
ELECTROMAGNETIC INDUCTION (PAPER II)*Lloyd S. Riggs, Auburn University*

INTRODUCTION

Electromagnetic induction (EMI)–based detection techniques find application in a variety of areas, including nondestructive testing (e.g., locating cracks in turbine blades), ore body location, as well as the detection and *identification* of landmines and unexploded ordnance (UXO). The common metal detector is probably the most ubiquitous EMI device in use today.

Typical components of a metal detector include a transmitter and receiver coil. As depicted in Figure B.1, electric currents that flow in the transmitter coil radiate a primary magnetic field that penetrates the surrounding medium and any nearby metallic object. A time-changing primary magnetic field will induce so-called eddy currents in the buried object, and these currents in turn radiate a secondary magnetic field that is sensed (picked up) by the receiver coil. An audio tone is produced whenever the metallic object causes the induced receiver coil voltage to exceed some threshold.

Modern metal detectors are quite sensitive and can detect buried low metallic (LM)–content landmines that contain only a few grams of metal [1]. Examples of modern-day metal detectors include the U.S. Army’s standard-issue AN/PSS-12 manufactured by Schiebel Corporation of Austria and the F3 manufactured by Minelab Corporation of Australia. Unfortunately, as the name implies, a metal detector will produce an audio alarm whenever *any* metallic object is brought near its search coil(s). At present, commercially available metal

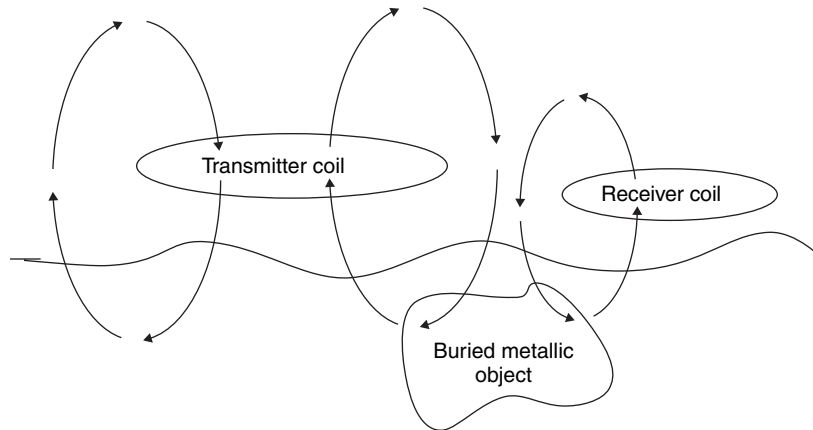


Figure B.1—Typical Electromagnetic Induction System

detectors have very limited ability to discriminate between landmines and buried metallic clutter. False alarms generated by metallic clutter severely limit the speed and efficiency of mine clearance operations. For example, Minelab, whose EMI instrumentation is frequently used in humanitarian demining operations, reports that it is not uncommon to remove 1,000 metallic clutter items per mine. The goal for modern EMI systems is, however, more than detection. In order to discriminate clutter from LM mines, additional information has to be gathered about the target.

The additional information that is available with an EMI sensor is contained in the details of the orthogonal mode structure of the eddy currents and associated induced fields, and how they evolve over time. The eddy current modes are related to the eigenvalues (referred to as “response coefficients,” or “ β s”) of the magnetic polarizability tensor [2,3]. EMI sensors are generally characterized as pulse induction or continuous wave, with the former using, as the name implies, short pulses of current in the transmitter coil while the latter forces a continuous sinusoidal current to flow in the transmitter coil. Both are capable of measuring how the eddy currents evolve over time, yielding time or frequency-dependent β s that are related to each other by Fourier transforms, and each technique has advantages and

disadvantages [4]. The GEM-3 manufactured by Geophex is an example of a continuous wave detector, and the AN/PSS-12 and F3 mentioned above are examples of pulse-induction detectors. Discrimination experiments with the AN/PSS-12 will be described in the next section.

ACHIEVING DISCRIMINATION CAPABILITY WITH A MODIFIED AN/PSS-12 [5]

EMI discrimination research has focused on either the UXO or the mine problem. In the former case, one is generally interested in discriminating between large unexploded bombs and surface clutter while in the latter, as described above, the problem is one of discriminating between LM-content landmines and clutter. UXO can be buried several meters deep while antipersonnel mines are typically buried no more than 6 inches below the surface. EMI sensors designed to detect UXO usually incorporate rather large coils (on the order of a meter in diameter) while sensors designed to detect LM mines usually employ coils less than 12 inches in diameter. It should be mentioned that large LM “plastic” anti-vehicular mines are frequently more difficult to detect (and therefore discriminate from metallic clutter) than smaller LM antipersonnel mines. This is because they both contain approximately the same amount of metal (usually a small metallic detonation tube and firing pin), but the anti-vehicular mine is usually buried deeper than the antipersonnel mine. For explanatory purposes, this discussion will focus on the mine problem emphasizing modifications to the Army’s AN/PSS-12 metal detector in order to enhance landmine discrimination capability.

Although the AN/PSS-12 is quite sensitive and can detect very small amounts of metal, it was not designed to discriminate among metallic objects, or, more specifically, between metallic clutter and LM “plastic” landmines. It has been shown that the response of a metallic object is characterized by distinct real-axis poles in complex frequency domain or equivalently by a sum of simple non-oscillatory exponentially decaying functions in the time domain [3]. For example, the response of a loop of wire (sometimes referred to as a q-coil) may be represented as $r(t) = A \exp(-t/\tau)$ with $\tau = L/R$, where L is the inductance of the loop and R is the resistance. An arbitrarily shaped metallic object will also exhibit an exponentially decaying response

with decay rate dependent on the object's shape and constitutive parameters (conductivity and permeability). Therefore, in theory at least, the potential exists to discriminate among metallic objects based on their different decay rates.

Several hardware modifications were made to the AN/PSS-12 to render the device more suitable for discrimination purposes. In particular, we observed that the first stage of amplification following the receiver coil is nonlinear and of limited bandwidth. We therefore bypassed the entire receiver circuitry of the AN/PSS-12 and attached the output of the receiver coil to the input of cascaded AD524 amplifiers—the first (nearest the receive coil) operated at a gain of 10 and the second at a gain of 100. Also a properly adjusted resistance in parallel with the receiver coil yielded a critically damped system response. A National Instruments Scope Card, NI-5102 (15 MHz, 20 MS/s, 8 bits), was used for data acquisition. The data acquisition card resides in the PCMCIA slot of a laptop computer and is controlled using National Instruments LabVIEW software. Our data acquisition system allows the entire exponentially decaying response of a conducting target to be sampled, stored, and then used “off line” to develop discrimination algorithms. An additional increase in system bandwidth was achieved by eliminating the upper half of the original bipolar AN/PSS-12 excitation waveform. The ability to capture an object's entire exponential response provides substantially more information than that available from the original AN/PSS-12 circuitry.

After modifying the AN/PSS-12's transmitter and receiver circuitry as described above, laboratory tests were conducted to ensure that we could capture, with good fidelity, the true exponential response of commonly encountered LM mines. A number of q-coils, all with the same diameter, were constructed using progressively higher wire gauge (thinner wire) so that the exponential decay rate of the loops increased with increasing gauge. The theoretical decay rates of the q-coils were computed and compared with the decay rates extracted from measured q-coil data. Excellent agreement between the two data sets was obtained. We then extracted the decay rates from commonly encountered LM mines and compared their decay rates with those of the q-coils. Because the LM mine decay rates fell within the range of measured loop decay rates, we concluded that our

modified AN/PSS-12 data collection system had sufficient bandwidth to accurately measure the decay rate of most LM mines.

Field trials with our modified AN/PSS-12 were conducted at the Fort A. P. Hill, Va., test site. The Joint Unexploded Ordnance Coordination Office in conjunction with the U.S. Army developed this test site, which contains a variety of different mine types and an assortment of metallic clutter commonly encountered in battlefield environments. The test site consists of a large 20 m × 49 m blind test grid and a smaller 5 m × 25 m calibration grid. Every square meter in both grids is set up as a decision opportunity for the detector under test (our modified AN/PSS-12). A landmine or possibly a piece of metallic clutter may be buried at the center of each grid square while some grid squares are intentionally left empty. The calibration grid is used as “ground truth” and data collected there can be used to develop discrimination algorithms. Ground truth associated with the calibration grid is publicly available, whereas only the U.S. government knows ground truth for the blind test grid. Performance is evaluated by an independent government contractor and ultimately presented in terms of a receiver operating characteristic (ROC) curve—created by plotting probability of detection versus probability of false alarm.

Our data collection procedure at Fort A. P. Hill included collecting background data with the search head in contact with the soil. We then subtracted the background data from five measurements made over each target location. The five measurements were made with the target at the center and at the top, bottom, right, and left side of the search coil. Multiple measurements per target location ensure that all independent target modes are measured [6].

A discrimination algorithm based on Bayes’ theorem was used to predict, based on the data collected, which squares in the blind grid contained mines. Figure B.2 shows the resulting ROC curve. Note that, at very low false alarm rates, the location of approximately half the mines was correctly identified. The other curves in the figure correspond to algorithms that incorporated only a subset of the five measurements described above. Our research indicates the importance of collecting data that adequately represents all the independent target modes.

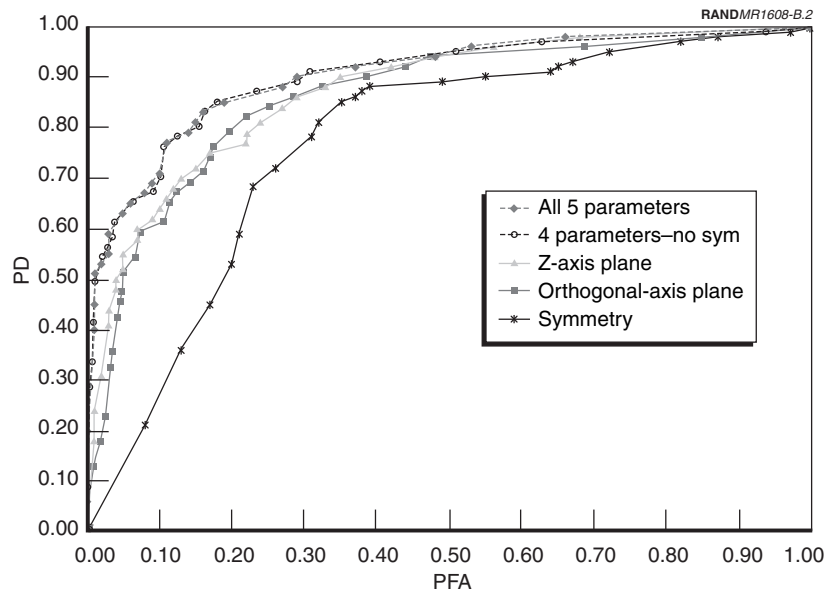


Figure B.2—ROC Curve Results for Modified AN/PSS-12 Sensor

STATE-OF-THE-ART AND FUTURE TRENDS IN EMI DISCRIMINATION RESEARCH

Results in the previous section clearly indicate that the potential exists to discriminate between mines and clutter based on a metallic object's low-frequency quasimagnetostatic response characteristics. It is important to mention that others, in particular researchers at Duke University [7], Johns Hopkins University [8], and AETC Inc. [9], have also conducted successful discrimination experiments. Although discrimination has been successfully demonstrated, the state of the art is still somewhat immature. In particular, "real-time" discrimination capability has yet to be demonstrated and questions remain as to the best way to present the operator with the additional information available from advanced sensors and signal-processing algorithms. A typical envisioned scenario could be that the handheld sensor is operated in two distinct modes. First, the advanced sensor would operate much like a common metal detector, producing an

audible alarm whenever a metallic object is nearby. In the second operational mode, perhaps initiated by a simple switch or button, the detector would provide additional information in the form of a heads-up display or electronic voice (or both) indicating which of a set of known threats is most probable. Of course, a host of machine-human interface problems as well as training issues must be addressed before this vision becomes a reality. Improvements in EMI sensor design are also needed. It is desirable to develop an EMI sensor that can pinpoint a target's "center of mass"—and obviously increased sensitivity and bandwidth are also desirable sensor features. Last, environmental issues must also be addressed with particular attention devoted to understanding how highly conducting soils can affect a metallic object's EMI response.

It is the author's opinion that a five-year research and development program funded at approximately \$1 million per year could realistically yield a robust real-time handheld discrimination system. The first two years of the envisioned program would focus on sensor improvements, with the next two years devoted to signal-processing development and machine-human interface issues. The final year of the program would be devoted exclusively to field trials leading to final user acceptance.

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