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Detection of Magnetic Material in Soil Subsurface using Electromagnetic Induction Method Based on Fluxgate Sensor

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Abstract. An instrument based on electromagnetic induction method for detecting magnetic material in soil subsurface has been developed. The instrument consists of a signal generator, an amplifier, a transmitter, receivers, detectors and a display. A coil is used as transmitter. As receiver and also detector is used a three dimensional self developed fluxgate sensor. The fluxgate sensor consists of two pick-up coils, four excitation coils, and a ferromagnetic core. The output voltage of the sensor is processed using an analog signal processing circuit. The sensor's capability in detecting magnetic material in the soil subsurface was observed by placing a sample of magnetic material in the subsurface, and then detected using fluxgate sensor in the direction of the x, y and z (3D). We found that the developed instrument is capable to detect two different objects that is separated at minimum distance around 10 cm with the maximum shallow depth of the target material is 10 cm.

Introduction

Electromagnetic induction surveys have been successfully operating throughout the world for more than 50 years in many applications, ranging from exploration of mineral and hydrocarbon to hydrogeology and environmental studies [1]. One of the advantages of the electromagnetic induction method is a quite wide of depth range of the order of meters to kilometers [2], depending on the frequency of the primary field and the selection of the survey methodology used.

Electromagnetic induction method is a non-destructive test for the physical properties characterization of the soil using electromagnetic waves. The electromagnetic induction device generally consists of two main parts, namely transmitter and receiver. The transmitter serves as a generator of primary electromagnetic field, meanwhile the receiver serves as a detector of the secondary electromagnetic field of the material. The secondary magnetic field intensity that measured by receiver is extremely small, so it requires sensors with high sensitivity and high resolution. Usually the magnetic sensor used in this method is an induction coil that has a very wide range of working area, i.e. 10^{-10} up to 10^{6} mT [3]. The disadvantages of this induction coil are: it measures the rate of magnetic flux change (dB/dt) only in a single dimension [4] and its lower ability to detect of two position of materials which separated by the order of centimeters [2]. To overcome these shortages, we need a three dimensional magnetic sensor that has high sensitivity, high stability and also cheap. There are 2 candidates that suitable for this purpose, namely GMR (Giant Magnetoresistance) or fluxgate sensor; both have developed in our laboratory in the last ten years [5,6,7,8,9]. For this research, we choose fluxgate sensor. A three dimensional fluxgate sensor has been developed to be used as receiver. The sensor has some benefits, e.g. high sensitivity and high temperature stability, small size and low power consumption [10]. In addition, the developed fluxgate sensor is capable to detect a weak DC or AC magnetic field, and also to detect the direction of the magnetic field. This work is a continuation of our previous work as stated in reference [8] and [9].

Experiment

There are two essential components in the development of the instrument, namely element of fluxgate and analog signal processing circuits. The fluxgate element consists of two pick-up coils, four excitation coils, casing, and a ferromagnetic core. Fluxgate element is designed with double pick-up coils with an oval-shaped core. Each pick-up coil is located in the center of the core and is flanked by the excitation coil [8]. Meanwhile the analog signal processing circuit has been developed for processing the output signal of the sensor. A calibrator, which serves as a source of DC magnetic field is used to characterize the fluxgate sensor for the DC magnetic field [11]. The characterization of the distance of DC magnetic field is carried out either without magnetic objects and with the magnetic object that placed around the sensor. Furthermore, the characterization of fluxgate sensor using alternating magnetic field is conducted to determine the sensor capabilities in the detection of alternating magnetic field, particularly at high frequencies. Based on this characterization results, the detection of the magnetic material position in the soil subsurface is conducted using the 3D(x, y, z) fluxgate sensor.

Characterization of Analog Signal Processing Circuit of Fluxgate. This circuit consists of two parts, namely an excitation circuit and a pick-up circuit. The excitation circuit used 4.096 MHz crystal and IC CD4060 as an oscillator. The using of pins 15 and 13 of the IC CD4060 will divide the crystal frequency of 4.096 MHz with the numbers 2^{10} and 2^9, according to the Eq. 1 and 2.

$$f_{exc} = \frac{4.096\ MHz}{2^{10}} = 4\ kHz \quad (1)$$

$$f_{fasa} = \frac{4.096\ MHz}{2^{9}} = 8\ kHz \quad (2)$$

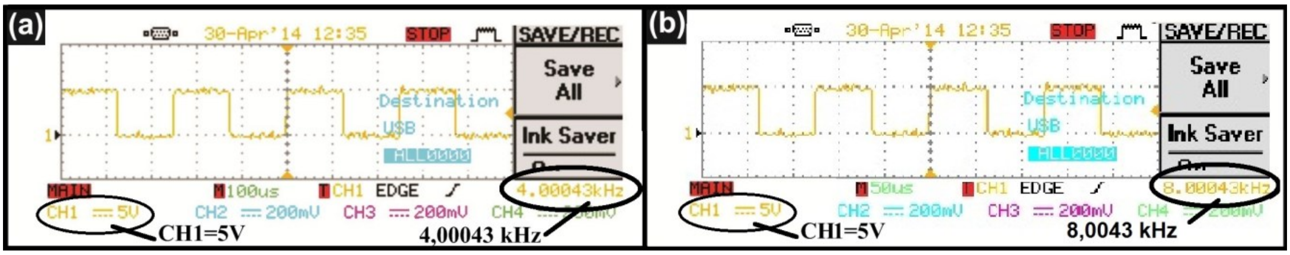


Figure 1. Output oscillator circuit for frequency of 4 kHz (a) and 8 kHz (b).

Thus, the frequency used for excitation coil and phase detector is 4 kHz (f_{exc}) and 8 kHz ($2f_{exc}$), respectively. The output of oscillator circuit of frequency of 4 kHz and 8 kHz are shown in Fig. 1 (a) and 1 (b). The 2^{nd}-order Butterworth filter, which has a cut-off frequency of 1.87 Hz, was used to pass the DC signal.

The Distance Characterization. Fluxgate as a proximity sensor will detect changes of magnetic field due to the distance-change between elements fluxgate and the measured object. This characterization was conducted to determine the distance range of the sensor. A ferrite core solenoids with a constant DC current was used as the source of the magnetic field. From this measurement, the distance range of the sensor is obtained 18 -30 cm as shown in Fig. 2. An iron cylinder with various diameters was placed between the solenoid and sensor. The measurement results of magnetic field for some distance are shown in Fig. 2(a). Fig 2 shows that the magnetic fields increase due to the presence of iron around the solenoid. The magnetic field of the solenoid magnetizes the dipole magnets of iron, and therefore generates a secondary magnetic field. As a result the magnetic flux caught by the sensor increased. Meanwhile, the ability of fluxgate sensor to detect the current changes in the solenoid that induces the iron 1 is shown in Fig. 2 (b). This Figure shows that secondary magnetic field that measured by the sensor increases proportional to the increasing of a solenoid-current.

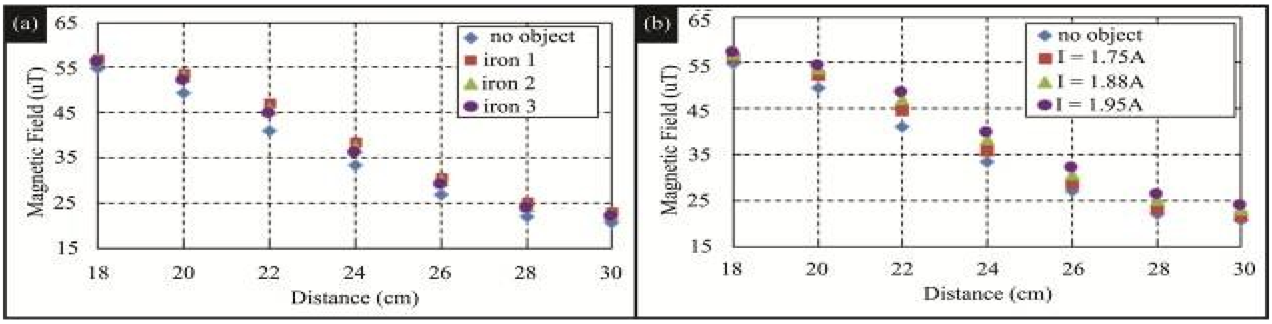


Figure 2. (a) Characterization of sensors fluxgate to the presence of magnetic material around the solenoid with a current (I) 1.883A (b) Effect of current changes in the solenoid to the induction field by iron 1 measured by the fluxgate.

Characterization of Fluxgate Sensor on Alternating Magnetic Field. An instrument as a source of alternating magnetic field has been developed. It consists of a sinusoidal signal generator, power amplifier, and a solenoid. Output of the alternating magnetic field source has frequency of 1 - 10 kHz, and it is amplified by 33.2 times [12]. This magnetic field must be detected by the fluxgate sensor, thus it is necessary to optimize the excitation circuit by modifying the pins used on the IC CD4060. From the excitation circuit optimization was obtained a stable signal using pin 6 and pin 4. This means that the used frequency of the excitation of the phase detector is 32 kHz and 64 kHz. An optimization of the 2nd-order Butterworth filter was conducted to restrict the working frequency range of the analog signal processing circuit of fluxgate sensor, and to overcome the signal disturbance at higher frequencies. Optimization is carried out by considering the quality factor (Q) of 0.707 and using 5-different cut-off frequencies, i.e. 17.049 kHz, 23.941 kHz, 34.098 kHz, 15.915 kHz and 33.863 kHz. The result of optimization is shown in Figure 3(a). It appears that the filter F03 with the cut off frequency 34.098 kHz has the widest working range and stable with gain of 0 dB up to 11 kHz, thus the F03 is used as a filter for the analog signal processing circuit of the developed fluxgate sensor.

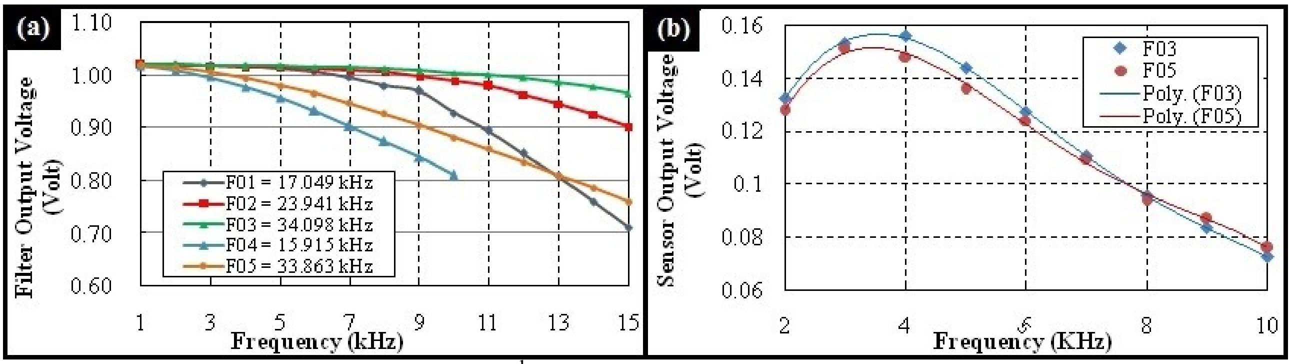


Figure 3. (a) Characterization of the 2^{nd}-order Butterworth filter, Q of F04 and F05 was neglected (b) Output voltage of fluxgate sensor against current frequencies with F03 and F05 filter.

The output of the analog signal processing circuit using filter with cut-off frequency 34.098 kHz (F03) in the detection of an alternating magnetic field is shown in Fig. 4(a) and (b). It is seen that the signal processing circuit capable to give a good response to the alternating magnetic field with frequencies of 5 kHz and 10 kHz.

The measurement results of the alternating magnetic field for some frequencies at a constant distance and constant current is depicted in Fig. 3.(b). The sensor output voltage is inversely proportional to the increasing of an alternating magnetic field frequency, due to the increase of an inductive reactance of solenoid. The high inductive reactance will block the alternating current passed through the solenoid, thus lowering the output voltage [8]. From the previous researchs were obtained three sensors (sensor 1, sensor 2, and sensor 3) with configuration of 2x(60/90/60) and sensitivity 1.32 nT/mV, 1.14 nT/mV and 1.23 nT/mV of each sensor respectively [12]. To determine the working range of the sensors, it has been performed characterization on a fixed-

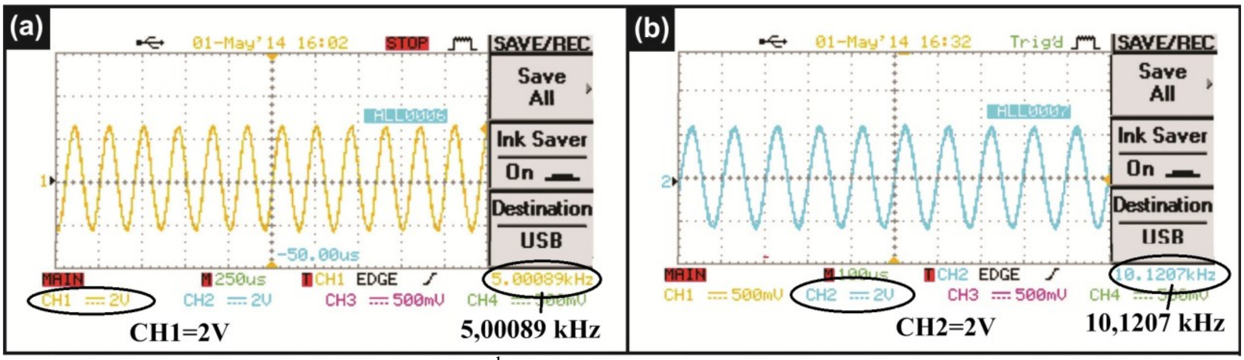


Figure 4. (a) Characterization of the 2nd-order Butterworth filter, Q of F04 and F05 was neglected (b) Output voltage of fluxgate sensor against current frequencies with cut-off frequency of 34.098 kHz and 33.863 kHz

distance (x = 20 cm) of the developed fluxgate sensor using a reference fluxmeter, by varying the current intensity of the transmitter. Fig. 5 shows measurement result of the sensor output voltage against the magnetic field inversely.

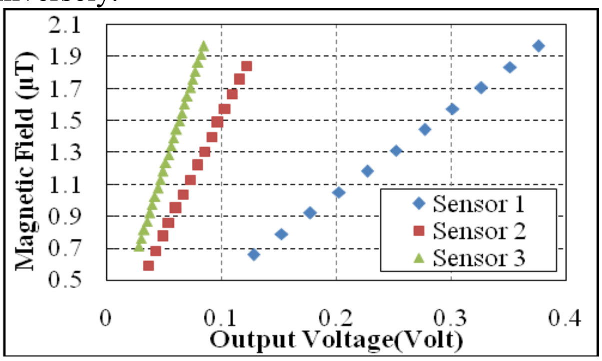


Figure 5. The output of sensor 1, sensor 2, and sesor 3 due to the output of the reference fluxmeter inversely.

From Fig. 5 was obtained the characteristic of the developed sensors against magnetic field inversely:

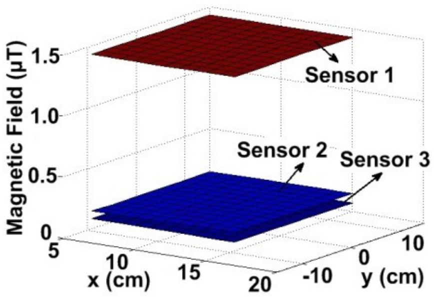
$$B_x = 5{,}275\ V_1 - 0{,}017 \quad (3)$$

$$B_y = 14{,}64\ V_2 + 0{,}056 \quad (4)$$

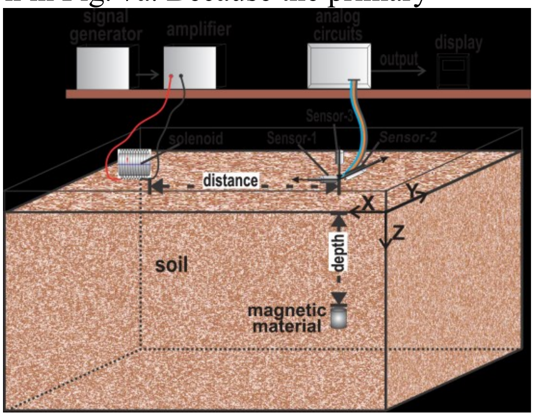
$$B_z = 22{,}27\ V_3 + 0{,}082 \quad (5)$$

where B_x, B_y and B_z are magnetic field (μT) in the x, y and z-direction, meanwhile V_1, V_2 and V_3 are output voltage of sensor 1, sensor 2 and sensor 3. The equations (3), (4) and (5) are then used to convert the results of measurements of the distance detection sensor characterization against AC magnetic field.

Detection of Magnetic Materials in the Soil Subsurface Using the Fixed Geometry. In the fixed geometry system, the magnetic field source (Tx) and sensors (Rx) was fixed at 20 cm. For the initial characterization, the current on the solenoid was kept constant at 0.12A with a frequency of 5 kHz. Tx-Rx moved simultaneously along the plane (x, y) so that the magnetic field distribution of the soil surface can be measured. The measurement results are shown in Fig. 6(a). It appears that the magnetic field measured by sensor 1, sensor 2 and sensor 3 are constant because all sensors only measure the magnetic field of the AC magnetic source with a constant distance. Furthermore, a ferrite rod diameter of 2 cm with a length of 3 cm was placed below the soil surface at position x = 10 cm, y = -2 cm, and z = -10 cm as shown in Fig. 6(b). Then, Tx-Rx moved simultaneously along the (x, y) plane, thus the magnetic field distribution of the soil surface with the presence of magnetic material can be measured. To determine the influence of increasing frequency to the sensor response, was conducted by changing the current frequencies of the solenoid. The measurement results of the 3D sensor response are shown in Figure 7. The presence of ferrite rod as a magnetic material only influence the amplitude of the magnetic field measured by the sensor 1, and does not change the shape of the curve measured, as shown in Fig. 7a. Because the primary -



(a)



(b)

Figure 6. (a) Output of the sensor 1, sensor 2 and sensor 3 when there is no magnetic material in the soil. (b) Set up of characterization of magnetic material in the soil subsurface.

field of the solenoid is quite dominant compared to the secondary field of magnetic materials. Whereas, ferrite rod twice detected by the sensor 2 in Fig. 7b. It appears that the lowest point at *b* position (x = 10 cm and y = - 2 cm), and the highest point at *a* position (x = 10 cm and y = -8 cm). In *a* position, wherein the ferrite rod is under the tip of the sensor, produces a resultant magnetic field detected by the sensor in the same direction of the reference field sensors, so that the sensor output shows the highest value. In the other hand, in b position, ferrite rod is under the rear end of the sensor, so the sensor captures the resultant magnetic field opposite to the reference field sensor, causing the sensor output shows the lowest value. Nevertheless, the amplitude curves in a and b position are similar. Meanwhile in Fig 7c ferrite rods once detected by the sensor 3.

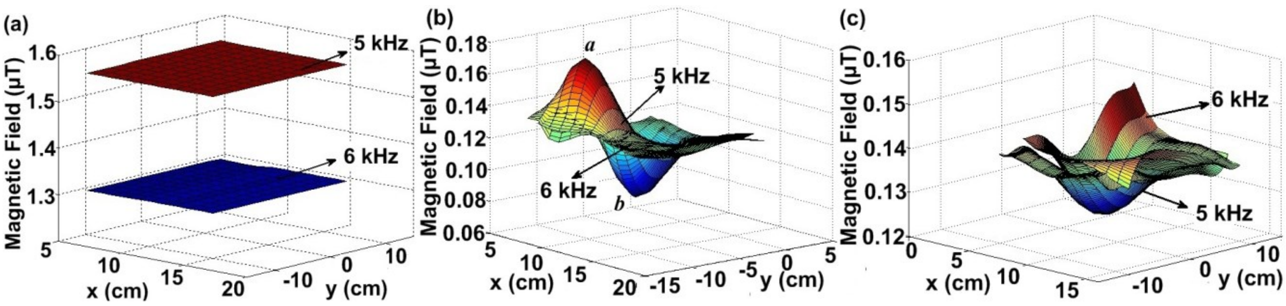


Figure 7. The output of sensor 3D on current in current frequencies of solenoid. (a). Sensor 1, (b). Sensor 2, and (c). Sensor 3.

Fig.7 also shows that the increasing frequency of the current source on the solenoid affects the secondary field generated by the magnetic material, due to the increase of inductive reactance of the magnetic material. It causes the eddy current in material will decrease, thus the secondary magnetic field generated is lower. As a result, the resultant of magnetic field caught by sensor is lower.

The response of the sensor to detect changes in the secondary field of magnetic materials in two different size and different positions is shown in Fig. 8. It appears that the developed sensor system capables for detecting two different objects apart at a distance of ± 10 cm, this indicates that the sensor system is highly sensitive in detecting small changes in the secondary magnetic field.

Summary

The fixed geometry detection system of magnetic material based on fluxgate sensor capables to detect the presence of magnetic materials in the soil subsurface. In this system, where the distance between the sensor (Rx) and the magnetic field source (Tx) is fixed, it is found that the presence of magnetic materials embedded in the soil subsurface changes the curve shape and the amplitude of the magnetic field of the sensor.

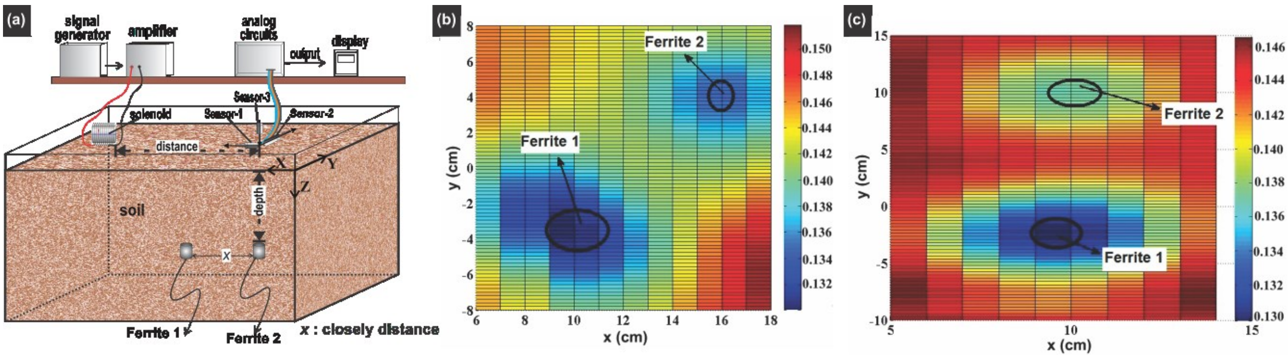


Figure 8. (a) Physical situation of experiment, (b) and (c) is the output curve of the fluxgate sensor in detecting two magnetic materials at different positions in the soil subsurface.

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