metal detecting can also have a creative side to it. Some folks enjoy building their own accessories, such as digging tools. A few even modify their detectors, most often for ergonomics. But only a small handful get down and dirty into the electronics of the metal detector. Mostly because metal detector technology is not well-understood by the majority of users, and there is darn little information available on the technical operation of detectors. Add to this a reluctance by manufacturers to share technical information—even a tendency to provide misleading information, particularly in advertising—and you wind up with a majority of detector users having a wrong impression of how it all works.

Compare this to another electronics-based hobby, amateur radio, in which many enthusiasts not only have a good working knowledge of the electronics, but often build and modify their own equipment, and with amateur radio magazines routinely covering technical issues.

Why in the world would the average detectorist need to know how a detector works? While some detector models have few user controls and are practically turn-on-and-go, many of the higher-end models have a number of controls for optimizing performance. So, the best reason to learn how detectors work is to better understand what the external controls are really doing and what their limitations are. Besides that, knowing how they work will help you wade through advertising claims. And, finally, it's just plain interesting.

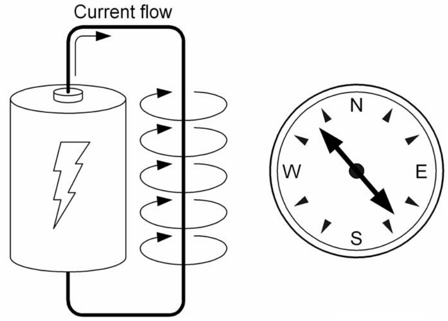

Figure 1: **Static magnetic field**

Magnetic fields

Metal detectors operate via the principle of *induction*. Induction is the method of coupling two circuits though an alternating magnetic field. To clarify, let's take a look at magnetic fields first.

When you pass a direct current (DC) through a wire a *static* magnetic field develops around the wire, as shown in Fig.1. You can check this out at home with a battery, wire, and compass. Place the compass near the wire, briefly touch the ends of the wire to the battery terminals, and watch the compass needle jump. *Briefly* is the operative word, because shorting out a battery in this manner can create a large current, and quickly heat the wire and the battery.

If you wrap the wire in a long tight coil (Fig. 2) you can enhance the magnetic field, because the coil "focuses" the magnetic field though its center, with each turn of wire adding more "flux" to the field. An iron core will further enhance the field, and produce a simple electromagnet often demonstrated in elementary school science class.

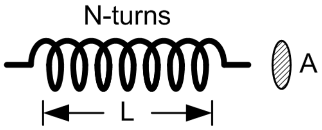

Figure 2: **Multi-turn coil**

As long as the DC current[1] is constant, the magnetic field will be constant. If the current is varied, then the magnetic field will follow. An alternating current (AC) in a wire produces an *alternating* magnetic field around the wire. That is, as the current continuously reverses direction, the polarity of the magnetic field does as well. Clamp-on ammeters[2] use this principle to determine the current in household wiring, without having to cut the wire.

The strength of the magnetic field depends on the current through the coil (I), the dimensions of the coil (length L and radius R), the number of turns of wire (N), and the material used as the core of the coil. Just so we can have an equation in this article, the maximum field strength of a short coil[3] is:

$$B = \frac{\mu N I}{2R}$$

where μ is the "permeability" of the core material[4]. This is the field strength exactly at the center of the coil, and reduces as you move away from the coil.

Induction

If a current through a wire can create a magnetic field, an obvious ques-

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1. "DC" means "direct current", so "DC current" means "direct current current", which clearly is redundantly repetitive. But in electronics, we also use the term "DC voltage", so DC has become synonymous with "constant".
2. An ammeter measures *amperes*, which is the unit of current.
3. Such as the "skinny donut" used in metal detectors (length L falls out of the equation).
4. Metal detector coils have air as the core material, for which $\mu = 4\pi \times 10^{-7}$ Henries/meter (H/m).

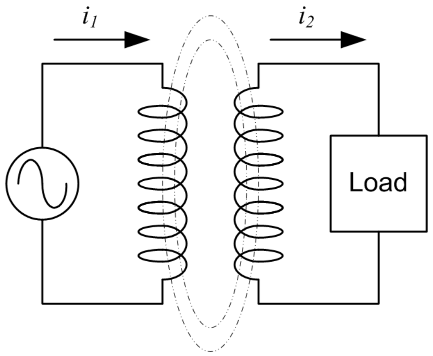

Figure 3: **Inductive coupling**

tion to ask is, can a magnetic field create a current in a wire? The answer is yes, but only in the case of a *changing* magnetic field. In other words, you can place a wire[5] in an alternating magnetic field and generate an AC current[6] in the wire. It might seem that placing a wire in a static magnetic field would generate a DC current, but not so. To generate a current with a static field, you have to move the wire *through* the field, for which you get a *transient*[7] current. If you move the wire through the field in a periodic manner, then you will get a periodic (AC) current. This is how a generator (alternator) works. But sitting still in a static magnetic field will get you zilch. Again, all this assumes a few things, like the wire is actually hooked up to something.

Curiously, an alternating magnetic field gives rise to an alternating electric field (and vice-versa). Although it's really not important to this discussion and involves some heavy-duty math, the basic idea is that a changing magnetic field will move electric charge, and electric charge in motion creates a changing magnetic field. So they sort of support one another, and the combination of the two is known as an electromagnetic (EM) field. The EM field is how radio signals travel through space.

I brought this up because I will refer to the alternating magnetic field as an EM field, and you will see others call it this as well. In actuality, the magnetic field portion is what detectors make use of, and the electric field part does nothing for us. So when I use the term "EM field", I'm still really talking about the alternating magnetic field[8].

OK, if we wind the wire up into a coil we can intensify the effect on both ends. Pass an AC current through the coil and we get a stronger EM field; put the coil in an EM field and we get a stronger AC current. If we take two coils and place them close to each other, then driving one coil with AC will create the EM field, which will *induce* an AC current in the other coil. And here you have a transformer (Fig. 3). All this stuff was figured out 170-odd years ago by Michael Faraday. It's called *induction*, because things are getting induced.

What magic is doing the inducing? With wires it's electron motion, where a magnetic field cutting across a conductor causes electrons to move, and where electron motion produces a magnetic field. Same as what I described with moving charges three paragraphs ago.

When you have a disconnected piece of metal in an EM field the electrons have no where to go. So they do something really odd: they just go around in circles, something called *eddy currents*[9] (Fig. 4). If you have a *really* strong EM field, you can get really high eddy currents, enough to make the metal heat up. Maybe you've seen an induction cooktop where eddy currents are generated in the metal pot to heat the food. Foundries also use induction crucibles to melt steel.

So with a metal detector, we shove an AC current through a coil, which produces an EM field around the coil. When a metal target is near the coil, the EM field induces eddy currents in the target. One thing to note: there is a 90 degree phase shift in the EM field (actually, between the EM field and the AC *voltage*), as described by Faraday's Law. So the eddy currents in the target produce a *reverse* EM field, i.e. 180 degrees out-of-phase with coil field, because there are *two* 90 degree shifts between the transmitted (coil) EM field and the target-induced EM field. See Fig. 4. This reverse target field then inductively couples with the receive coil and generates the signal that says you've found something. You can either think of this reverse target field as separate from the transmit field, or as a distortion of the transmit field—I've seen it described both ways and either is correct.

As I said, eddy currents tend to be circular. Which is why they're called eddy currents, just like what you find in streams. A whole bunch of tiny circular eddy currents will add and subtract across the surface of the target to determine the nature of the overall eddy current, which in turn determines the nature—and strength—of the reverse EM field. The circular nature of eddy currents means that circular targets will better support them because of the way they add up. In fact, given a round target and a square target of identical surface area, thickness, and metal type, the round target will give a slightly stronger response.

Would there be a difference between a solid round target like a coin and an open round target like a ring? It turns out there is. A ring will give a *stronger* response, even though it has

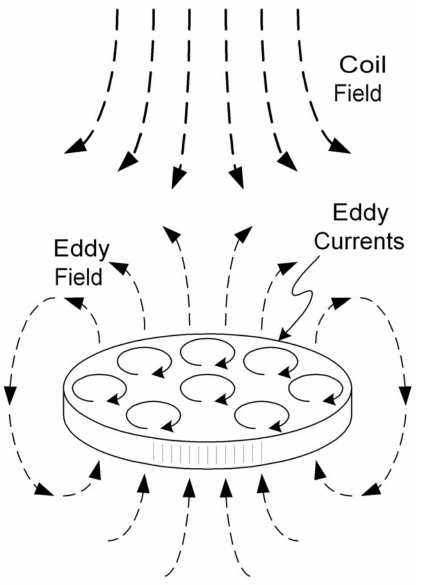

Figure 4: **Eddy currents & field**

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5. Generally, the wire must be part of a closed-loop circuit.
6. Likewise, "AC current" is redundant, so just pretend AC means "alternating". Usually, AC refers to a periodic (repeating) signal, often a simple sinusoid.
7. A transient signal (voltage or current) is not constant, nor is it periodic, so it generally is not considered DC or AC.
8. A static magnetic field is not considered an electromagnetic field, even when it is produced by an "electromagnet".
9. So I lied, the wire does not have to be part of a closed-loop circuit, which is why I qualified footnote #3 with the word "generally".

less surface area. That's because it is more like a shorted loop of wire, in which the induced current flows around the loop, instead of moving in smaller surface circles as it does with a solid disc. So the extra metal in the middle of the coin actually hurts the response. It's a fairly subtle effect, but it's there.

You can demonstrate this for yourself, by comparing a ring and a coin to see which gives the greater response. This does not account for possible conductivity differences, so a better test is to compare two coins, one with most of the center drilled out. I used two pre-zinc Lincoln cents, with a 5/8" hole drilled through one. Both a VLF (all-metal mode) and PI detector indicated the drilled-out cent 3/4"-1" deeper than the solid cent. I repeated the experiment with silver Washington quarters with the same result. So, with the conductivity variable removed we see that the ring shape will slightly edge out the solid coin, even when the metal and diameter are identical.

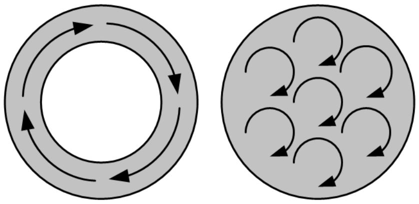

Figure 5: **Ring vs. Coin**

Two final notes. The induced eddy current in a metal target is not always 90° out-of-phase. The phase shift actually depends on the conductivity of the metal, and only a perfect conductor gives a 180° (total) phase shift. And this is how we discriminate, by looking at the received signal's phase shift. Higher conductive targets, like silver, are closer to 180°. Interestingly the drilled-out coins have a (very) slightly higher resistance than the solid coins and this shows up in the target phase number. Also, while a ring response is a tad stronger than a coin, a broken ring is *really lousy*. Now the induced currents can't travel around the ring so they're back to moving in tiny surface circles, but in a target that has very little surface area.

Resources

1. Eddy Currents, ETI, April 1981
2. Electromagnetics, John Kraus
3. Fundamentals of Electricity & Magnetism, Leonard Loeb