



## Optimization of Fluxgate Sensor Performance using Firefly Optimization Algorithm to Reduce Noise Level

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### ABSTRACT

The aim of optimizing a fluxgate sensor for high performance is to obtain the overall dimensions of the sensor magnetic core based on the given specification using the available materials economically to achieve lower noise level at both reduced weight and size. A fluxgate sensor design optimization method is employed by using a firefly algorithm to design a high-performance fluxgate sensor that meets the specification of minimum noise level at reduced weight and size of the sensor. The application of the methodology employed demonstrated the effectiveness and practicality of the firefly algorithm technique in resolving the fluxgate optimization problem to achieve good sensitivity and lower noise of the sensor. The simulation results of the optimized sensor achieved a noise reduction of **36.49%**, that is, 3.465 pT/VHz was registered as compared to 5.4562 pT/VHz of the highest field noise solution at 1 Hz in the range of  $\pm 75\mu\text{T}$  after optimization using a firefly optimization algorithm.

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### INTRODUCTION

In today's competitive market environment, there is an urgent need for the decrease of the fluxgate sensor size and to reduce the noise, since miniature low noise fluxgate sensors and reduced manufacturing processes have become the key to survival in a global economy (Hsieh *et al.*, 2013). Optimum fluxgate sensor performance is accomplished by optimizing the dimension of the core and pick-up coil (Ripka, 2001). On the other hand, there is a strong relationship between the sensor core, pick-up coil, and detection circuit (Can & Topal, 2015). For minimum noise and maximum sensitivity, the geometry and dimensions of sensor core, excitation and pick-up coils are very important in matching

the excitation and detection circuits (Ripka, 2001).

The fluxgate sensor design aims to obtain the overall dimensions of the sensor core to use these data for fabricating fluxgate sensor. The fluxgate sensor design needs to be carried out based on the given specification using available materials economically to achieve lower noise level, smaller weight, reduced size, and optimum operating performance (Tumanski, 2013).

The fluxgate sensor design is worked out by using various methods based on accumulated experience realized in different formulae, equations, tables and charts. The fluxgate sensor design methods vary between the various fluxgate sensor manufacturers.

While designing a fluxgate sensor, much emphasis should be placed on lowering its noise while reducing the sensor core and pick-up coil and reducing to a minimum permeating effect and resistance thermal noise respectively in its operation. The design should be satisfactory concerning sensitivity, noise, stability, and power consumption in the event of long-term usage in portable applications (Chen *et al.*, 2011).

To meet the above requirements, the fluxgate sensor designer should be well familiar with the magnetic and electrical properties of the sensor core materials used in the fluxgate sensor. In addition to this, familiarity with the amount of current capacity of the coils used in the excitation and pick-up winding of a fluxgate sensor is very important.

In this paper, a fluxgate sensor design optimization method is employed using the firefly algorithm to design a fluxgate sensor

that meets the specification of minimum noise level and enhanced sensitivity.

The paper is organized as follows: The optimized fluxgate sensor design optimization method using firefly algorithm is presented in Section 2. Section 3 concludes the paper.

### Firefly Algorithm-Based Fluxgate Sensor Design Optimization

This section describes the method for the determination of the optimum fluxgate sensor, namely the fluxgate sensor exhibiting lower noise and enhanced sensitivity with smaller core size.

The methodology concerns the optimization of a fluxgate sensor with the following technical characteristics:

- Single-axis, parallel-type second harmonics fluxgate sensors,
- The magnetic circuit of closed type,
- Wire-wound technology for both excitation coil and pick-up coil windings.

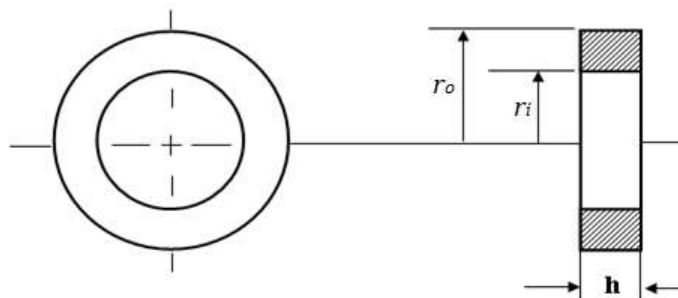


Figure 1: MnZn Ferrite Ring Core Geometric Dimensions.

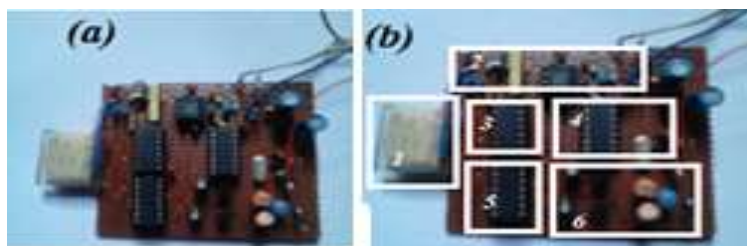


Figure 2: Complete Fluxgate Sensor System



Figure 1 illustrates the geometric dimensions of a ferrite ring core of the complete fluxgate sensor shown in Figure 2. The optimum fluxgate sensor is implemented with the help of a Firefly Optimization Algorithm (FOA). The FOA is one of the nature-inspired metaheuristic algorithms. The inspiration comes from the flashing light of the firefly. Though the true functions of such signalling systems are still being debated, two fundamental functions of such flashes are to attract mating partners (communication) and potential prey. Based on the flashing characteristics of fireflies the novel firefly algorithm was developed by Xin-She Yang at Cambridge

University (Yang, 2013). Such an algorithm is powerful in dealing with design problems of fluxgate sensors with a large number of design variables and multiple objectives, under complex nonlinear constraints (Yang, 2013).

The process of finding the optimum fluxgate sensor is implemented with the help of FOA, which uses five design variables as input parameters to make the fluxgate sensor optimization process achieve the best results possible. These input parameters are shown in Table 1. The geometry constraints and operating limits are shown in Table 2.

Table 1: Fluxgate Sensor Design Variables and Ranges

Variables	Range	Unit
Core outside radius ( $r_o$ )	5 – 10	mm
Core height ( $h_c$ )	1 – 4	mm
Pick-up Coil bobbin thickness ( $T_b$ )	1 – 10	mm
The amplifier feedback resistor ( $R_f$ )	1 – 270	k $\Omega$
Amplifier input resistor ( $R_i$ )	1 – 5	k $\Omega$

Table 2: Fluxgate Sensor Design Constraints

Variables	Range	Unit
Core thickness ( $C_t$ )	$\leq 3.0$	mm
Core aspect (height to diameter) ratio ( $R_{core}$ )	$\leq 10$	-
Coil aspect (length to height) ratio ( $R_{coil}$ )	$\leq 20$	-
Number of Pick-up coil turns ( $N_s$ )	$\leq 2000$	-
Sensor output voltage ( $S_{ov}$ )	$\leq 5.0$	-

The FOA allows many variations in design variables (Yang, 2013). These variations permit the investigation of enough candidate solutions. For each one of the candidate solutions, it is checked if all the geometry and operating constraints (limits) are satisfied. If they are satisfied, the noise is estimated and the solution is characterized as acceptable. The candidate solutions that violate the geometric and operational constraints are characterized as non-acceptable solutions. Finally, among the acceptable solutions, the fluxgate

sensor with the minimum noise level is selected as the optimum fluxgate sensor. The FOA implementation is based on the following steps:

For  $x_1 = 1$  to  $r_o$ .

For  $x_2 = 1$  to  $h_c$ .

Calculate the effective cross-section area of ring core material (shown in Figure 1).

Calculate the effective magnetic path length of ring core material (shown in Figure 1).



If core thickness violates the geometric constraint, then the solution is rejected and the next loop is executed.

For  $x_3 = 1$  to  $T_b$ .

If the core aspect ratio violates the core geometric constraint, then the candidate solution is rejected and the next loop is executed.

Calculate pick-up coil dimensions.

Calculate the total length of the pick-up coil winding.

Calculate the resistance of the pick-up coil. If the number of turns of pick-up coil winding is violated, then the solution is rejected and the next loop is executed.

Calculate the induced output voltage of pick-up coil and sensitivity.

For  $x_4 = 1$  to  $R_f$ .

For  $x_5 = 1$  to  $R_i$ .

Calculate the overall output voltage of the sensor.

If the overall output voltage of the sensor specified is violated, then the candidate solution is rejected and the next loop is executed.

Calculate the total sensitivity of the sensor.

Calculate pick-up coil resistance thermal noise.

Calculate the amplifier voltage noise.

Calculate the amplifier current noise.

Calculate the amplifier feedback resistor thermal noise.

Calculate amplifier gain resistor thermal noise.

Calculate overall sensor voltage noise.

Calculate the total magnetic field noise of the sensor.

Optimum fluxgate sensor is the one with the minimum magnetic field noise.

Giving different values for the design variables and constraints (geometric and operational constraints) as shown in Table 1 and Table 2, the total minimum magnetic field noise of the fluxgate sensor is calculated from this equation:

$$\text{Minimize } H_n(x) = \frac{\sqrt{v_{tot}}}{S_{tot}}$$

where  $H_n$  is the equivalent magnetic field noise of sensor,  $v_{tot}$  is the spectral density of the total sensor noise, and  $S_{tot}$  is the total FMS sensitivity.

Table 3: Values of Optimum Fluxgate Sensor

No. of Iterations	Core Outside Diam. (mm)	Core Height (mm)	Bobbin Thickness (mm)	Amp. Feedback Res. (kΩ)	Amp. Input Res. (kΩ)	EMFN (pT/VHz)
1	10.7614	3.45298	3.97123	73.45	1.12	5.4562
2	10.7614	3.45298	3.97123	73.45	1.12	5.4562
3	10.6818	1.39983	4.90201	100.00	1.73	4.6168
4	11.1050	1.38509	5.00000	99.01	2.06	4.3863
5	11.1050	1.38509	5.00000	99.01	2.06	4.3863
16	11.1440	1.36797	4.99895	96.35	2.05	4.2899
17	11.1440	1.36797	4.99895	96.35	2.05	4.2899
18	11.1440	1.36797	4.99895	96.35	2.05	4.2899
19	11.1440	1.36797	4.99895	96.35	2.05	4.2899
20	11.1440	1.36797	4.99895	96.35	2.05	<b>4.2899</b>

Table 3 presents the first five (higher noise level) and the last five (lowest noise level) solutions from the total 20 accepted solutions (iterations). It is noticed

that the lowest solution (optimum fluxgate sensor) gave magnetic field noise of **4.2899 pT/VHz** and the highest field noise solution gave 5.4562 pT/VHz. This indicates that the



optimum solution of **21.38%** lower than the highest field noise solution of 5.4562 pT/VHz was achieved. The optimum fluxgate sensor is the sensor number 20 of

Table 3, whose parameter values are technically characterized as shown in Table 4.

Table 4: Parameter Values of Optimum Fluxgate Sensor

Parameters	FOA Model	Unit
Core outside diameter	11.144	mm
Core height	1.367	mm
Number of Pick-up coil turns	646	-
Pick-up Coil bobbin thickness	4.99	mm
Amplifier Feedback resistor	96.35	kΩ
Amplifier input resistor	2.05	kΩ
Noise level at 1 Hz	<b>4.2899</b>	pT/VHz

So the optimum solution satisfies the constraints of Section 2.

**Variation of Core outside Diameter and Sensitivity Analysis**

Table 5 presents the values of the output variables (sensitivity and noise) when only one of the input variables is varied and more specifically the Core Outside Diameter (COD) which takes 5 values from 10 mm to 14 mm with a step of

1 mm. All the rest of the solution loop variables (core height, the core number of pick-up coil turns, coil bobbin thickness, feedback resistor, and input resistor) remain constant and equal to the respective values of the optimum fluxgate sensor (sensor number 20 of Table 3).

Table 5: Variation of Core Outside Diameter (solutions are sorted by magnetic field noise)

S/N	COD (mm)	Core Height (mm)	Bobbin Thickness (mm)	Amp. Feedback Res. (Ω)	Amp. Input Res. (kΩ)	Sensor Output Voltage (V)	EMFN (pT/VHz)
1	10.00	1.36797	4.99895	96.35	2.05	3.6783	4.5353
2	11.00	1.36797	4.99895	96.35	2.05	3.8623	4.3193
3	12.00	1.36797	4.99895	96.35	2.05	4.0462	4.1229
4	13.00	1.36797	4.99895	96.35	2.05	4.2302	3.9437
5	14.00	1.36797	4.99895	96.35	2.05	4.4141	<b>3.7793</b>

Table 5 shows that among the 5 candidate solutions, only three candidate solutions are accepted. Comparing Tables 3 and 5, it is concluded that the optimum solution has now a magnetic field noise of **3.7793 pT/VHz**, which is **30.73%** improvement of the highest field noise

solution of 5.4562 pT/VHz. This means that with the specific variation of the core outside diameter, a lower field noise solution was found. In Figure 2, the sensor output noise and voltage versus the core outside diameter are plotted.

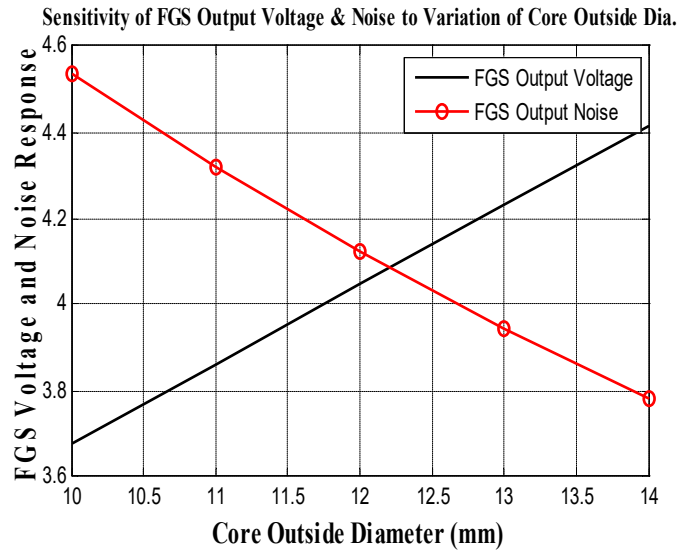


Figure 2: Fluxgate Sensor Output Noise and voltage vs. Core outside Diameter.

From Figure 2, it can be concluded that the output voltage is increased and the output noise is decreased with an increase of core outside diameter.

Table 6 presents the values of the output variables (output noise and voltage) when only one of the input variables is varied and more specifically the core height of the sensor ring core takes seven values.

#### Variation of Core Height

Table 6: Variation of core height (solutions are sorted by magnetic field noise)

S/N	COD (mm)	Core Height (mm)	Bobbin Thickness (mm)	Amp. Feedback Res. ( $\Omega$ )	Amp. Input Res. ( $k\Omega$ )	Sensor Output Voltage (V)	EMFN (pT/vHz)
1	11.1440	1.000	4.99895	96.35	2.05	3.7629	4.4334
2	11.1440	1.500	4.99895	96.35	2.05	3.9340	4.2406
3	11.1440	2.000	4.99895	96.35	2.05	4.1050	4.0639
4	11.1440	2.500	4.99895	96.35	2.05	4.2761	3.9013
5	11.1440	3.000	4.99895	96.35	2.05	4.4472	3.7512
6	11.1440	3.500	4.99895	96.35	2.05	4.6182	3.6123
7	11.1440	4.000	4.99895	96.35	2.05	4.7893	3.4832

All the rest solution loop variables remain constant and equal to the respective values of the optimum fluxgate sensor (sensor number 20 of Table 3). Table 6 shows that among the seven candidate's solutions, only six candidate solutions are accepted. Comparing Table 3 and Table 6, it is concluded that the new optimum solution

has now a magnetic field noise of **3.4832** pT/vHz, which is **36.16%** improvement of the highest field noise solution of 5.4562 pT/vHz. This means that with the specific variation of the height of the ring core, a lower solution was found. In Figure 3, the sensor output noise and voltage versus the core height are plotted.

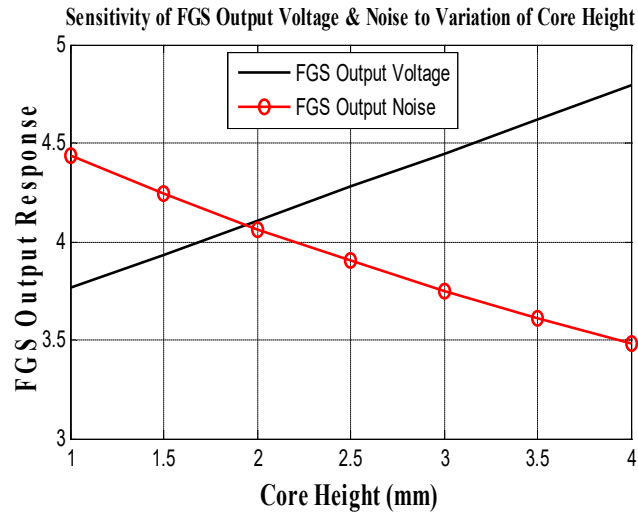


Figure 3: Fluxgate Sensor Output Noise and voltage vs. Ring Core Height.

From Figure 3, it can be concluded that the output voltage is increased while the output noise is decreased with an increase in the height of the ring core.

From this sensitivity analysis of the sensor, it is evident that there is a strong relationship between the sensor core dimensions and both its sensitivity and noise (Can & Topal, 2015). For example, the output noise decreased with increasing core outside diameter and height (with the rest of the input parameters remaining constant) while the output sensitivity

increases with increasing core outside diameter and height. The optimum solution is obtained by selecting values of input variables so that the fluxgate sensor satisfies the constraints with the maximum output voltage and minimum output noise. The selection is implemented and executed with the help of the FOA and the program was written and executed in MATLAB. The results of the sensitivity analysis carried out on the optimum fluxgate sensor of Table 3, is presented in Table 7.

Table 7: Results of Optimization Sensitivity Analysis

Parameters	FOA Model	Unit
Core outside diameter	12.22	mm
Core height	1.95	mm
Number of Pick-up coil turns	646	-
Pick-up Coil bobbin thickness	5.18	mm
Amplifier Feedback resistor	105.35	k $\Omega$
Amplifier input resistor	1.75	k $\Omega$
Sensor output voltage	76.95	mV/ $\mu$ T
Noise level at 1 Hz	3.465	pT/VHz

Comparing Tables 4 and 7, it is concluded that the new optimum solution has a magnetic field noise of 3.465 pT/VHz.

Finally, this means that with the specific variation of the core outside diameter and height, a lower field noise solution was





found to be **3.465 pT/VHz**, which is **36.49%** improvement of the highest field noise solution of 5.4562 pT/VHz.

## CONCLUSION

The fluxgate sensor design is a complex task that includes many variations in design variables to manage to lower the noise level, maximizing the sensitivity, and satisfying fluxgate sensor constraints (specifications) concerning power consumption, excitation current, and temperature stability due to thermal resistances of windings in the event of long-term application. This paper employed a fluxgate sensor design optimization method to design a fluxgate sensor that meets the constraints of minimum output noise. The efficiency of the developed fluxgate sensor design optimization algorithm is demonstrated through a design example. The simulation results of the optimized sensor achieved a noise reduction of **36.49%**, that is, 3.465 pT/VHz as compared to 5.4562 pT/VHz of the highest field noise solution at 1 Hz in the range of  $\pm 75\mu\text{T}$  after optimization using a firefly optimization algorithm.

## REFERENCES

- Can, H. & Topal, U. (2015). Design of ring core fluxgate magnetometer as attitude control sensor for low and high orbit satellites. *Journal of Superconductivity and Novel Magnetism*, 14/1-5.
- Chen, Z.; Zhou, S. and Jiang, A. (2011). Miniaturization design on magnetic induction sensors. In *Proceedings for International Conference on Electronic, Mechanical Engineering Information Technology*, 4626–4629.
- Hsieh, C.H; Dai, C.L. and Yang, M.Z. (2013). Fabrication and characterization of CMOS-MEMS magnetic microsensors. *Sensors*, 13/14728-14739.
- Ripka, P. (2000). New directions in fluxgate sensors. *Journal of Magnetism and Magnetic Materials*, 215-216, 735-739.
- Ripka, P. (Ed), (2001). *Magnetic sensors and magnetometers*. Artech House, Boston, MA.
- Tumanski, S. (2013). Modern magnetic field sensors: A Review. *Przegląd Elektrotechniczny*, 89/1-12.
- Yang, X.S. (2013). Multi-objectives firefly algorithm for continuous optimization. *Engineering Computation*, 29/175–184.