Design and Development of a Fluxgate Magnetometer for Small Satellites in Low Earth Orbit

Owais Talaat Waheed, Atiq-ur-Rehman
AOCS Section, Satellite Research & Development Centre-Karachi, (SUPARCO) Pakistan
Email: owaistalaat, atiq2k@gmail.com

Abstract — The paper discusses the design and development of a Fluxgate Magnetometer, for use in space for Attitude Determination and Control (ADC) of Low Earth Orbits (LEO) satellites. The designed sensor consists of two coils, drive and sense and is based upon the principle of mutual induction. A toroidal core based design was finalized and fabricated on which the drive and sense coil are coupled. Three different design approaches were adopted. Overview of these designs is discussed with detailed discussion on the most promising design. The developed sensor has the resolution better than 200nT. Results achieved are quite stable and the response of the sensor is in the range of ±50000nT. The results achieved are quite similar as predicted by simulations of overlapped waveforms.

Keywords — Magnetometer, Fluxgate, Attitude Determination and Control, Low Earth Orbits

1 INTRODUCTION

The fluxgate type magnetometer is a magnetic field sensor with good sensitivity as well as easy construction. Basic principle of this magnetometer is mutual induction between drive-coil and sense-coil signals and processing the superimposed output. The core is excited by current through the drive winding and saturates alternately in either direction. Mutually induced voltage interacts with the geomagnetic field and induces a voltage in the pickup coil, as per Faraday's Law:

$$V = -N.\frac{d\phi}{dt}$$

Where, V is induced Voltage, N is the number of turns, and $d\phi/dt$ is rate of change of magnetic flux

If sensor is introduced to intense magnetic field, core approaches saturation and will show non-linearity. Following are the results that should ideally be achieved by the designed sensor.

The waveforms in figure-1 show effect of magnetic field on the drive (or excitation) waveform. Waveform (f) depict the effects of magnetic field, which shows alternating positive and negative pulse, which is desired output of the sensor, so that appropriate sampling of this waveform is useful.

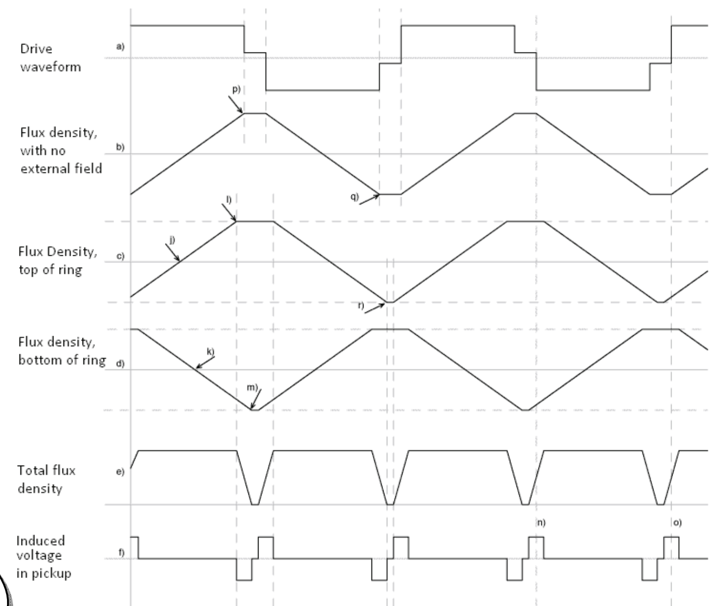

Figure 1 - Induced Voltage in pickup coil due to mutual induction of excitation and sense waveforms

Fluxgate Magnetometer have space heritage and is used for determination of attitude of satellite in many space missions. However, no considerable work has been reported in Pakistan on this type of magnetometer for use in space.

2 GEOMAGNETIC FIELD OF EARTH

The Earth has a varying magnetic field which is comprised of a highly complex sense of radiation and plasma zones, primarily due to the action of the charged particles of the solar wind impinging on the field. Following figure show magnetic field with respect to latitude and longitude of earth. The Magnetosphere has slight changes over 5 years, so magnetic field models, such as IGRF and WMM are usually for 5 years from epoch. These models predict the reference field which can be used compared with Magnetometer output to determine satellite's attitude.

So, the maximum magnetic field that the sensor can encounter in space (LEO satellites from 500km and above) is not more than ±50000nT.

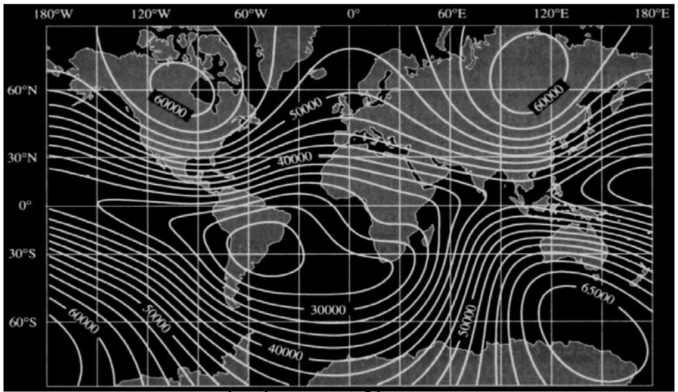

Figure 2 - Globally Varying Magnetic Field

3 Magnetic Core And Winding

A Magnetic core is a magnetic material with a high magnetic permeability, but is usually chosen to be magnetically ‘soft’ which means that they are made of materials that don’t maintain a significant magnetic field when external field is removed. Properties of the device crucially depend on the following factors:

- The geometry of magnetic core
- Property of material (hysteresis and permeability)
- Lamination of core to reduce eddy currents

In order to maximize the sensitivity of device, it is essential to minimize the initial permeability of core material. Preferred core material is Nickel-Iron alloy. It is also desirable to reduce the dimensions and mass of core to limit the head of magnetometer boom. The wire of 0.2mm diameter with 100 turns for excitation and 200 for sense are used for required sensitivity of magnetometer. More the number of turns more will be the sensitivity. Sample Magnetic core with coil winding is shown in following figure:

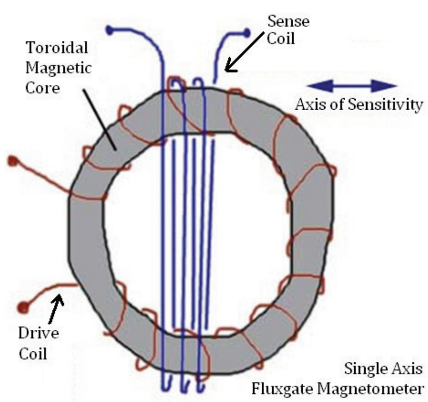

Figure 3 - Arrangement of Excitation and Sense Coil of Magnetic Core

3.1 Construction

At an abstract level, there are three parts of magnetometer:

- Toroidal core with Excitation and Sense Coils
- Drive/Excitation Circuitry
- Sense Circuitry

There are two possible constructions of toroidal cores, twin or dual core magnetometer and ring core magnetometer, following figure shows the flux lines passing through these two types of magnetometer.

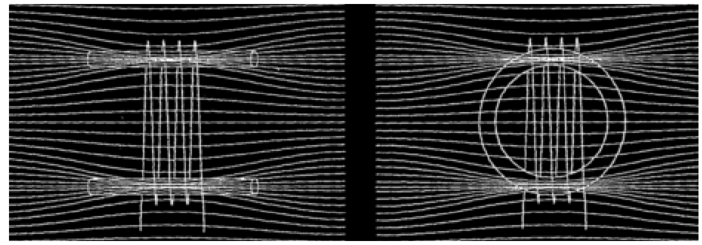

Figure 4 - Flux line for dual core and ring core magnetometer

There is a significant problem with twin core magnetometer, that the small differences in the drive winding geometries and in the material properties of two cores will provide spurious outputs in the sense coil. The advantage of a ring core magnetometer is that sense windings are equally sensitive in any axis which lies in the plane of the drive windings. The advantage is that a pair of sense windings at 90° to each other will provide for two axis determination of the magnetic field components using a single core. Three axis measurements can then be achieved with two cores mounted orthogonally with suitably arranged sense coils. A possible arrangement for the sense coils is shown in figure 5 showing the two cores, and the three orthogonal sense windings. A fourth winding may be added to design shown at 45° to each of the others, which can be used as an additional input to the magnetic field determination and will also provide for a redundant element should any one axis measurement fail.

At initial stage, the sensor is deigned for 1-axis, and later on this is replicated to incorporate all 3+1 axes, so mainly the paper discusses design of single axis fluxgate magnetometer and its utilization to form a 3-axis sensor.

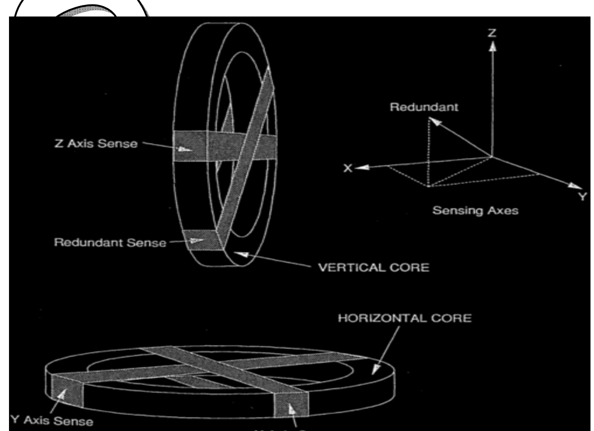

Figure 5 - Sense coils with redundant axis configuration

4 Detailed Electronic Design

The components required for determination of attitude are three magnetic field vectors in term of DC voltages ranging from 0V to 5V. Sensor is compatible to normal voltage range of ADC. If no magnetic field is present, the output voltage will be 2.5V. Setting this criterion is due to bi-directional nature of magnetic field, so 2.5V to 5V is allocated for positive field and 0V to 2.5V is for negative field. As, fluxgate magnetometer has three parts, excitation circuit, excitation and sense coil, and sense circuit. Excitation circuit is aimed to generate square waveforms that are then fed to excitation coil. Following figure shows the block diagram for the whole system, diagram only elaborates the sequence of steps or idea behind the development of the sensor.

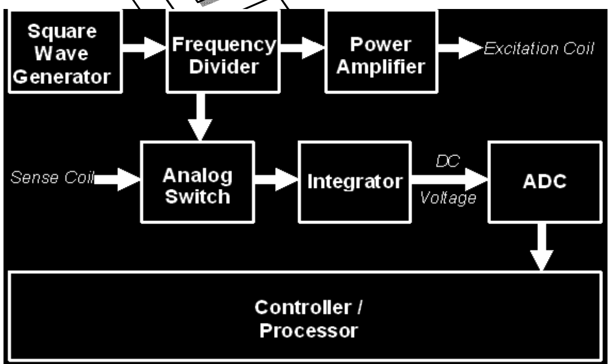

Figure 6 - Block Diagram of Fluxgate Magnetometer

5 EXCITATION CIRCUIT

The excitation circuit consists of an astable mode 555 circuit. The 555 circuit generates the 40kHz frequency square wave. This frequency is to be divided by 2 in order to have the square wave of 20kHz frequency which is further used for synchronization purpose.

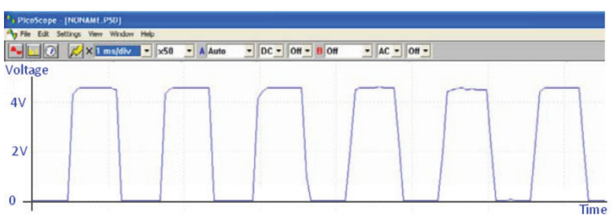

Figure 7 - Excitation output 40kHz

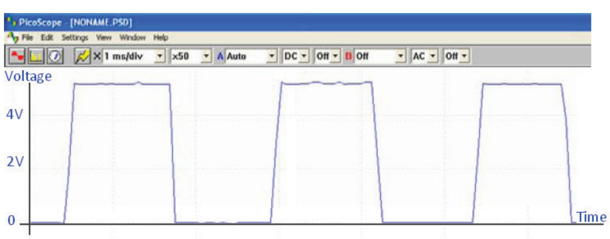

Figure 8 - Excitation output 20kHz

A D-Flip Flop is used for frequency division. This frequency is further divided by 2 by the D Flip Flop in order to get the 10kHz frequency. This 10kHz square wave has 0 and 5V values. In order to have the -5V to 0 to +5V output (level shifting, saturating the core on both sides), op-amp LM741 is used as a comparator. This signal is fed into the power amplifier LM675 (unity gain follower) which is finally applied to the excitation coil. The excitation waveform after connecting the coil to the circuit is shown in figure. Change in shape of waveform is due to mutual and self induction.

Figure 9 - Excitation output after connecting coil

The 40kHz frequency is divided by 2 for sampling later stages of sense outputs. The positive pulse is generated in the sense winding when the signal in the excitation winding goes from +5V to 0V and negative pulse is generated when the signal in the excitation winding goes from 0V to -5V. Similarly during the same single cycle as the signal goes from -5V to 0V again the negative pulse is generated and as the signal goes from 0V to +5V a positive pulse is generated. Concluding, two consecutive positive and two consecutive negative pulses occur in the sense winding. The frequencies below 800Hz, core saturation was observed on both sides and the erroneous signal was generating at the sense winding with two positive and two negative pulses, so the approach was not adopted.

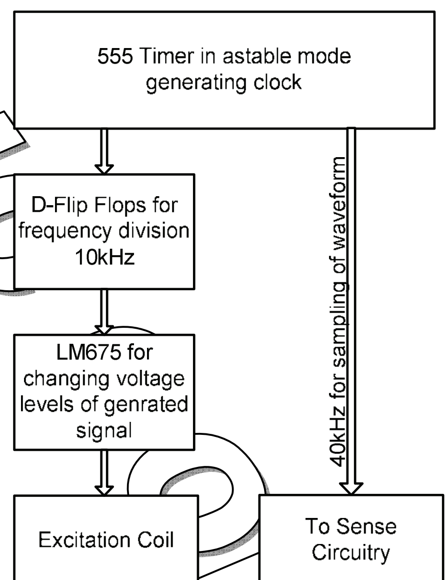

Figure 10 - Block Diagram of Excitation Circuit

The signals of 1kHz and above at the excitation saturates the core in only one direction. But actually what happens at the sense winding is that the positive pulse is induced as the signal in the excitation winding goes from +5V to 0V and the negative pulse as the signal goes from 0V to -5V. And there is no saturation as the excitation signal goes from negative to positive level. Thus, the signal is determinable and has the same frequency as of the excitation winding. It clearly demonstrates that the sense circuit is to be synchronized with the excitation circuit at the excitation frequency. The other question arises why 10kHz frequency was applied, the greater the frequency greater will be sensitivity. Initially the change of 80mV was achieved in the positive and negative peaks of the sense signal at this frequency. Initially, 1kHz frequency was applied [555 generates 4kHz frequency] and a change of around 40mV in the positive peaks and 40mV in the negative peak was observed of the sense signal at this frequency. Frequency was changed from 1kHz to 10kHz and was finally selected. The voltage levels at the excitation coil were not exactly +5V and -5V but around 3.8V on both sides. Hardware based block diagram of Excitation circuit is shown in Fig 10.

1. Sense Circuit

The sense signal is processed in order to have a DC voltage that varies with the orientation of the magnetometer sensor. The sense circuit was made in three configurations that will be explained one by one.

A. *First Circuit Configuration*

The first circuit was simple based on the simple theory of sensor signal processing. The circuit was designed on 1kHz excitation signal. First of all the sense signal was buffered using op-amp LM741. This is done so that the sense signal is not distorted as it is assumed that the sense coil could not source the current required by the next block. The analog switch is then used in order to synchronize the sense circuit and the excitation circuit (synchronous phase detection). The control terminal of the switch is connected to the 1kHz signal of the Flip Flop for synchronization. A capacitor of 22uF is connected at the output in order to have a relatively steady dc. The output comes out to be just below negative. This greatly slows down the response of the circuit (big capacitor). The amplifier/filter (low pass) with the cut-off around 0.4Hz is then connected. The output varies from 200 to 400mV approximately. Further cascading the amplifier saturates the output. The range is very small and if the circuit is kept in place for a few days output slowly and gradually move towards saturation (+5V). Then there would be no change even if sensor orientation is changed. This point was not comprehended at this stage. Thus this design was not taken further for implementation and the next circuit configuration was tested.

B. *Second Circuit Configuration*

The second circuit was designed based on the patent *[Patent No.: 4677381 Date of Patent: Jun. 30, 1987 Name: "Flux-gate Sensor Electrical Drive Method and Circuit"]* and RM100 Nanotesla Meter User's Manual DOC ID 000290. The circuit was designed on 1kHz excitation signal. The sense signal is ac amplified [RM100 Nanotesla Meter User's Manual] using op-amp, around 10 times (depending upon the levels of the sense output). Thus the ac output varies around 400mV (40m x 10 = 400mV) on either side. Two switches are used for synchronous phase detection. The output of the ac amplifier is fed into the input of the two switches. The control signal of 1kHz for controlling the switches comes from excitation circuit D-FF (divided by 4). The output of the switches goes into the inverting and non inverting input of the integrator (amplifier/filter). The integrator is connected at 0.4Hz frequency. The output is further integrated at 0.5Hz. The integrator output is negative dc voltage and varies around 1V in its entire range. The output is inverted using op-amp and a diode is connected with a load at the output so that the output does not goes negative. Finally the output varies around 1.2V. But the erroneous part was the non linearity in the change of dc voltage with orientation of the sensor.

C. *Third Circuit Configuration*

This circuit configuration gave most promising results and was finally implemented. The excitation frequency was changed to 10kHz. The sense coil output varies around 95mV on either side due to orientation of sensor. The sense coil waveform is shown in the following figure (connecting coil only, circuit is disconnected).

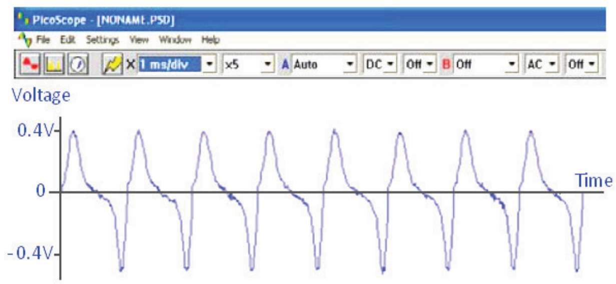

Figure 11 - Sense coil output at 10kHz frequency (+ve field)

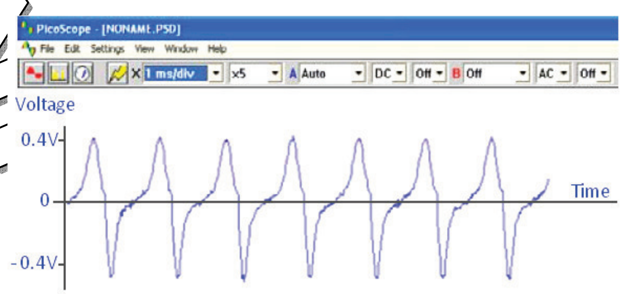

Figure 12 - Sense coil output at 10kHz frequency (-ve field)

The block diagram of sense circuit, which details the flow of signal conditioning to result DC voltage as an output that can be converted to corresponding Magnetic field value after calibration is given in figure 13.

The sense coil output is sample using sampling waveform of 40kHz. This samples the significant portion of sense waveform. The resulting output after sampling the signal is (for +ve field) is in figure 14. The output is sent into level-1 op-amp based integrator with cut off frequency of around 0.3Hz. DC voltage is obtained as an output that varies with the orientation of the sensor. The gains are controllable using potentiometer for calibrating scale factor. The dc level can also be changed using potentiometer to nullify any DC output on magnetic field of 0nT. The output is fed into another integrator that amplifies and filters the output further at around 0.6Hz. The final output varies from +1.5V to 0 from North (maximum magnetic field direction) to East (zero magnetic field direction) and 0 to -1.5V from East (zero magnetic field direction) to South (minimum magnetic field direction).

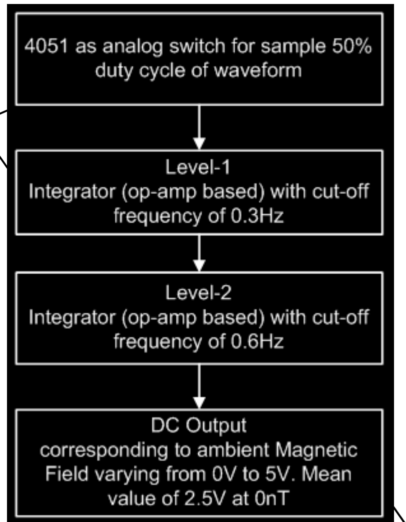

Figure 13 - Block Diagram of Sense Circuit

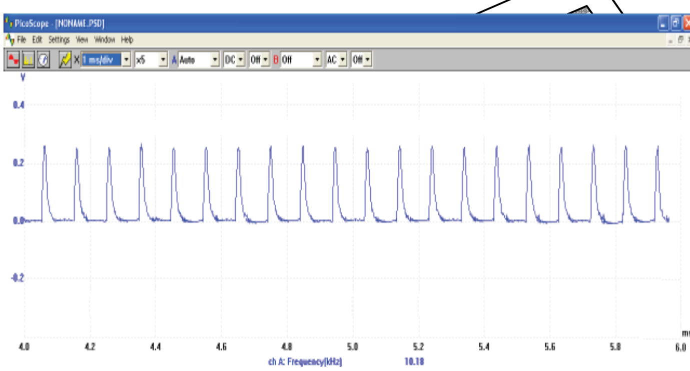

Figure 14 - Sampled Sense waveform (+ve field) 50% of the waveform was not sample

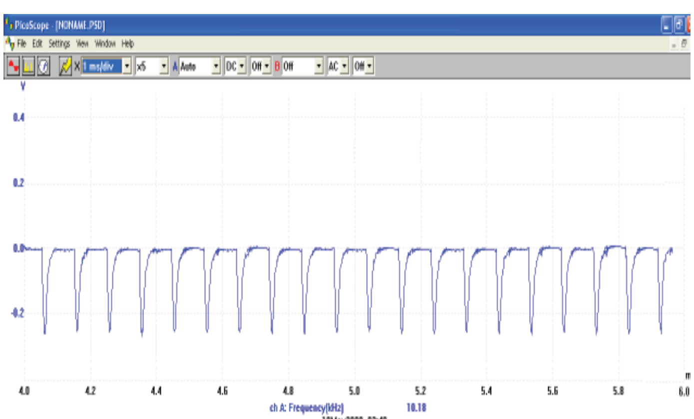

Figure 15 - Sampled Sense waveform (-ve field) 50% of the waveform was not sampled

This DC level is not compatible for devices working between voltage range 0-5V. For compatibility purpose, the output is clamped to the mean of 2.5V (for 0nT). Now 4V designates maximum field towards North (approx 34000nT) and 1V designates minimum field towards South (approx -34000nT).

6 CONCLUSION

The designed fluxgate magnetometer output lies between voltage ranges of 0-5V, which shows compatibility with usual components of system. The field corresponding to output voltage is shown in following figure:

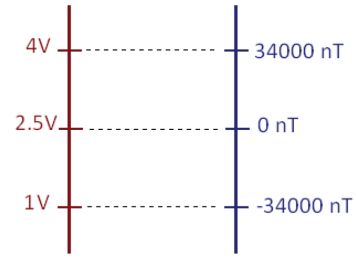

Figure 16 - Field corresponding to output Voltage

The sensitivity of the designed fluxgate magnetometer comes out to be 4.4 V/Gauss. Moreover, at this sensitivity, the resolution of the designed sensor comes out to be less than 200nT. Only area that needs to be highlighted is that if the magnetometer is turned on for very long time, the output voltage starts saturating and no change in output voltage occurs even if there is any change in sensor orientation or if a strong field is introduced. This issue indicates inappropriate core selection or magnetization of core. The issue can be resolved using a set/reset circuit which demagnetizes the core. Sensor calibration can be done in Helmholtz Coil Facility as a future work, by introducing known field and orienting.

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REFERENCES

[1] RM100 Nanotesla Meter User's Manual document ID-000290

[2] Fluxgate Sensor Electrical Drive Method and Circuit Patent Number 4677381 Date of Patent: 30th June, 1987

[3] Development, construction and analysis of the 'Ørsted' fluxgate magnetometer published in Meas. Sci. Technol. 6 (1995) 1099-1115

[4] Wertz, James R., "Spacecraft Attitude Determination and Control", ISBN 90-277-0959-9

[5] "Fluxgate Magnetometer" http://www.invasens.co.uk/FluxgateExplained.PDF

[6] Nobel, Dr. Richard, "Fluxgate Magnetometer", 2007, http://homepage.ntlworld.com/clarcana/proj/magnetometer/index.html