

DESIGN OF A LOW-COST 2-AXES FLUXGATE MAGNETOMETER FOR SMALL SATELLITE APPLICATIONS

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ABSTRACT

This paper addresses the design and analysis results of a 2-axes magnetometer for attitude determination of small satellite. A low-cost and efficient 2-axes fluxgate magnetometer was selected as the most suitable attitude sensor for LEO microsattellites which require a low-to-medium level pointing accuracy. An optimization trade-off study has been performed for the development of 2-axes fluxgate magnetometer. All the relevant parameters such as permeability, demagnetization factor, coil diameter, core thickness, and number of coil turns were considered for the sizing of a small satellite magnetometer. The magnetometer which is designed, manufactured, and tested in-house as described in this paper satisfies linearity requirement for determining attitude position of small satellites. On the basis of magnetometer which is designed in Space System Research Lab. (SSRL), commercial magnetometer will be developed.

Keywords: magnetometer, attitude determination, amorphous magnetic material, fluxgate sensor

1. INTRODUCTION

One of the most important elements for the successful mission operation in a satellite is its attitude determination and control. The modern high precision satellites should accommodate an attitude determination and control system possessing a high pointing accuracy. The trend toward the small satellite development with a slogan, "faster, better, and cheaper" requires a development of low cost, low mass, and smaller attitude control system and components.

A satellite attitude determination and control system consists of sensors, actuators, and electronic controller assemblies. The reference targets such as the Earth, star, and Sun can be used to determine the satellite attitude. LEO (Low Earth Orbit) satellites experience various disturbances such as gravity gradient, atmospheric drag, solar pressure, and earth magnetic field during a mission life. The earth magnetic field is the most dominant disturbance for LEO satellites. This is why magnetometers have been implemented as one of the most popular sensor for attitude determination of LEO small satellites (Wertz & Larson 1999).

Figure 1 illustrates various attitude determination sensors used for small satellites from 1990 to the present. Sun sensor and magnetometer occupy 68% of total sensors implemented for microsattellites between 10 kg to 200 kg (Kim et al. 2004). Both sensors satisfy low mass and low

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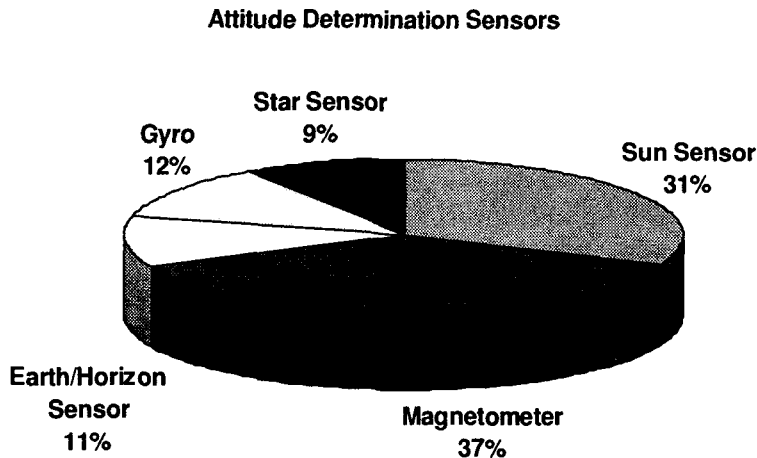


Figure 1. Attitude Determination Sensors used for Small Satellites between 1990 and the Present.

power consumption requirements suitable for LEO small satellites. Since the sun sensor cannot be operated during eclipse and the magnetometer contains relatively low accuracy magnetic field data, the best way to determine the satellite attitude is to combine the data from the sun sensor and the magnetometer to compensate for these weaknesses.

The development of magnetometer is increasing steadily both at home and abroad. A magnetometer is used in attitude determination of satellites, for measuring Earth magnetic field data, and for controlling several vehicles for navigation. The research of magnetometers has continued since mid 1990s. During this time, fluxgate magnetometers and Hall-Effect magnetometers have been developed. However the satellites developed in Korea often use commercial foreign manufactured magnetometers instead of the ones developed in Korea due to the failure and accuracy concerns. Most microsattellites do not require high accuracy, and the current design the is being developed can be verified and investigated in space environments and the result can be used for the commercial product. The magnetometer which is developed in-house, as described in this paper, has a higher accuracy than other magnetometers despite being smaller, lighter, and cheaper.

2. ANALYSES OF MAGNETOMETER DATABASE AND SIZING

The database of magnetic sensors used for small satellites from 1990 to the present was constructed to investigate the characteristics of magnetometers. The main considerations for design parameters of a magnetometer for small satellites are mass, size, and accuracy. Figure 2 presents the mass distribution of magnetometers used for small satellites between 1990 and the present. In order to make a magnetometer smaller, the established magnetometer data was analysed. The data was used in deciding the mass and size of the magnetometer developed by SSRL. As shown in Figure 2, the magnetometer mass is linearly proportional to the satellite mass, except one magnetometer was used as a payload on a 20 kg class satellite. It is found that the magnetometers of small satellites between 10 kg and 200 kg have average mass of less than 0.5 kg. The equation (1) represents the

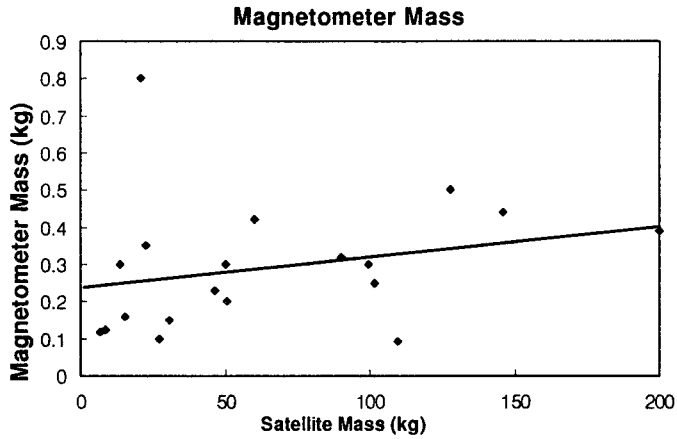


Figure 2. Magnetometer Mass Distribution used for Small Satellite between 1990 and the Present.

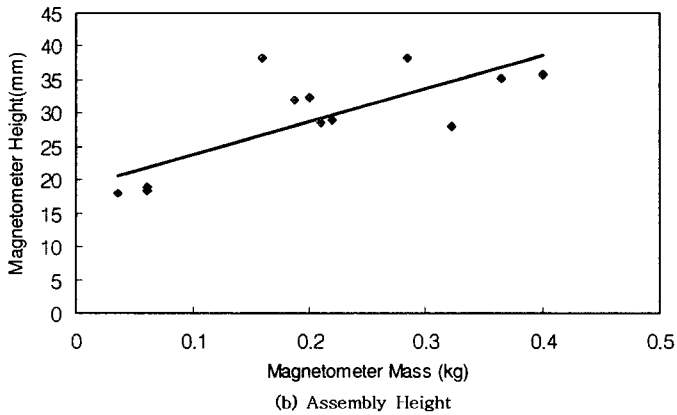
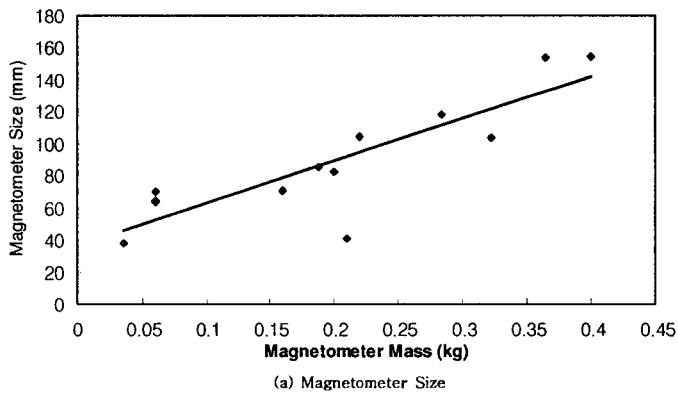


Figure 3. Magnetometer Size and Height.

Table 1. Magnetometer Requirements.

Parameter	Requirement
Size	$< 100 \times 100 \times 30 \text{mm}^3$
Mass	$< 0.3 \text{ kg}$
Linearity	$< 30 \text{ nT}$

characteristic trend between satellite mass and magnetometer mass.

$$\text{Magnetometer Mass}[\text{kg}] = 0.0013 \times \text{Satellite Mass}[\text{kg}] + 0.175 \quad (1)$$

The characteristic equation (1) is used to derive the average mass of magnetometers suitable for microsatellites. It can be seen that the baseline target mass of magnetometer developed for small satellite is around 300 g based on the equation (1). The sensor size is also to be limited in the small satellite design. To estimate the magnetometer size, we surveyed the size of magnetic sensors for small satellites. Figure 3a and 3b show the magnetometer size and height in accordance with satellite mass, respectively. The equation (2) and (3) present the relationship between magnetometer mass and its size, magnetometer mass and its assembly height, respectively.

$$\text{Size of Magnetometer}[\text{mm}] = 263.88 \times \text{Magnetometer Mass}[\text{kg}] + 36.243 \quad (2)$$

$$\text{Height of Magnetometer}[\text{mm}] = 49.073 \times \text{Magnetometer Mass}[\text{kg}] + 18.883 \quad (3)$$

The maximum dimension of a magnetometer suitable for small satellites was selected based on equations (2) and (3). The requirements for the size and height of the magnetometer assembly box have been established for this design to be less than 100 mm and 30 mm, respectively. When the accuracy of the magnetic sensor is increased, it is better for the attitude determination. It is estimated from the IGRF (International Geomagnetic Reference Field) data analysis that the 30nT sensitivity will be required. Table 1 represents the requirements of the magnetometer developed for microsatellites.

3. DESIGN OF RING-TYPE CORE MAGNETOMETER

3.1 Selection of sensor core

The selection of fluxgate core is a complex process depending on the type and geometry of the sensors. It is related to the characteristics of core material, the type of processing of the output signal, the excitation frequency and required temperature range. There are some basic requirements for the material properties as follows; high permeability, low coercivity, nonrectangular shape of the magnetization curve, low magnetostriction, low Barkhausen noise, low number of structural imperfections and low internal stresses, smooth surface, uniform cross section and large homogeneity of the parameters, low saturation magnetization, and high electrical resistivity.

Most studies on core material composition and processing parameters have shown that the minimum noise can be achieved for near-zero magnetostriction alloys. The material, traditionally used for the sensor core, is high permeability, low magnetostriction permalloy in the form of a thin tape. Recently the amorphous materials are being utilized to minimize the effect of excitation frequency. Amorphous materials are alloys that are mainly based on iron and cobalt, with additions of boron

Table 2. Characteristics of Amorphous Materials (Kim et al. 2000).

	2605SA1 (Iron-based)	2714 A (Cobalt-based)	2826 MB (Iron-Nickel-based)
Permeability	45000	80000	5000
Coercivity (Oe)	0.09	0.02	0.047
Magnetostriction (ppm)	27	$\ll 1$	12
Saturation Magnetization (telsa)	1.56	0.57	0.88
Electrical Resistivity ($\mu - \Omega\text{-cm}$)	130	142	138
Density (g/cc)	7.19	7.59	7.9

Table 3. Basic Parameters of Coil Materials (Ripka 2000).

Parameter	Copper	Aluminum
Density (g/cm^3)	8.9	2.7
Specific Electrical Resistivity (Ωm)	0.0178×10^{-6}	0.027×10^{-6}
Tempco of Resistance ($\%/^{\circ}\text{C}$)	0.39	0.4
Coefficient of Linear Expansion ($\text{ppm}/^{\circ}\text{C}$)	16.6	25

and silicon. The main advantages are high permeability and low loss, and the disadvantages are the lower saturation magnetization compared to crystalline iron alloys and the limited magnetic core design possibilities. The characteristics of amorphous materials are compared in Table 2 (Kim et al. 2000). It is seen that 2714 A material satisfies most of the requirements mentioned above.

3.2 Selection of sensor coil

A typical fluxgate sensor coil consists of a multilayer solenoid. The sensor coil requires stable and linear characteristics. The temperature coefficient of the sensitivity depends mainly on the thermal expansion of the material. Increasing the coil diameter increases the sensitivity, and R/L (Resistance/Inductance) factor depends on the amount of copper; the number of turns and the wire thickness are selected to match the input noise characteristics of the amplifier. A disadvantage of the large area induction coils is their susceptibility to vibrations, which changes the effective coil area and thus, in the presence of the DC field, causes noise. It is necessary to construct them to be mechanically stable and mount them securely. The magnetic sensor coil is commonly made of copper and aluminum. Table 3 shows characteristics of copper and aluminum (Ripka 2000). Copper is a common material for coils. However, if the weight is a critical factor of a satellite, aluminum material might be a better choice. In this paper, copper coil was selected because of the electric resistivity and linear expansion coefficient. As shown in Table 3, the density of aluminum is three times lower than that of copper.

3.3 Effect of sensor parameters on sensitivity

The output voltage of a fluxgate magnetometer will be derived in its most general form from Faraday's law. Equation (4) describes an output voltage and equation (5) is sensitivity of magnetic sensor.

$$\text{Output Voltage[V]} = N_S \times A \times \mu_a \times H_{ex} \times \omega \quad (4)$$

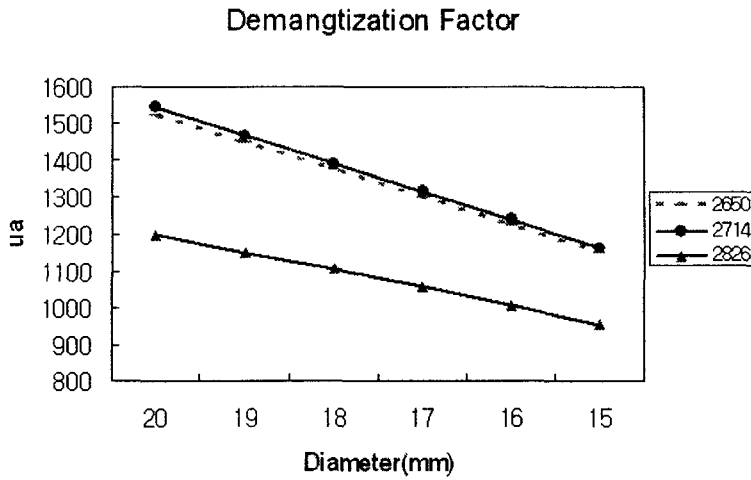


Figure 4. Apparent Permeability according to Core Diameter and Materials.

$$\text{Sensitivity}[\text{Tesla}] = N_S \times A \times \mu_a \times \omega \quad (5)$$

Where μ_a is apparent permeability of magnetic sensor core, H_{ex} is amplitude of output voltage (volts), N_S is number of coil turns, A is surface area enclosed by turn, and ω is frequency (Hz) of magnetic sensor.

As presented in equation (4) and (5), the following elements are implemented to increase the sensitivity of sensors; increased number of sensing coil turns, expansion of core section area, frequency increase or use of high apparent permeability materials. Since the apparent permeability is inversely proportional to demagnetization number of the core, the demagnetization number of the core should be reduced to increase the apparent permeability. The ratio of sensor diameter and thickness can be lowered for the reduction of demagnetization number of the core. However, the optimal adjustment is required to eliminate the impact on the core area. High permeability and low coercivity materials with increased number of sensing coil turns have to be employed to raise the sensor sensitivity without an additional power consumption. However, as the number of turns is increased, the total mass of sensor will become a factor, which affects the sensitivity. Thus all the factors need to be weighed and optimized (Burger 1972).

3.4 Trade-off study on 2-axes fluxgate magnetometer

As mentioned before, the optimal parameters must be traded-off for the development of the sensor with a high sensitivity. It is assumed that the suitable core's diameter of microsatellite is less than 20 mm when the thickness of coil rounding the core including assembly box thickness and margin considered is 0.0127 mm. The demagnetization and the apparent permeability are calculated by equation (6) and (7), respectively (Ripka 2000).

$$D = \frac{T}{d} \quad (6)$$

$$\mu_a = \frac{\mu}{[1 + D(\mu - 1)]} \quad (7)$$

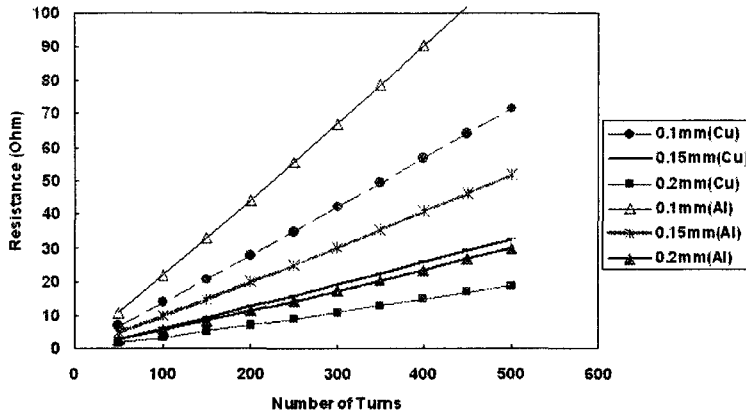


Figure 5. Number of turns and Resistance for Various Coil Materials and Thickness.

Sensing Coil for Magnetometer

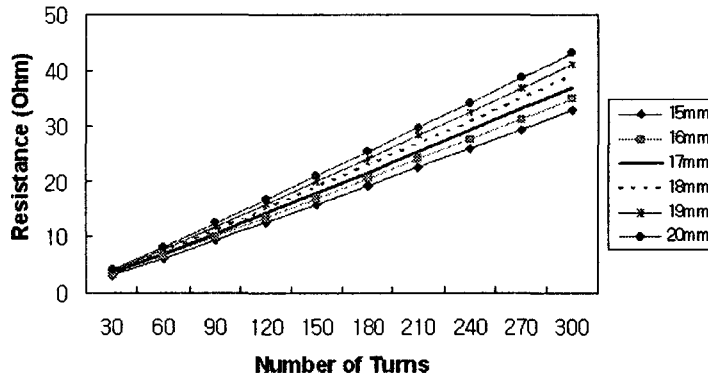


Figure 6. Number of Coil Turns and Resistance for Core Diameter.

Where D is demagnetization factor, T is thickness of the tape, d is diameter of the sensor core, μ_a and is apparent permeability.

As shown in Figure 4, the apparent permeability is increased with the core diameter. Apparent permeability is the most important factor in determining sensitivity. In order to obtain better sensitivity, a magnetic sensor with 20 mm diameter has been chosen. The sensor sensitivity is improved with each turn of the sensing coil. The core diameter was first selected prior to the selection of the coil turns. The thinner the core thickness is the better. Since the excessively thin coil can be easily broken, the coil which can hold the tension should be selected.

The relationship between the number of turns and resistance was obtained in Figure 5 for various coil diameters from 0.05 mm to 0.2 mm (Ripka 2000). The sensing coil has the best performance at

Table 4. Magnetometer Specification.

Design	Specification
Core Material	Amorphous Material 2714A(cobalt-based)
Core Diameter	20 mm
Core Thickness	0.03 mm
Core Width	40 mm
Coil Material	Copper
Coil Diameter	0.1 mm
Driving Coil	250 turns
Sensing Coil	210 turns

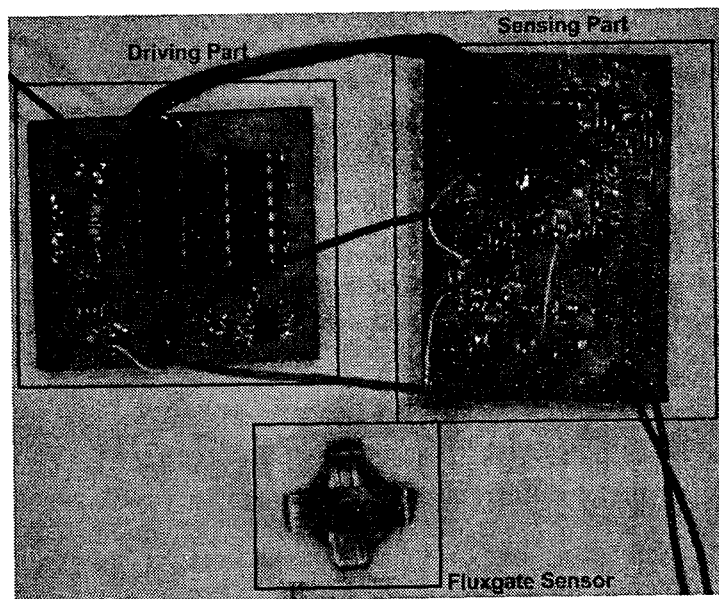
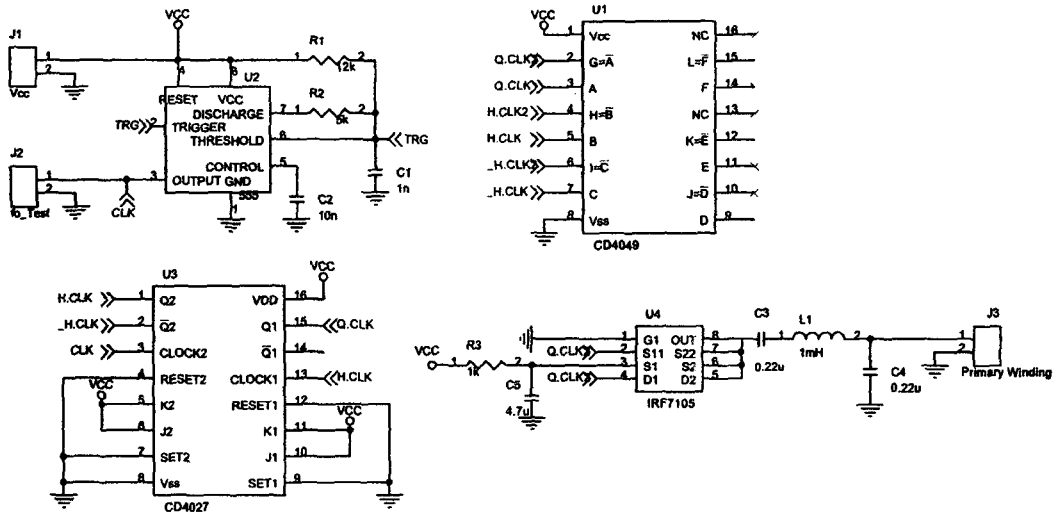


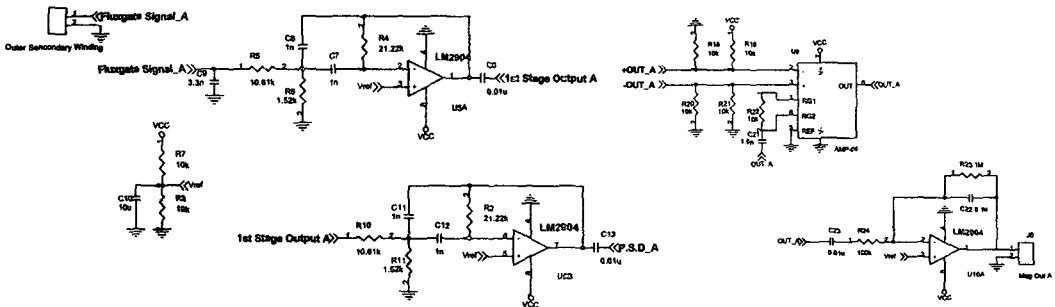
Figure 7. Magnetometer Block Diagram and Real Model.

30 ohm resistance. As shown in Figure 5, The sensor sensitivity is getting better with the number of coil turns. But, since the sensor mass is increased with the number of turns, two parameters of mass and sensitivity have to be properly compromised. Likewise, mutual inductance of sensing coil and driving coil must be considered with the coordination of each resistance and inductance.

As shown in Figure 6, the cross point at 20 mm of core diameter is about 210 turns. The sensing coil of magnetic sensor is selected to be 210 turns and 250 turns for the driving coil. The number of driving coil turns is determined depending on number of sensing coil turns because mutual inductance must be zero. Table 4 illustrates the magnetometer specification selected for the development.



(a) Driving Part of Magnetometer



(b) Sensing Part of Magnetometer

Figure 8. Circuit of Magnetometer.

3.5 Manufacture and test of 2-axes fluxgate magnetometer

The magnetometer circuit and magnetic sensor have been manufactured to measure the Earth magnetic field. Figure 7 illustrates the actual magnetometer fabricated. The magnetometer circuit consists of two parts; one is to actuate the circuit to saturate the magnetic sensor core and the other is to sense the magnetic field. In order to remove the secondary harmonics the sensing coil of magnetic sensor passed the BPF (Band Pass Filter), the output signal is compared with a reference signal generated by PSD (Phase Sensitive Detector). The final output data is obtained after passing the differential amplifier and integrator. The driving coil must provide enough current to saturate the sensor core in order to minimize noise.

Figure 8 presents the magnetometer circuit; Figure 8a is the driving part of magnetometer to saturate the sensor core and Figure 8b is the sensing part of magnetometer including PSD, BPF and Integrator. The driving circuit test has been performed to measure the characteristics of magnetome-

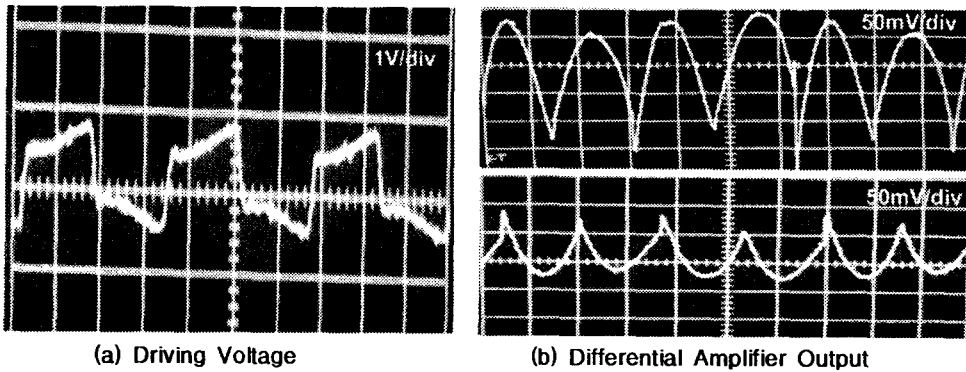


Figure 9. Fluxgate Sensor Driving and Output Test.

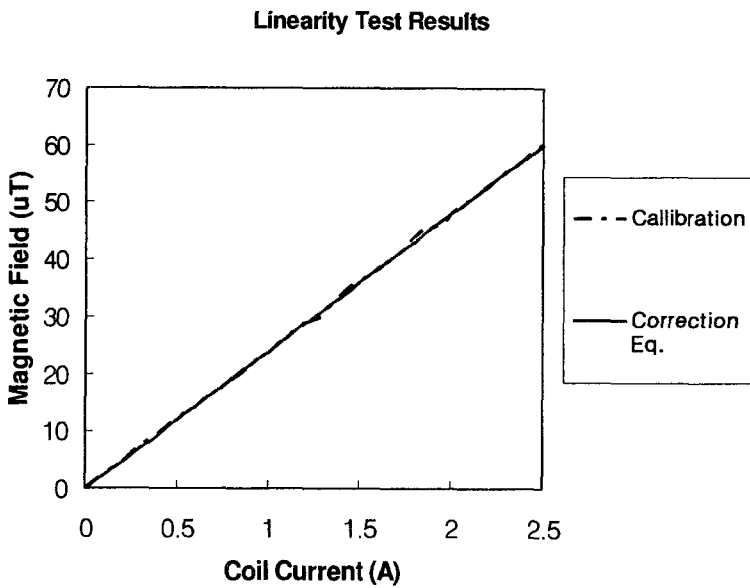


Figure 10. Magnetic Field Linearity.

ter. The driving circuit generates the frequency using 555 timer for saturation of the fluxgate sensor core. Figure 9a represents waveform of driving circuit. It is seen that the result is enough to detect the zero-offset of sensor output. When the driving frequency is entered to the fluxgate sensor, the sensor measures magnitude of the Earth magnetic field and removes the unnecessary signal. If the above process are repeated continuously, the reliable data can be obtained.

The linearity test is also done for each axis. Figure 10 is compared data between the calibration

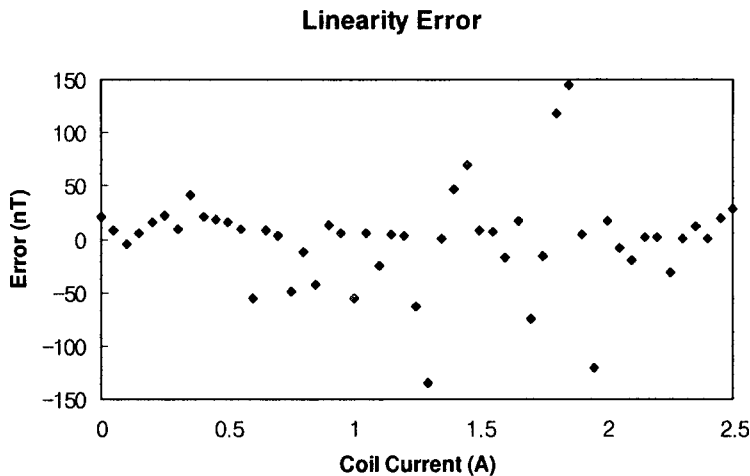


Figure 11. Linearity Error of Magnetometer.

and correction values. The measurement range of magnetometer is between $-60\mu\text{T}$ and $+60\mu\text{T}$. Figure 11 shows the error between calibration and 1st order polynomial. Even the maximum error is 150 nT, the average linearity error of fluxgate magnetometer is measured to be ± 28.86 nT whose measurement error meets the magnetometer specification.

4. CONCLUSIONS

The magnetic sensor is widely implemented for attitude determination of LEO small satellites because of its low mass, low power consumptions and small size. In this paper, to develop the fluxgate magnetometer, a core and coil materials are selected with optimal sizing analysis by considering several parameters such as permeability, demagnetization factors, coil diameter, and number of coil turns. Following the analysis, the magnetometer was developed and the linearity test was performed. The result of the error analysis satisfies the requirements. Average error of 2-axes magnetometer is approximately 28.86 nT by RMS. The magnetometer which is developed in SSRL is adequate for use in microsattellites that usually have pointing accuracy. After we investigate to reduced the error of magnetometer, it will be implemented in our microsattelite and developed as a commercial product.

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REFERENCES

- Burger, J. R. 1972, *IEEE Tran. Magn*, 8, 4
 Kim, C. K., Lee, I. H., Chung Y. C., & O’Handley, R. C. 2000, *Materials Science and Engineering*, B76. 211

Kim, S. J., Lee, M. H., & Chang, Y. K. 2004, in Proceedings of the 2004 KSAS Spring Conference (Seoul: KSAS), p.860

Ripka, P. 2000, *Magnetic Sensor and Magnetometer* (London: Artech House), pp.1-128

Wertz, J. R., & Larson, W. J. 1999, *Space Mission Analysis and Design* (Portland: Space Technology Library), pp.353-380