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Design of Fluxgate Magnetometer Sensors

[1]Gautami Singh
[1]M.Tech Student
[1]R&D Centre, Nadiad, India

***Abstract*— Various types of Fluxgate magnetometer sensors are designed and developed for the determination of very weak magnetic field. The sensor core used here consists of high gradient hysteresis curve and of very low power loss. Excitation current is passed through the primary winding. The secondary coil picks up the imbalance in the magnetic flux due to the ambient magnetic field which acts oppositely in each half of the sensor core. This generates second harmonics in the secondary coil having a minimum frequency twice the fundamental drive frequency. Various sensor designs like taped core sensor, toroidal core sensor and PCB based sensor of different specifications are tested and reported. For attaining better stability and linearity of the measurement, the ambient magnetic field is zeroed by an artificial field created by compensating coil or feedback coil by passing appropriate dc current. In this way, the compensating magnetic field is equivalent to the ambient magnetic field and do not depend on amplifier parameters. From this technique, we can measure the magnetic field of very small value with improved accuracy. The sensor developed here are intended for all digital fluxgate magnetometer using FPGA based control circuits for future space payload design.**

***Index Terms*— Vector magnetic field, Fluxgate Magnetometer, Permeability, Low noise amplifier**

I. INTRODUCTION

Fluxgate magnetometers are very commonly used device for measurement of very weak magnetic field. It is a device which measures the vector magnetic field i.e. both magnitude and direction [1]. The fluxgate sensor can measure DC or low-frequency AC magnetic field of small value with good accuracy and resolution [2]. It consumes less power, reliable and robust [3].

Initially, in 1930, the first magnetometer was developed which were rod core type and then the Forster and Vaquier types were developed [4]. Double rod core has open ends which cause non-uniform magnetic field and increased noise due to small differences in the drive winding geometries. This causes spurious output in the secondary coil [5]. It is generally used for NDT (Non-destructive) applications [6]. Ring core or toroid core are considered to be balanced double sensor where two half cores are parts of closed magnetic field. Ring core generally has higher noise than rod core owing to the demagnetization effect but it allows fine tuning of the core symmetry by rotation with respect to the pick-up coil. Also, the mechanical stress noise levels are uniformly distributed throughout the geometry and noise levels are uniform throughout the geometry [5]. They are generally used for applications in space as it is more robust against external factors such as temperature, vibration and vacuum. External noise can be cancelled by deeply saturating the highly permeable core and increasing the core diameter [6]. Also, the voltage noise density reduces rapidly when excitation frequency doubles up. This significantly reduces the field noise [7].

Also, there is a strong relationship between the diameter of the core and both the sensor sensitivity and noise [6]. With the increase in the core diameter, the sensitivity improves and noise level also reduces. Also in order to increase the sensitivity, signal to noise ratio (SNR) and remove the residual magnetization, the core has to be deeply saturated. This can be achieved by tuning the secondary winding with parallel or series capacitor [8].

Fluxgate magnetometers were widely used in space applications in the past since 1958 (Sputnik 3) and nowadays used commonly in satellites with scientific payloads for mapping the magnetic field of planets to study its past climate change. Rugged and reliable fluxgate magnetometer design is difficult and complex task [9].

For attaining better linearity of the measurement, many fluxgate sensors use the feedback mechanism to null the ambient magnetic field. It creates a compensating magnetic field by passing dc current through a separate coaxial feedback coil to the sense coil or by passing dc current back to the sense coil itself [10].

Conventional fluxgate magnetometer sensors possess high sensitivity and excellent accuracy but main drawbacks are high power consumption, bulky volume of a coil and less integration capability. But with recent development in research of magnetometer sensor, system miniaturization has become necessary. So, far fluxgate sensors are used for aircraft navigation system, military detection and medical applications. With the miniaturization of the fluxgate sensors, the scope of application has increased which are used for modern digital navigation, bio imaging system and space exploration [11, 12]. These miniaturized fluxgate sensors reduced the overall weight of the sensor, less power consumption and stable response. Among the various reported miniature fluxgates, the dual type (Vacquier-type) micro-fluxgates possess low noise level down to 5 nT/ $Hz^{1/2}$ at 10 Hz [13]. Most of the PCB based fluxgate magnetometers have closed core configuration with race-track or ring core geometries. This causes easy and uniform saturation of the sensor core with small excitation current [14, 15].

To develop light weight, accurate, sensitive and stable fluxgate magnetometer sensors, various sensors are developed. These sensors are tuned and tested for twice the fundamental drive frequency. The results of various sensors are compared based on sensitivity and stability of the second harmonic output response. The required stability, sensitivity and linearity is highly dependent on the sensor design specifications. This can be validated by various tests which are performed and reported here. By performing various tests, the fluxgate magnetometer can accomplish the best sensitivity, stability and linearity in performance.

II. PRINCIPLE OF OPERATION

The fluxgate magnetometer sensor consists of a core having hysteresis curve slope of high gradient, a primary coil and a secondary coil. The primary coil of the fluxgate sensor is excited using ac square wave signal having an amplitude large enough to saturate the core. The core saturates evenly in negative and positive cycles in absence of external magnetic field. The flux generated in two halves of the core cancel each other and total flux is zero. In presence of the ambient magnetic field, the core saturates unevenly in two halves of the core. The secondary coil picks up this imbalance in the magnetic flux due to ambient field twice per drive cycle. This generates the second harmonic in the secondary coil having frequency minimum twice the drive frequency. The working principle of the fluxgate magnetometer is shown in Fig.1

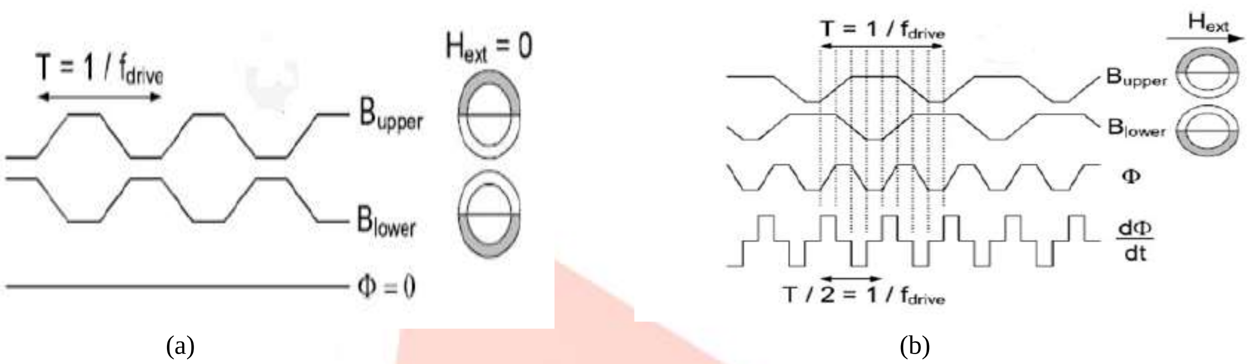


Fig. 1. Basic fluxgate sensor working principle (a) absence of ambient magnetic field (b) presence of ambient magnetic field

The sensing mechanism of a fluxgate magnetometer is based on Faraday's law. For a coil of wire, the relation of induced voltage Vi to change of magnetic flux with time is given by Eqn.1

$$Vi= \frac{d\phi}{dt} \quad (1)$$

For a coil of wire with N turns, an area A perpendicular to the magnetic field, and a core with effective relative permeability μr in a magnetic field H, this equation becomes

$$Vi= \frac{d\phi}{dt} = \frac{d(NA\mu_0\mu_r H)}{dt} \quad (2)$$

μ_0 is the permeability of free space. However, as A, μr and H are time-dependent so by expanding

$$Vi= \frac{d(NA(t)\mu_0\mu_r(t)H(t))}{dt} \quad (3)$$

Considering each time-varying term independently gives a generalized induction equation for a coil of wire with a permeable core:

$$Vi= NA\mu_0\mu_r\frac{dH}{dt} + NH\mu_0\mu_r\frac{dA}{dt} + NH\mu_0 A\frac{d\mu r}{dt} \quad (4)$$

The first term in Eqn (4) generates the voltage in response to a changing magnetic field. However, it cannot be used to sense the constant magnetic field since $\frac{dH\text{constant}}{dt} = 0$. The second term generates the voltage in response to a change in the area of the sense coil. This could theoretically be used to measure the magnetic field by rotating the coil to change the effective cross-section area but this approach is impractical. The third term generates voltage in response to changes in the effective permeability inside the coil of wire and forms the basic equation for a fluxgate magnetometer. The first and second terms are error sources to a fluxgate and often need to be isolated and removed. For now, we will consider only the third term:

$$Vi = NH\mu_0 A\frac{d\mu r}{dt} \quad (5)$$

III. SENSOR REALIZATION

a. Design of Taped Core Magnetometer Sensor

The sensor core is made of µ metal tape Metglas 2714A, a cobalt based alloy ribbon having a very small thickness of 15 µm. Such small thickness is required to reduce the noise and power loss. This µ metal tape core is cut having height of 8 mm and length equivalent to 10 turns i.e. 892 mm. Now this ribbon core is wound on a plastic pipe of 28.4 mm diameter and insulated using Teflon tape. 300 turns of primary winding of copper wire having 0.274 mm diameter is wound helically on the insulated core. Finally, the secondary coil is wounded with 500-500 turns centre tapped on the plastic bobbin having 0.193 mm diameter. The designed taped core sensor is shown below in Fig. 2

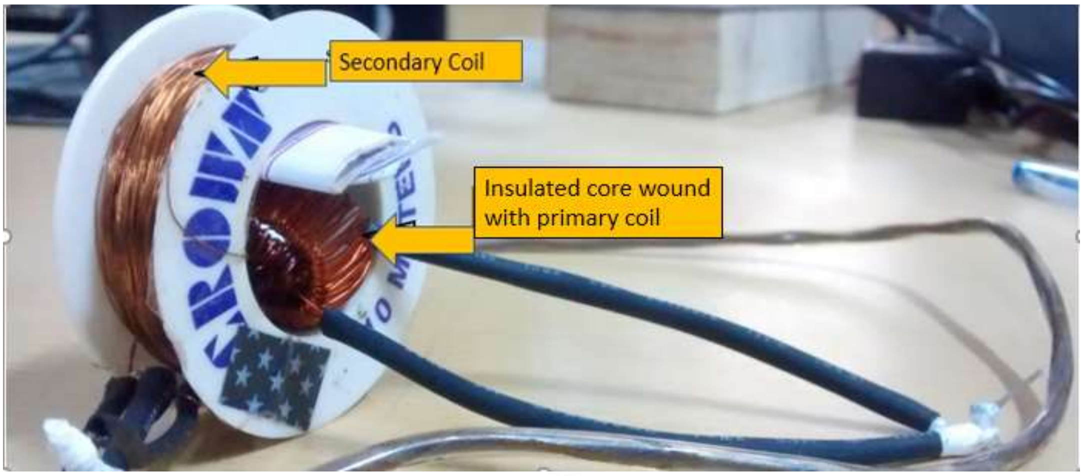


Fig. 2: Taped Core Sensor

b. Design of Toroid Core Fluxgate Sensor

The toroid core of the sensor is made of cobalt based Metglas 2714A having 39.8 mm outer diameter. The core has a higher initial permeability which reduces the number of turns and high permeability over a wide range of operating frequencies. The primary coil is made with the copper wire having 0.274 mm diameter of 300 turns. The secondary coil is wounded with copper wire of 0.193 mm diameter on the plastic bobbin having centre tapped 500-500 turns. The designed toroid core sensor is shown below in Fig. 3

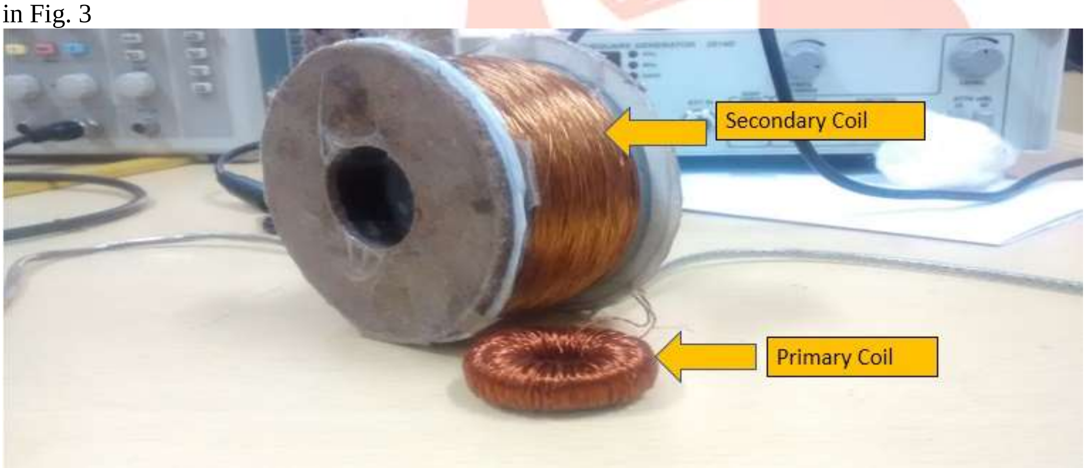
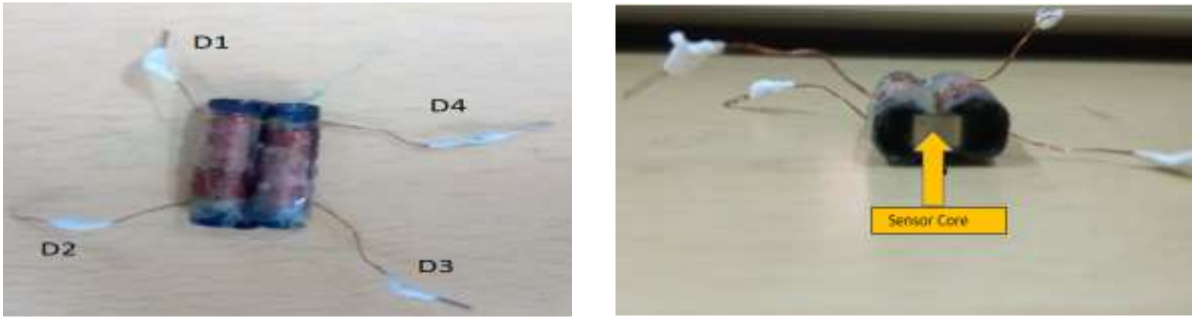


Fig. 3: Fluxgate Toroid Core Sensor

c. Design of PCB based Fluxgate Sensor

For making a drive coil, two tubes each of 1-inch length and 8 mm diameter are wound helically with 150 turns of copper wire having 0.102 mm diameter. Less diameter of wire reduces the overall weight of the sensor. Both the tubes are joined together with glue. The primary coil is centre tapped by connecting the diagonally opposite terminals D2 and D4 as shown in Fig. 4 (a). The sensor core is made of µ metal tape Metglas 2714A, a cobalt based alloy. It possesses low core loss, ultra-high permeability and hysteresis curve of high gradient. The µ metal tape core is wounded together with 10 turns inside both the shrink tubes together to form oblong shaped core as shown in Fig. 4 (b)



(a) (b)

Fig. 4: Primary Coil of PCB based Fluxgate Sensor

The secondary coil is wounded with 150-150 turns centre tapped copper wire having the same diameter as that of the primary coil copper wire. The secondary coil is placed around the primary coil and mounted on the PCB. The secondary coil is tuned to 30 kHz and tuning capacitor is placed on the PCB itself as shown in Fig. 5

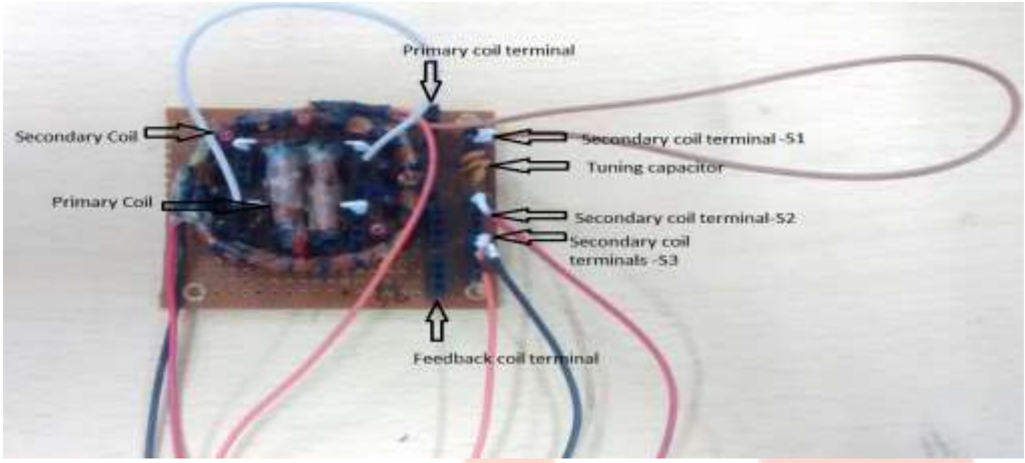


Fig. 5: PCB based Fluxgate Sensor

IV. Fluxgate Magnetometer Electronics

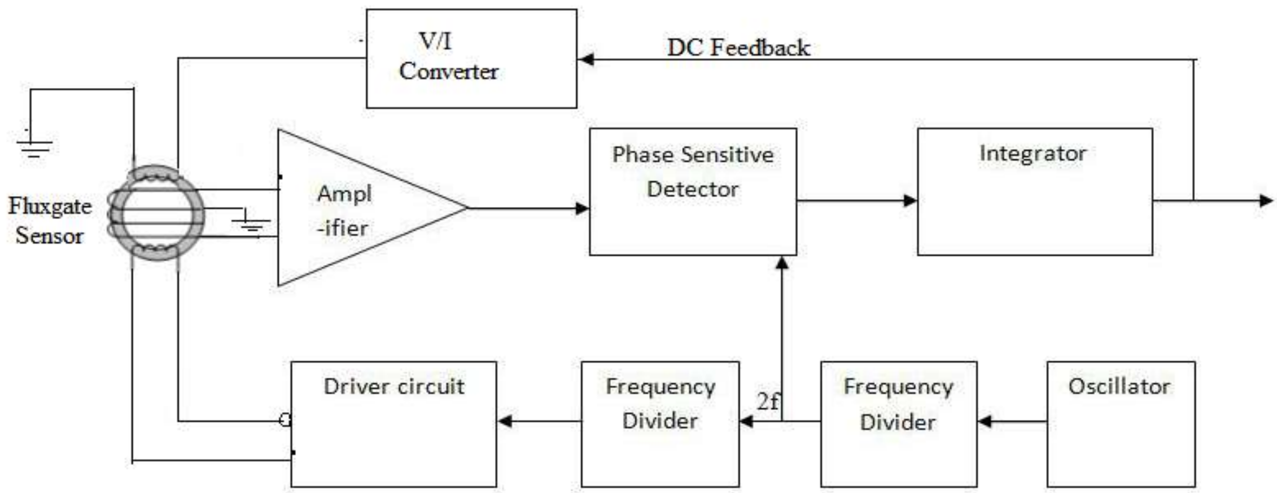


Fig.6: Block Diagram of proposed fluxgate magnetometer electronics

The block diagram of the magnetometer sensor as shown in Fig.6 consists of an oscillator, a frequency divider, a driver circuit, a fluxgate sensor, amplifier, phase sensitive detector (PSD) and integrator.

The oscillator circuit is used to generate the square wave ac excitation signal. This square wave ac signal is divided by factor of 2 by frequency divider circuit for equal duty ratio. This signal is used as a control signal in PSD (Phase Sensitive Detector) and also to the second frequency divider circuit which again divides the signal by factor of 2. This square wave ac signal is split and amplified. This inverted and non-inverted square wave signal excites the primary coil of the sensor as shown in Fig. 6.

In presence of ambient magnetic field, the core saturates and permeability becomes minimum. The secondary coil picks up the imbalance in the magnetic flux due to the ambient magnetic field which acts oppositely in each half of the sensor core. This generates the second harmonic in the secondary coil having frequency minimum twice the fundamental frequency. The secondary coil is tuned to increase the sensitivity and signal to noise ratio (SNR). The second harmonic output response signal of the sensor is amplified using a low noise amplifier.

The amplified inverted and non-inverted op-amp output signal is given as reference signal to the PSD along with control signal generated from frequency divider circuit. Hence PSD generates filtered and synchronized rectified DC output. The output of PSD is converted into pure DC voltage output using the integrator having magnitude equivalent to the ambient magnetic field.

V. RESULTS AND DISCUSSION

a. Testing the Taped Core Magnetometer Sensor

The primary coil of taped core sensor is excited with square wave ac drive signal. In presence of the ambient magnetic field, voltage is induced in sense coil in the form of second harmonic signal. From the output response, it can be seen that response is not stable and has a little offset. Also, the sensor is bulky. The waveform of second harmonic generation is shown in Fig. 7

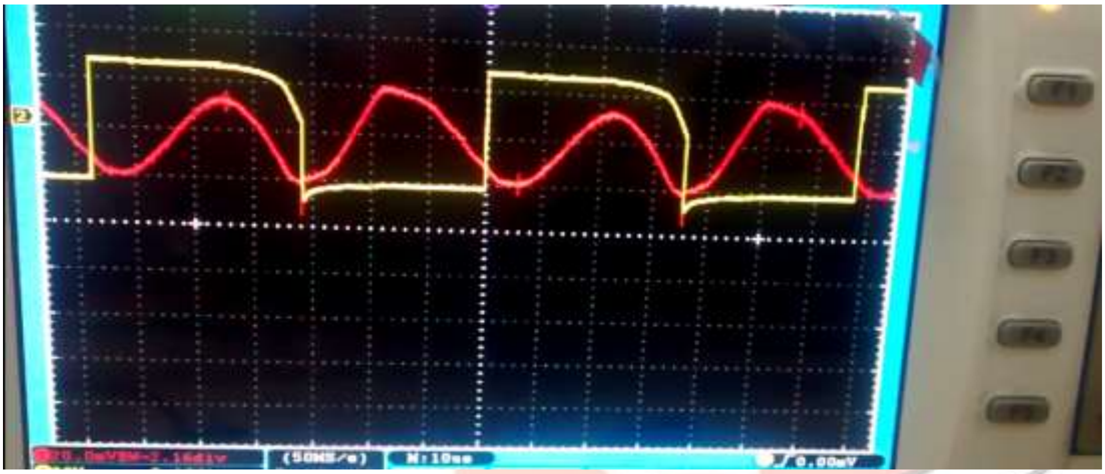


Fig. 7: Second Harmonic Response of Taped Core Magnetometer Sensor

b. Testing the Toroid Core Magnetometer Sensor

The primary coil of toroid core sensor of 300 turns is excited with square wave ac signal. In presence of the ambient magnetic field voltage is induced in sense coil in the form of second harmonic signal which is shown in Fig. 8.

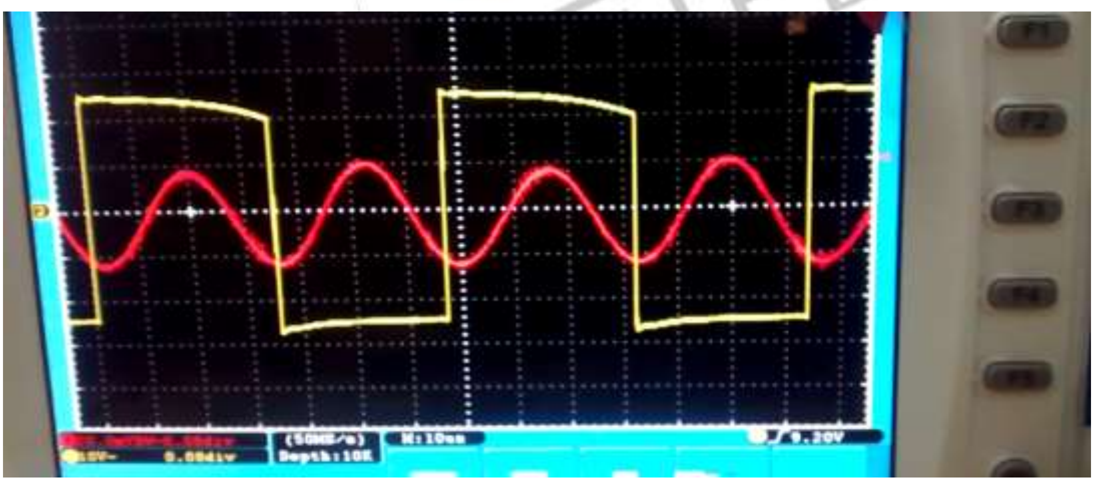


Fig. 8: Second Harmonic Response of Toroid Core Sensor

The second harmonic response of the secondary coil is quite noise free and has no offset as shown in Fig 8. But this sensor is also very bulky due to the weight of the toroid core.

c. Testing the PCB Based Sensor

Previous taped core and toroid core sensors were bulky because primary coil and secondary coil were wounded with 32 (Standard Wire Gauge) SWG and 36 (Standard Wire Gauge) SWG respectively. Changing the orientation of the sensor changed the position of drive coil w.r.t sense coil caused noisy output response. Hence PCB based sensor is designed in which the primary coil and the secondary coil are wound with 42 (Standard Wire Gauge) SWG which has less diameter reducing the overall weight of the sensor. The sensor is mounted on the PCB which can be connected to any electronic circuit easily. Moreover, the PCB based design increased the robustness of the sensor. The sensor is quite sensitive, accurate and gives stable output response The PCB based sensor is tested for second harmonic as shown in Fig. 9

Fig. 9: Second Harmonic Response of PCB based Sensor

The setup for testing of one of the fluxgate magnetometer sensor is shown below in Fig. 10.

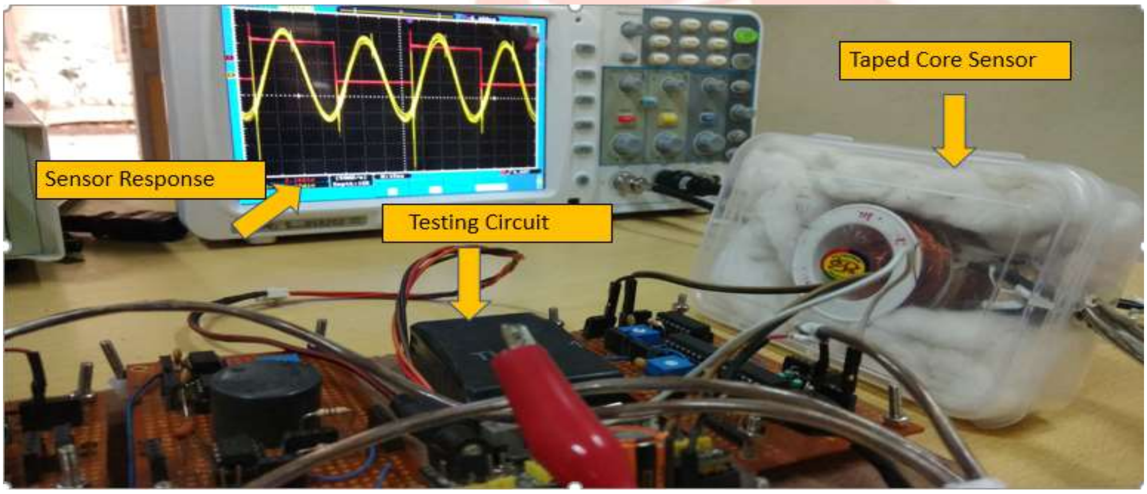
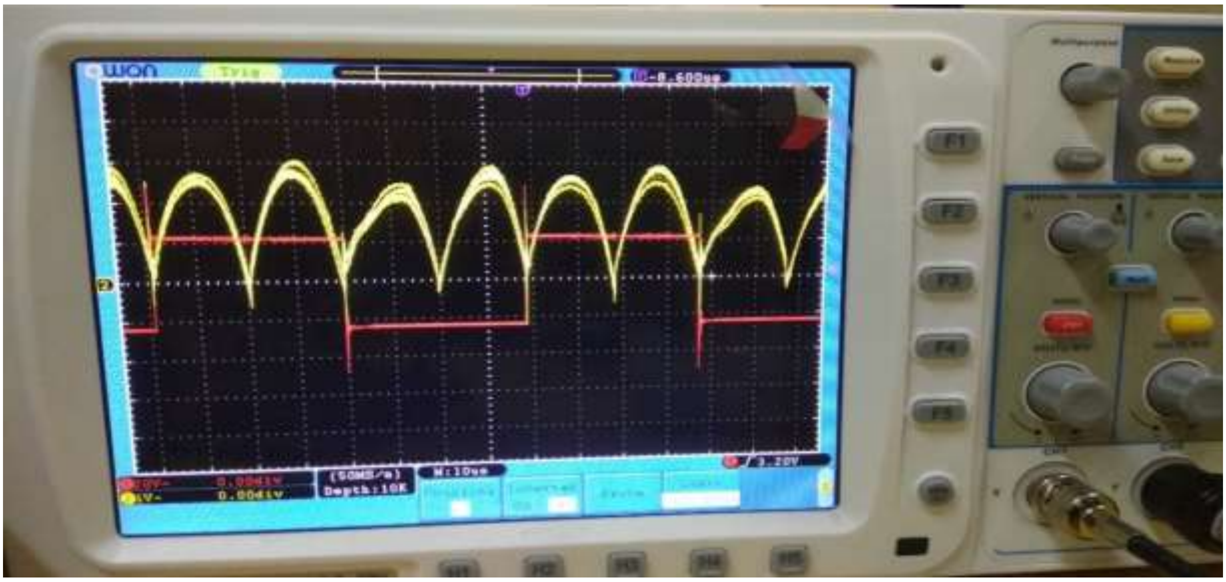


Fig. 10: Setup for testing of fluxgate magnetometer sensor

d. Sensor Response of Phase Sensitive Detector

Control Signal generated from frequency divider and the reference signal from the amplifier is given as input to Phase Sensitive Detector(PSD). This produces filtered and synchronized rectified dc output voltage response as shown in Fig. 11. The induced emf in the secondary coil in earth's magnetic field at PSD stage is 2.5 V



. **Fig. 11:** Filtered and rectified DC output of Phase Sensitive Detector

e. Sensor Response of Integrator

The filtered and synchronized dc rectified output of Phase Sensitive Detector (PSD) is connected to low pass filter working as the integrator to get pure DC voltage output. The DC output response of integrator. The DC output response of integrator is shown in Fig. 12.

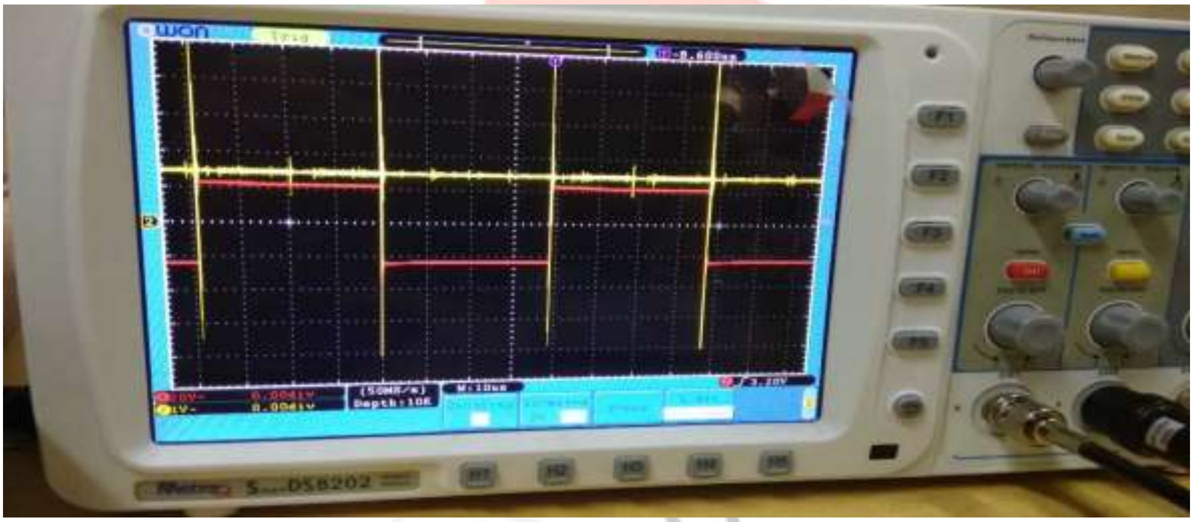


Fig. 12: DC output response of Integrator

f. Generation of Field Compensation

A feedback coil of 1000 turns are wounded and dc current through the coil is calculated to cancel the earth's magnetic field which is in the range of 0-1 mA. By varying the voltage across the feedback coil by potentiometer we can observe that at the particular voltage the output response is zero which shows that earth's magnetic field is canceled which is shown in Fig. 13.

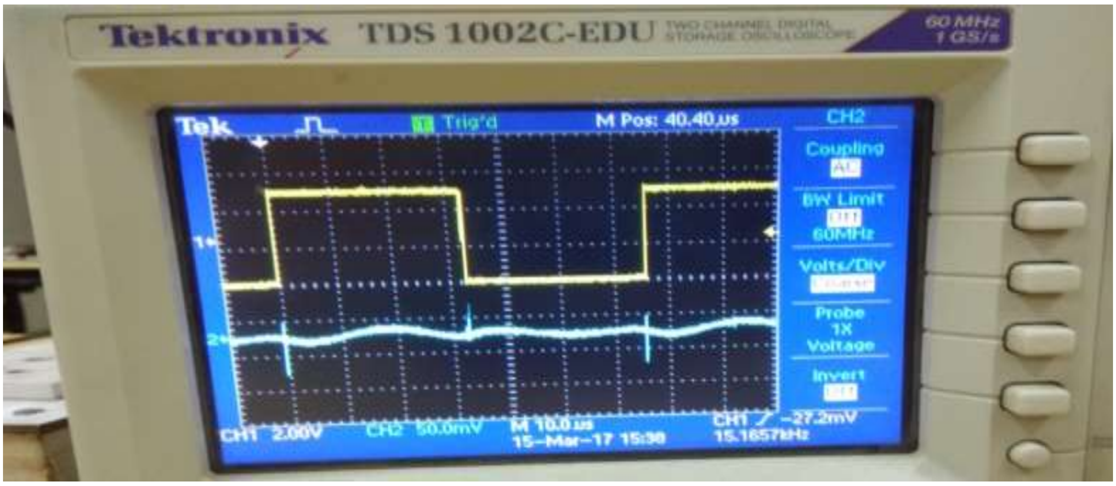


Fig. 13: Feedback coil response cancelling the earth's magnetic field

Table 1: Induced voltage in various Fluxgate Magnetometer Sensors due to earth's magnetic field

Sensor Type	Number of Turns		Coil Resistance		Induced Voltage
	Primary Coil	Secondary Coil	Primary Coil	Secondary Coil	
Taped Core Sensor	300	500-500 centre tapped	3 Ω	100 Ω	2.4 Vpp
Toroid Core Sensor	300	500-500 centre tapped	3.2 Ω	132 Ω	1.2 Vpp
PCB based Sensor	150-150 centre tapped	150-150 centre tapped	16.4 Ω	164 Ω	0.9 mVpp

VI. CONCLUSION

In order to measure very weak magnetic field, utilization of highly accurate and sensitive fluxgate magnetometer becomes very important. Hence various types of fluxgate sensors like taped core, toroid core and PCB based sensors are developed and reported. It is concluded that out of these developed sensors, PCB based sensor is more stable and accurate. Moreover, the sensor is light in weight, less expensive and can be connected directly to the electronic circuit increasing the robustness of the sensor. The taped core sensor is bulky but has better amplitude of induced emf compared to toroid core sensor and PCB based sensor.

By testing the various sensors on the processing circuit, amplified second harmonic output response is obtained. The filtered and synchronized full wave rectified dc output of PSD is converted into pure dc voltage with the help of integrator. This DC voltage obtained at integrator output is proportional to the magnitude of the ambient magnetic field. The development and testing of such fluxgate magnetometer provide accurate vector magnetic field. These data acquired by the magnetometer sensor will form the foundation of the comprehensive study of such kind of magnetometer sensors and its further development.

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About the Author:

Gautami Singh: She holds the degree in Bachelor of Engineering (B.E) in Instrumentation and Control Engineering from L.D College of Engineering, Gujarat Technological University. She is currently pursuing M. Tech in Instrumentation and Control Engineering at Dharmsinh Desai University, Nadiad. She is a research intern at R&D Centre, DDU, Nadiad and working mainly on design and testing of various Fluxgate Magnetometer Sensors under the guidance of Dr. H.S Mazumdar, Head of R&D Centre, DDU Nadiad.