Design and Implementation of a Low Cost VLF Metal Detector with Metal-Type Discrimination Capabilities

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DESIGN AND IMPLEMENTATION OF A LOW COST VLF METAL DETECTOR WITH METAL-TYPE DISCRIMINATION CAPABILITIES

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ABSTRACT

Land mine detectors, security metal doors that we all go through in buildings and airports, as well as metal mining detectors are just examples of metal detector use in our daily lives. In this paper we present a cost efficient, low complexity very low frequency (VLF) handheld reconfigurable metal detector (MD) design and implementation that has the capability of discriminating between various metal types. A concentric coil consisting of an outer transmitter coil, an inner receiver coil and a feedback coil. The coils operate in the 5.5 KHz frequency range. An amplitude and phase detection circuits were designed to detect and distinguish between metal types. The detection algorithm was implemented using a PIC microcontroller. The results from the actual implemented metal detector are shown and discussed for 3 types of metals: Iron, Copper, and Aluminum at various distances. The MD can detect metals about 16 cm below its coils.

Index Terms— Metal Detectors, Very Low Frequency, Microcontroller, Coils, Analog Circuits.

1. INTRODUCTION

A time varying current passing in a conductor produces an electromagnetic field around that conductor; this is what Ampere's law states. This phenomenon has various important applications in our daily lives. An induced voltage is obtained in a closed circuit if it falls under the effect of a time varying magnetic flux [1]. Combining these two important phenomena we can send and receive electromagnetic waves. This is the basic principle behind modern wireless communications. Another important application of such phenomena is the Metal Detector that has been out there for some time now.

Metal detectors (MD) have a wide application proliferation in our daily lives. They are used in security, military and civilian applications. Their operation depends on simple principles that rely on Ampere's and Faraday's laws. The magnetic field generated from the transmitter coil induces an Eddy current in the metal underneath, this causes a magnetic field to be generated from the metal, and added to the original field. Thus, the presence of a metal object is detected as variations in the induced voltage in the receiving loop. The presence of the metal also has an impact on the phase of the captured signal with respect to the reference.

Several types and methods have been proposed to the design and implementation of such devices, most of them are proprietary for the companies that manufacture them. All types utilize a transmitter antenna and a receiver one to send and capture electromagnetic waves. There are three widely used techniques for MD design:

- The Beat Frequency Oscillator (BFO).
- The Pulse Induction (PI).
- The Very Low Frequency (VLF).

The VLF operates in the range of 3-30 kHz, while the BFO operates in the 100s kHz and the PI in 100s Hz range. In this work, a VLF type MD is designed and implemented because it does not suffer from the dual frequency operation and synchronization issues that the other two methods suffer from, thus simplifying the design process.

Most MDs that we see nowadays only indicate the presence of a metal object only, regardless of its type. MD used in security applications at the building doors and with security personnel only gives a beep if a metal object is found. Landmine and handheld metal detecting equipment also does not distinguish between different metal types [2]. In [3] a dual receiver medium frequency (MF) MD was proposed for food processing applications operating at 800 kHz that only reports the presence of a metal object in the food that is passed between the center transmitter coil and the two receiver coils on both sides of the conveyor belt.

In this work, a low cost, low complexity MD is designed and implemented and its capability to discriminate between various types of metal objects is investigated. This is based on the experimental identification between the amplitude and phase values for various metal objects at various distances from the MD. It has been shown that these relationships are induced experimentally in [3] and there is no specific method to deduce them since they are a function of the metal type, shape, and size.

The paper is organized as follows; section 2 describes the design operation and the constituting parts. Section 3 discusses the circuit design of all portions as

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well as the coil design and implementation. Section 4 shows the results and section 5 concludes the paper.

2. MD DESIGN AND SPECIFICATIONS

Fig. 1 shows the main block diagram of the designed MD. The design follows [4] in its coil construction methodology (although we have different number of turns and AWG wires, the coil was wound manually in the lab), but differs in the circuitry and functionality that follow. The transmitter portion consists of the oscillator and the transmitter coil. The receiver portion consists of the receiver coil, the amplitude and phase detection circuitry, and the PIC microcontroller with the attached LCD display.

The transmitter frequency used was 5.5 kHz. The transmitter and receiver coils are wound in a concentric fashion, where the transmitter coil is at the outer radius. The receiver amplitude and phase detection circuits are designed and built using a series of simple passive filters, amplifiers and logic gates. The outputs of both circuits are fed to a PIC 16F877A microcontroller for processing. The PIC holds the program that discriminates between various metals based on the phase and amplitude measurements recorded at various soil distances. Although the soil does have an effect on the response of the magnetic field from the MD [5], this design detects metal objects that are buried at shallow distances (~16cm) at which we can neglect such dependency. Antipersonnel (AP) landmines are buried at shallow distances and our MD design can be used for such metal detection applications. An LCD display connected to the PIC microcontroller will show the presence of the metal as well as its type after correlating the results with those stored in the microcontroller program. The relationships between the amplitudes and phases as functions of their distance from the coil are measured and recorded, and the results of the implemented MD are discussed in section 4.

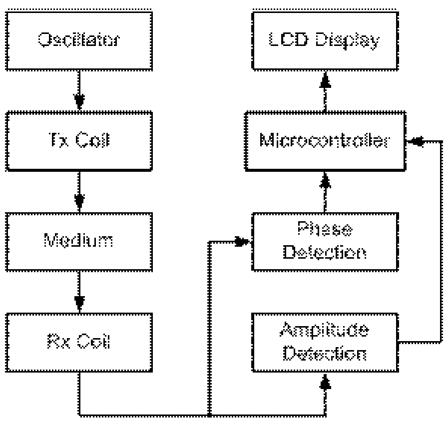

Figure 1. MD main block diagram.

3. CIRCUIT DESIGN

3.1. Coil Design

The VLF MD has three coils; the transmitter coil, the receiver coil and the feedback coil. These coils are wound in a concentric fashion with the transmitter coil being the outermost one, and the receiver coil the innermost one, with the feedback coil over the receiving coil. Details about the coil dimensions and number of turns are shown in Table I. An AWG 28 wire was used for the transmitter coil while an AWG 30 was used for the receiver and feedback coils. All three coils were wound in the lab manually. The feedback coil is needed to reduce the effect of the transmitted signal on the receiver coil. It is designed to allow the detection of change in the received signal with minimal interference from the transmitter coil. It is wound in the reverse direction of that of the transmitter coil over the receiver coil. Both coils are wound around a plastic hollow cylinder.

TABLE I
Dimensions and number of turns of each coil used.

	Transmitter	Receiver	Feedback
Number of turns	85	275	35
Radius	8 cm	4 cm	4.2 cm

The inductance of the transmitter coil was measured to be 2.487 mH, which incorporates the feedback coil inductance as well. A 0.33 μF capacitor was used to resonate the coil at 5.55 kHz. The receiver coil measured was 9.4mH, and a capacitor value of 100 nF was used to resonate it around 5.2 KHz. This frequency difference between the transmitter and receiver is utilized to be some kind of a reference in normal mode of operation.

3.2. Oscillator circuit Design

The circuits are designed to operate in the 5.5 kHz range. A simple low cost Wein-Bridge oscillator was designed. The oscillator circuit is shown in Fig. 2. The resistor and capacitor values of R and C are designed to have a resonance at 5.5 kHz according to $\omega_o = 1/RC$, while R1 and R2 are designed to have a gain of two. The power supply used for all circuits was 9V. For those circuits that need a derivative of that, a LM7805 voltage regulator circuit was used.

3.3. Amplitude Detection circuit

The amplitude detection circuit consists of buffer that is followed by a half wave rectifier to eliminate the negative portion of the received signal. A non-inverting amplifier is used to amplify the signal level followed by a two stage integrator for DC signal conversion (total f_{cutoff} =51Hz). The DC output is then fed to the PIC analog port for processing within the PIC program. Fig. 3 shows the schematic of the amplitude detector circuit.

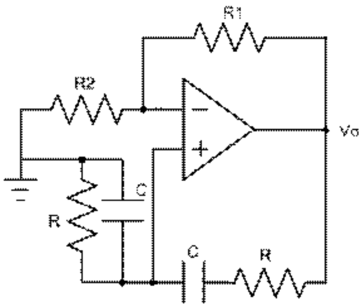

Figure 2. Oscillator circuit.

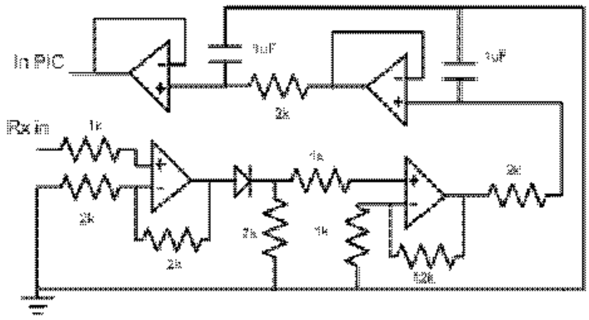

Figure 3. Amplitude Detection Circuit

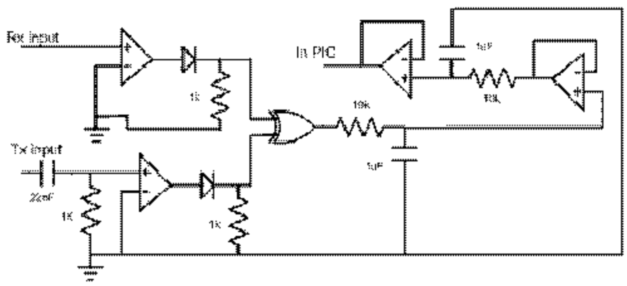

Figure 4. Phase Detection Circuit

3.4. Phase Detection circuit

This circuit is used to detect the phase difference between the local oscillator signal (transmitted phase) and the received signal. Fig. 4 shows the stages of this circuit. The first stage converts the incoming and locally generated sinusoidal signals into digital square wave signals at the outputs of the rectifying diodes and using comparator circuits. A first order phase detector XOR gate is used to find the phase difference. A following two stage first order low pass active filter is then used to convert the phase difference pulse into a DC voltage level (integration process). The two stage filter has a cutoff frequency of about 10 Hz. This output is then passed to the second PIC analog input. An internal mapping function is implemented to represent the measured DC level into its corresponding phase shift. This is proportional to the area under the pulse generated from the first order phase detector (XOR gate).

3.5. PIC Programming

PIC 16F877A is used in this design. It was programmed using C language. This device accepts the DC levels from both the amplitude and phase detection circuitry, converts them to their corresponding digital representations using an internally implemented analog-to-digital converter (ADC), and performs the analysis according to the program stored. The major advantage of this implementation is its reconfigurable functionality via PIC reprogramming. Any additional signal processing features that depend on the amplitude and phase measurements can be added without any hardware change. A flowchart showing the program flow of the PIC is illustrated in Fig. 5. This program will detect a metal presence if a change in the amplitude or phase is detected (depending on which occurs first). Then the type of metal as a ferrous material (iron) or non-ferrous material (copper, aluminum) is identified based on the amplitude change and then presented on the LCD.

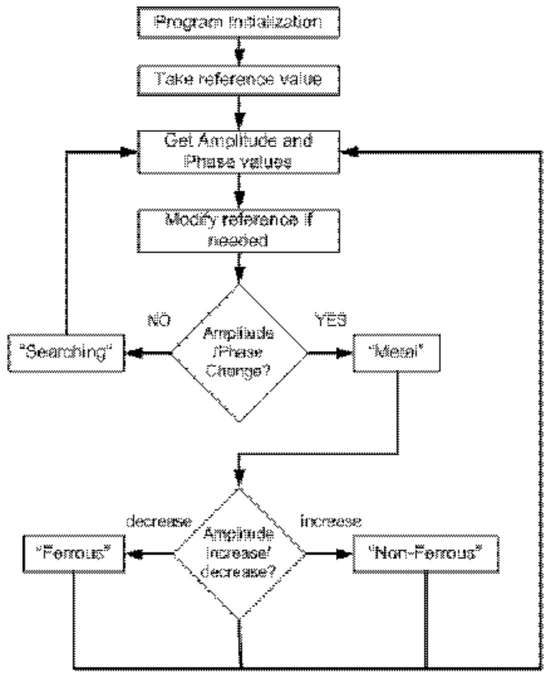

Figure 5. Flow chart of the PIC program.

4. RESULTS

The coil and its corresponding circuits were built and constructed as was shown in section III. Fig. 6.a and 6.b show the circuits and the coil built. Three metal types with various shapes were investigated and tested using our lab constructed MD; Iron, copper, aluminum heat sink and aluminum disk. The shapes of them varied, while their dimensions were $(10.25\times7.25\times0.7)$ cm^3, $(10\times6.7\times1)$ cm^3, $(8.3\times6.8\times3.1)$ cm^3 and $((6^2\pi)\times3.9)$ cm^3, respectively. Fig. 7 shows the variation of the incoming signal amplitude for each metal as a function of distance from the MD. The curves show that for the case of ferrous material, the received signal is lower than the reference (in our case $630mV_{pp}$), while non-ferrous material like copper and aluminum, the amplitude increased beyond the reference. This is due to the fact that the eddy currents generated in the iron piece will dissipate much of the power (proportional to μ_r), thus the reflected signal will be lower than the reference.

Fig. 8 shows the phase difference as a function of distance. The phase difference is inversely proportional to distance for all metal types. It should be noted that beyond about 10cm, the MD designed cannot distinguish between ferrous and non-ferrous material, but can still indicate that a metal is present up to 16cm. This number also depends on the size of the object, where it was observed that larger objects can be detected at longer distances. It was found that the discrimination between various metals in the detection range is highly dependant on their size and shape, so the amplitude curves will not be able to discriminate between the metal types other than whether they are ferrous or non-ferrous material.

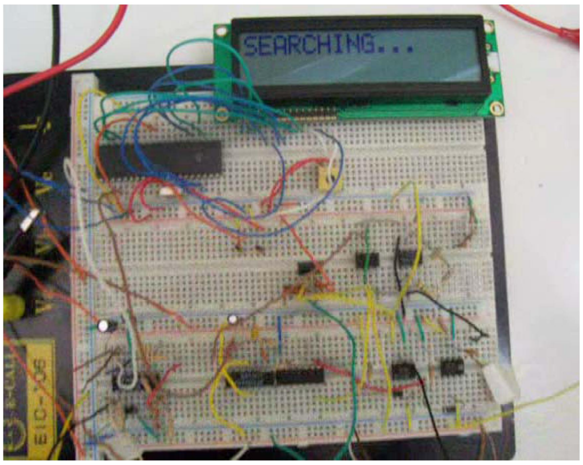

Figure 6.a. Implemented MD discrimination circuit.

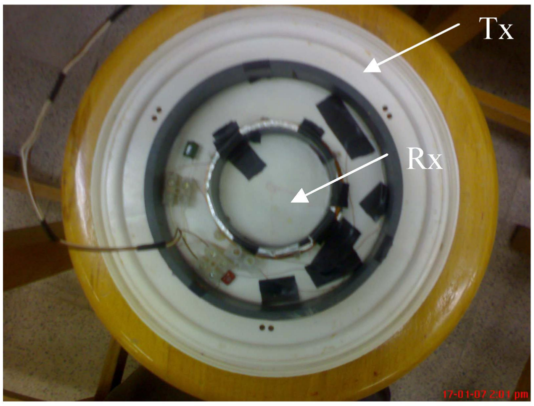

Figure 6.b. Implemented Tx, Rx and feedback coils.

5. CONCLUSIONS

A low cost, low complexity handheld reconfigurable VLF MD was designed and implemented. The MD has the capability to distinguish between various metal types, whether ferrous or non-ferrous material. The amplitude and phase relationships of the received signals from three metal types were recorded as a function of distance. A PIC microcontroller was used to analyze the measurements out of the amplitude and phase detecting circuits and display it on a two row LCD screen. For specific metal dimensions and shapes, the MD can be used to discriminate between specific metal types if some extra tables are added within the PIC program.

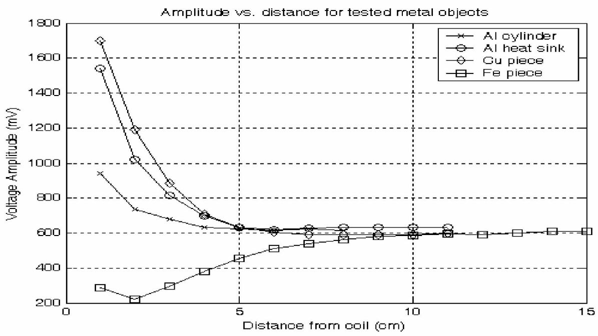

Figure 7. Amplitude vs. distance for different metals.

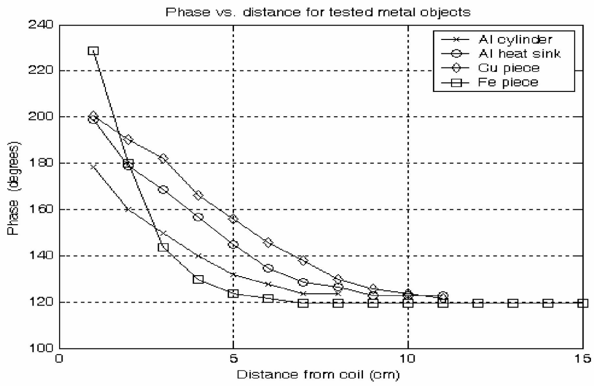

Figure 8. Phase vs. distance for different metals.

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