Applied Mechanics and Materials Vol. 771 (2015) pp 55-58
© (2015) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMM.771.55
Submitted: 2014-07-27
Revised: 2015-02-28
Accepted: 2015-03-07
Online: 2015-07-02

Fluxgate Based Detection of Magnetic Material in Soil Subsurface

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Keywords: Excitation coil, fluxgate, magnetic material, pick-up coil, soil subsurface.

Abstract. The aim of this work is to develop a new tool for detection of magnetic material in soil subsurface based on fluxgate sensors. The fluxgate element consists of two pick-up coils, four excitation coils, and the ferromagnetic core. The fluxgate sensor was characterized using a calibrator serving as an external magnetic field source. In this paper we report the influence of the frequency of the primary magnetic field of the solenoid on the sensor response, the influence of soil magnetic susceptibility, and the effect of the presence of magnetic material in the soil subsurface to the sensor response. Capability of the sensor to detect magnetic properties of a material in soil subsurface was observed by placing a magnetic material sample below the soil surface. An AC magnetic field with specific frequency was applied to the material, and the response of the material to AC magnetic field was then detected using the fluxgate sensor in the direction of the x, y and z (3-dimension). We found that change in frequency of the AC current will change the frequency of the AC magnetic field in the solenoid, thus the frequency of the output voltage of the sensor also change. We also found that the sensor output for the agricultural soil is higher than the sensor output for sand soil. The detection system reported here is potential candidate for detection of magnetic material in soil subsurface with low cost.

Introduction

Nowadays, fluxgate sensors have been used in electronic compasses [1], magnetic trackers [2], distance sensors [3, 4], and detection of AC magnetic field [5]. As the fluxgate sensor has possibilities to perform measurements in multiple configurations, electronic devices can be designed to allow the simultaneous measurements of multiple fluxgate sensors.

In this paper, we report use of a fluxgate sensor as a detector of magnetic materials in soil subsurface. This work is a continuation of our previous work that has obtained a fluxgate sensor with high sensitivity to detect AC magnetic field emitted by a magnetic material in soil subsurface [6]. In order to provide real results, we then developed a 3-dimensional fluxgate sensor so that the magnetic field is derived from the magnetic material in soil subsurface can be sensed by fluxgate sensors in 3-directions (x, y, and z).

Experiment

A fluxgate sensor made in this research consists of two main components, that is, a fluxgate element and a signal-processing circuit. The fluxgate element consists of two pick-up coils, four excitation coils, and a ferromagnetic core. The output voltage of the sensor's element was processed by using an analog signal processing circuit with 3 signal processors. Each signal processing circuit of sensor is composed of two parts: pick-up and excitation circuits. Furthermore, the output of the analog signal processing circuit entered the digital circuit which served to convert the analog voltage into a digital number. A digital circuit was built using a 16-bit ADC (analog to digital converter) with a speed of 500 kbps. The fluxgate sensor was characterized using a calibrator serving as an external magnetic field source. The calibrator was a solenoid with the following characteristics: diameter of 4 cm, length of 30 cm, 600 turns of wire, and resistance of 3.529 ohms. Fluke 5000B was used as a DC current source supplying a constant DC current to the solenoid.

Capability of the sensor to detect magnetic properties of a material in soil subsurface was observed by placing a magnetic material sample below the soil surface. An AC magnetic field with specific frequency was applied to the material, and the response of the material to AC magnetic field was then detected using the fluxgate sensor in the direction of the x, y and z (3-dimension).

Results and Discussion

Influence of the frequency of the primary magnetic field of the solenoid on the sensor response. The output voltage response of the fluxgate sensor to the AC magnetic field source is shown in Fig. 1. The change in frequency of the AC current will change the frequency of the AC magnetic field in the solenoid, thus the frequency of the output voltage of the sensor also change. Increase in frequency of the AC magnetic field will accelerate the oscillation of the sensor's output signal and reduce the amplitude of the sensor's output voltage. The amplitude of the sensor's output voltage is inversely proportional to the increase in the frequency of the AC magnetic field due to an increase in the inductive reactance of the coil. The increase in inductive reactance coil will block AC current through the solenoid, thus the output voltage is reduced (as shown in Fig. 1.(a)). Meanwhile, the sensor's output voltage due to an external magnetic field for some variation of AC frequency at different distances is depicted in Fig. 1.(b). The output voltage sensor is inversely proportional to the measured distance, according to the previous studies [4]. This is due to an increase in the distance between the sensor and the coil so that it reduces the amount of magnetic flux captured by the sensor.

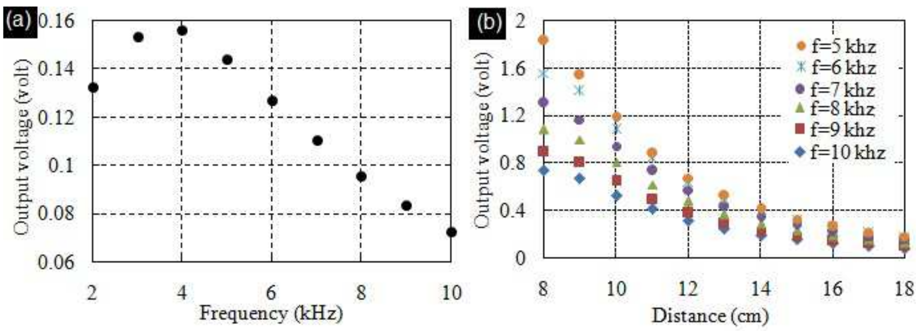

Fig. 1. (a) Output voltage of the sensor with configuration of 2x (60/90/60) against AC frequency. (b) Output voltage of the sensor against the distance between the sensor and the coil for variation of AC frequency.

The influence of soil magnetic susceptibility on sensor response. Capability of the sensor in detecting the magnetic properties of the soil was observed by measuring the magnetic field distribution on the soil surface. In this study, we used two different types of soils: agricultural soil (soil 1, χ=771,3x10^3 m^3/kg) and sand soil (soil 2, χ= 676.15x10^3 m^3/kg). The characterization results of the sensor on the soil surface are shown in Fig. 2.(a).

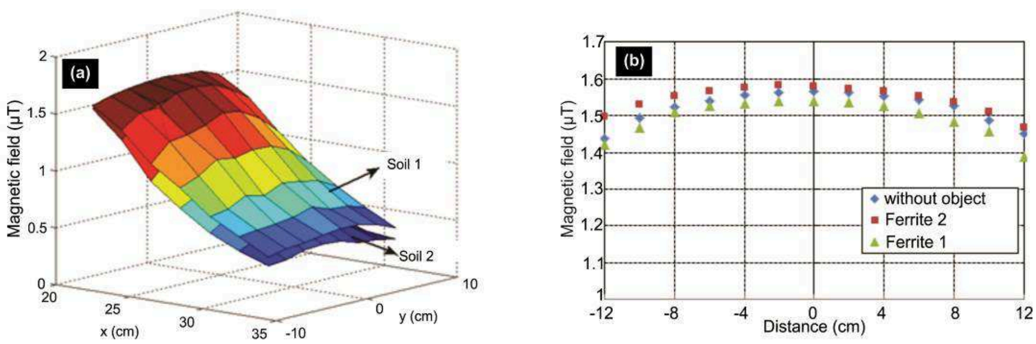

Fig. 2. (a) Sensor characteristics on the soil surface (b) Sensor response on presence of magnetic material in soil surface and subsurface.

As seen in Fig. 2.(a), the output voltage of the sensor in the soil 1 is higher than soil 2. It is related to the difference in magnetic susceptibility values of soil 1 and soil 2. Noting that magnetic susceptibility is the degree of magnetism of a material, the higher the magnetic susceptibility of a material, the easier it becomes magnetized. As a result, the magnetic field measured at the surface of soil 1 higher than that of soil 2, in accordance with Eq. (1).

$$\mathbf{B} = \mu_0 \mathbf{H}(1+\chi) \tag{1}$$

were $\boldsymbol{B}$ and $\boldsymbol{H}$ are magnetic induction and magnetic field intensity, μ_0 is vacuum permeability, and χ is the magnetic susceptibility of soil.

The presence of magnetic material in the soil subsurface to the sensor response. The sensor response to the presence of magnetic material in soil subsurface was studied by placing a ferrite cylinder below the soil surface. Two methods were carried out at this stage; the first was the distance of sensor (Rx) to the magnetic field source (Tx) was changed and the second was distance of sensor (Rx) and the magnetic field source (Tx) was fixed at 20 cm.

(Tx-Rx) changed. At this stage the magnetic material was placed in a fixed position (10, 0, -8) cm below soil-2 surface, while the distance of the sensor to field source was varied from (32, 12, 0) cm to (32, -12, 0) cm. Sensor response curve in the presence of magnetic material in the soil subsurface is shown in Fig. 2.(b). It appears that the amplitude of the sensor's output are changed; it is caused by a secondary field of the magnetic material. Fig. 2.(b) shows that although the type of magnetic material that is induced by the magnetic field is the same, but the polarities of the magnetic poles in the two materials are not always the same. Through this measurement method it has not been seen a significant change in shape of the curve due to the presence of a magnetic material below the soil surface, only the amplitude of the sensor output are changed.

(Tx-Rx) fixed. Further characterization was done at a distance of the magnetic field source (Tx) and sensors (Rx) fixed at 20 cm. The current in the solenoid was kept constant at 0.12A with a frequency of 5 kHz. Furthermore, Tx-Rx moved simultaneously along the plane (x,y) so that the magnetic field distribution in the surface of soil 2 can be measured. The measurement results are shown in Fig. 3.(a). It appears that the magnetic field measured by the sensor 1 (S1), sensor 2 (S2), and sensor 3 (S3) are constant because all sensors only measure the magnetic field of the AC magnetic source with a constant distance. The curve in Fig. 3.(a) is considered as the reference field for the fixed Tx-Rx configuration. Then, measurements were performed with a magnetic material (ferrite cylinder) that placed below the soil surface as shown in Fig 3.(b).

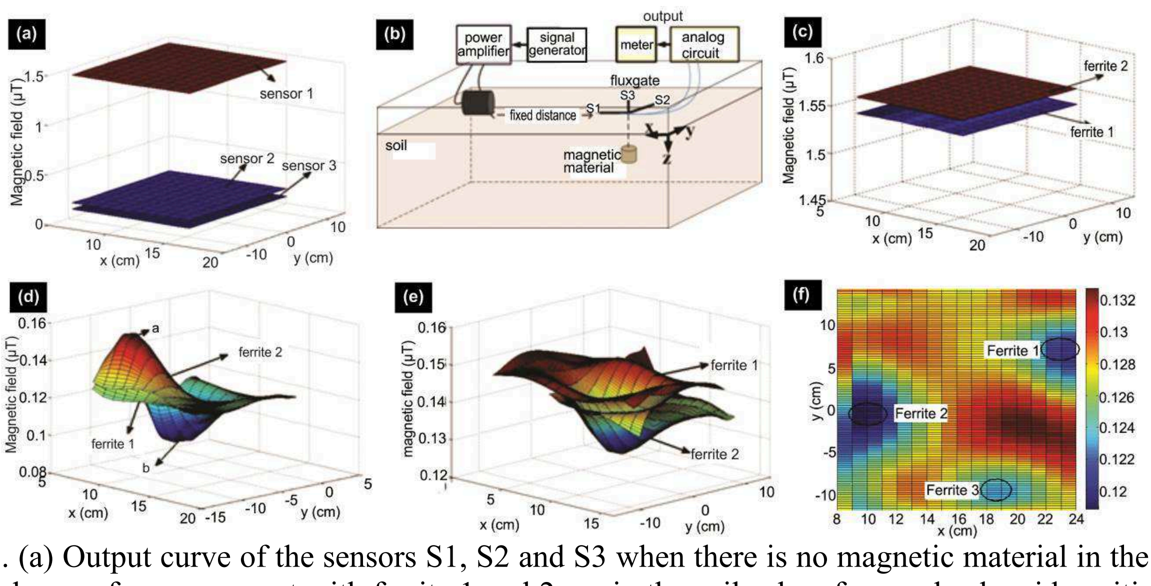

Fig. 3. (a) Output curve of the sensors S1, S2 and S3 when there is no magnetic material in the soil. (b). Scheme of measurement with ferrite 1 and 2 are in the soil subsurface and solenoid position on the horizontal (north-south). (c). Response of S1 to the presence of magnetic material. (d). Response of S2 to the presence of magnetic material. (e) Response of S3 to the presence of magnetic material. (f) Output curve of S3 for detecting magnetic objects at three different positions.

The response of S1 to the presence of ferrite 1 (D = 2cm) and ferrite 2 (D = 4cm) are shown in Fig. 3.(c). The S1 only measures the magnetic field parallel to the source, so there is no shape change of the curve, but its amplitude changes as a result of the presence of magnetic materials. This is due to the primary magnetic field of the solenoid more dominant than the secondary magnetic field of material. The response of S2 to the presence of the magnetic material is shown in Fig. 3.(d). The ferrite placed at position x = 10 cm and y = -2 cm was detected twice by the S2, where the lowest position at the point b (x = 10 cm and y = - 2 cm) and the highest position at the point a (x = 10 cm and y = -8 cm). Superposition of the primary magnetic field and secondary magnetic field of ferrite is detected by the sensor either at the position a or position b with nearly equal value, as seen in Fig. 3.(d) that has almost symmetrical. This shows that the resultant of primary and secondary magnetic field at the positions *a* and *b* are the same. However, the position of sensor causes the direction of the resultant field that detected by the sensor is the opposite.

The response of S3 on the existence of a magnetic material below the soil surface is shown in Fig. 3. (e). The ferrite placed at x = 10 cm and y = -2 cm was detected by the S3 right at that position. It is seen that the lowest point at position x = 10 cm, y = -2 cm is in accordance with the ferrite position. The difference in the size of the ferrite is detected by the larger amplitude of the sensor output to the reference position.

The response of the sensor S3 in detecting the changes of the secondary magnetic field of materials at three different positions is shown in Fig. 3.(f). It is seen that area with the lowest field intensity indicates the position of each ferrite. The ferrite 1 is detected at the position of x = 22 to 24 cm and y = 5 to 8 cm, whereas the ferrite 2 is detected at the position x = 9 to 12 cm and y = -2 to 2 cm, and meanwhile the ferrite 3 is detected at the position x = 18 to 19 cm and y = -9 to -10 cm. The width of the detection area of the curve is proportional to the diameter of the ferrite, in which the diameter of ferrite 2 > the diameter of ferrite 1 > the diameter of ferrite3.

Summary

The development of magnetic material detection system in the soil subsurface based on fluxgate sensors has been carried out successfully. The ability of the system to detect magnetic properties of the soil was observed by measuring the magnetic field distribution on the soil surface. It has been found that the sensor output for the agricultural soil is higher than the sensor output for sand soil. This is related to the difference in the magnetic susceptibility of the soil. The detection system with a fixed geometry (Tx-Rx fixed) has been capable of detecting the differences of magnetic response of the material in the soil subsurface due to changes in the size of the magnetic material. It has also been capable of detecting materials at three different positions with a good response.

Acknowledgment

The authors would like to thank to Universitas Negeri Jakarta that has funded this research.

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Instrumentation and Measurement Systems

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