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MAGNETOMETER WITH PULSE-EXCITED MINIATURE FLUXGATE SENSOR

Jan Kubík* — Michal Janošek — Pavel Ripka*****

Fluxgate sensors with racetrack cores manufactured with printed circuit board technology are described. Their properties as results of FEM modelling and experimental measurements with sine wave excitation current are given. An alternative signal extraction method using gated integrators is described for short current pulse excitation of these sensors, reducing noise over traditional 2nd harmonic detection. A feedback-operated magnetometer with pulse excited PCB sensor is described using this detection technique. 14 840 V/T and 1313 V/T sensitivity in closed-loop and open-loop respectively was achieved for sensor IIA (9.6 kHz, 300 mA pp 12.5 % duty cycle excitation current). The maximum linearity error has been measured as 80 ppm of full-scale range 100 μT. The stability of magnetometer offset was 8.3 nT in 2 hours. Noise measurement resulted in PSD of 96 pT/√Hz @ 1 Hz.

Keywords: fluxgate sensor, printed circuit board, pulse excitation, gated integrators, signal extraction, magnetometer

1 INTRODUCTION

Fluxgate sensors are widely used in precise vectorial measurement of weak (up to 1 mT) DC or low-frequency AC magnetic fields. Typical applications are the geomagnetic field sensing for compass or field variation monitoring. Traditionally, the fluxgate sensor consists of ferromagnetic core (rod, double rod, toroidal, race-track) and wire wound excitation and pick-up coils. Typical wire wound fluxgate sensor is a very precise, expensive and bulky device. Therefore, a new technology of fluxgate sensor construction was introduced in [1] to provide smaller and cheaper devices. This technology utilizes the well-known printed circuit board (PCB) technology for the construction of the fluxgate sensor. A PCB fluxgate sensor with race-track core has been developed. The details of manufacturing technology are described further, and also effects of different winding parameters (number of turns, alignment) are discussed. Sensor properties have been determined with FEM analysis and experimentally verified in sine wave excitation mode. In order to reduce sensor excitation power consumption, a pulse excitation of PCB sensors has been proposed in [5], suffering of worsened noise parameters when the signal was detected traditionally with 2nd harmonic detection. To overcome this, an alternate signal extraction method with gated integrators is described, which leads to better noise parameters. A feedback magnetometer with pulse excited miniature fluxgate sensor is further described, and the results as of sensitivity, linearity, noise, offset stability and perming error are given.

2 PCB FLUXGATE SENSORS

2.1 Sensor construction

The ferromagnetic core is embedded in the multilayer PCB laminate and the excitation and optionally even pick-up coils are formed of copper routes and electroplated holes ("vias") on the PCB, no wire wound coils may be necessary. In previous works, the core was amorphous tape glued to the laminate [3] or electrodeposited layer (either crystalline or amorphous). The core shape was ring [1]. Due to mechanical stress transfer from the laminate on the core, the sensor sensitivity, noise, temperature offset stability and temperature sensitivity stability were badly affected. Sensors with electrodeposited cores also suffered from poor magnetic properties of that material.

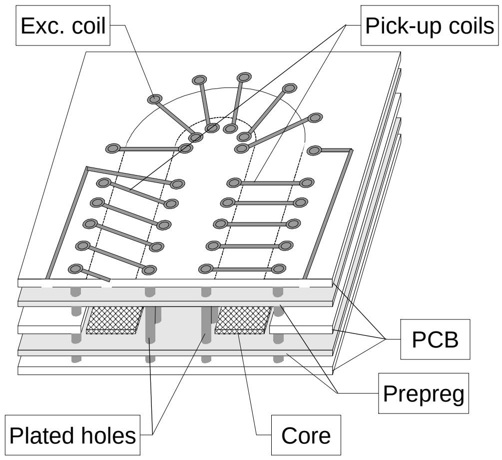

Fig 1. PCB sensor construction layers (from [4])

The new core-embedding technology was introduced in [4]. The sensor core made of 25 μm thick Vitrovac 6025X sheet was wet-etched separately from the PCB laminate.

The 30 mm long and 8 mm wide core (race-track shape, width 1.8 mm) was used due to lower demagnetizing factor, which leads to higher sensitivity and lower cross-field error compared to ring-core. The sensor PCB (Fig 1) consists of 3 layers of 0.2 mm thick laminate, two Prepreg solid adhesive layers between the laminates and two copper

* Czech Technical University, Faculty of Electrical Engineering, Technická 2, 166 27 Prague 6, Czech Republic, E-mail: jan.kubik@centrum.cz
**Czech Technical University, Faculty of Electrical Engineering, Technická 2, 166 27 Prague 6, Czech Republic, E-mail: janosem@fel.cvut.cz
***Czech Technical University, Faculty of Electrical Engineering, Technická 2, 166 27 Prague 6, Czech Republic, E-mail: ripka@fel.cvut.cz

layers on both outer laminate sides. The core-shaped hole had been milled in the middle layer laminate and the previously wet –etched core had been inserted before the PCB layers were bonded together by high pressure (1.5 MPa) and temperature (180 °C). The excitation and pick-up coils were formed by the two layers of copper routes and electroplated holes (‘vias’).

In the first generation, two sensors with 2x15 excitation coil turns and 27 pick-up coil turns were made, one with single and one with double layer of core material. Following the experience from the first generation, it was decided to produce 2 new prototype designs. The first prototype IIA (generation II, type A) with even distribution of excitation coil turns around the core and minimum possible coil resistances of excitation and pick-up coil, and the second prototype IIB with maximum number of pick-up coil turns using the smallest vias available. The IIA prototype had to utilize a mutual alternation of excitation and pick-up coil turns in the straight part of the core.

2.2 Sensor properties [6]

FEM modelling has been made using the following measured parameters: $H_C = 6$ A/m, $B_R = 0.4$ T, $B_S = 0.54$ T and $\mu 4 = 25000$ for $H = 0.4$ A/m.

For the IIA sensor with 46 turns excitation coil with turns approximately equidistantly placed around the core, nearly all the core volume is deeply saturated by 150 mA excitation current.

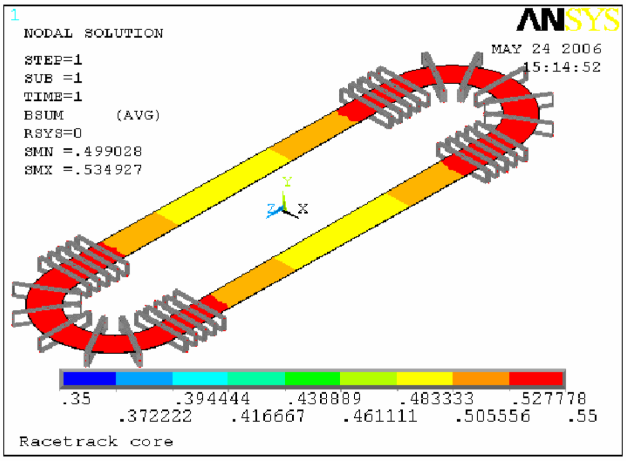

Fig 2. Core flux density FEM model of IIB excitation coil, $I_{EXC} = 150$ mA

The IIB sensor has excitation coil with 30 turns around the core round parts. The result of FEM simulation for the same excitation current is shown in Fig. 2. The magnetic flux density in the central part of the core is significantly lower than for IIA core even for this high-permeability material, and further increase of the excitation current does not significantly improve this.

Similarly the performance of the pick-up coil was modelled. The compensation current was determined as 23-27 mA for B = 25 µT for sensor IIA and 11 -13 mA for sensor IIB respectively, which was further confirmed by measurements.

The dimension of both IIA and IIB sensors is 33.5×15.4×1.2 mm, with the number of turns of excitation and pickup coil according to Tab 1.

Table 1: Sensor properties

IIA	N1 - Excitation	46
	N2 - Pickup	20
IIB	N1 - Excitation	30
	N2 - Pickup	37

2.3 Sensor parameters in sinewave excitation mode

The sensor prototypes of the previous generation (marked 3A and 3B) and also of the 2nd generation (IIA and IIB) were tested in open-loop sine wave excitation mode with 300 mA p-p current. The sensor output was measured by lock-in amplifier at 2nd harmonic frequency of 10 kHz excitation frequency.

The sensitivity of all sensors is naturally increasing with excitation frequency - up to 4180 V/T @ 400 kHz (270 V/T @ 10 kHz) for sensor 3A. However, it was shown in [4] that lower excitation frequency yields in better sensor stability due to better saturation of the core (higher excitation field penetration depth).

As for sensor 3A, the sensor offset stability in -20 to +70 °C was 127 nT and 21 nT for 200 kHz and 10 kHz excitation frequency respectively. The 3-hours offset stability of this sensor was 3.9 nT and the noise PSD was 53 pT/√Hz @ 1Hz (10 kHz).

For the second generation of the sensors, IIA and IIB, which were in detail described in chapter 2, the results comparison as for sensitivity, noise PSD and linearity error is shown in Table 2 (300 mA p-p, 10 kHz sinewave excitation current).

Table 2: Sensor parameters, as measured in open loop with 2nd harmonic detection for sinewave excitation of 300 mA p-p, 10 kHz

	Sensitivity (V/T)	Noise PSD @ 1Hz (pT)	Linearity error (ppm FS=100 µT)
IIA	140	51	17 000
IIB	270	62	3 000

3 SENSOR EXCITATION AND SIGNAL EXTRACTION

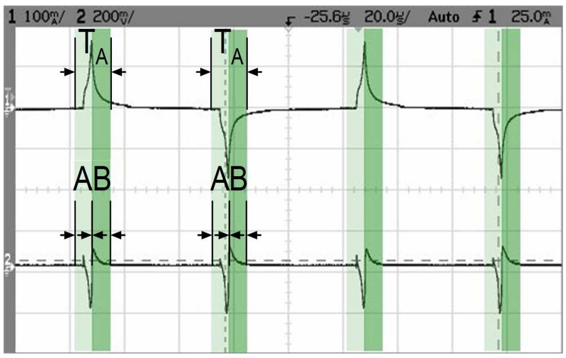

Fig 3. Fluxgate response (bottom trace) on pulse excitation (top trace) of 300 mA p-p, 10 kHz excitation frequency

The short current pulses excitation mode utilizing the FET bridge was introduced in [5] in order to lower the power consumption of the sensor excitation. The pulse excitation led to the pulse response of the sensor (Fig. 3).

While using traditional 2^{nd} harmonic detection, the noise of the sensor 3B increased from 63 to 710 pTrms/√Hz @ 1 Hz. The main source of this noise degradation was due to presence of noise in the inactive part of the excitation period. In order to reduce this noise, signal extraction should only be utilized in the active part of the period.

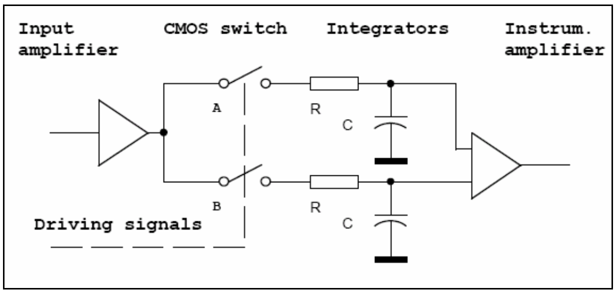

Fig 4. Gated integrators A and B

The use of two gated integrators (Fig 4) switched-on only in the active part of the excitation period was proposed together with current feedback loop compensating the measured field in [7].

The positive and negative signal parts (Fig 3) are integrated with corresponding passive RC integrator in the active part of the period T_A. Integrators' processing windows (A, B – negative and positive) are of equal and stable duration.

In order to suppress nonlinearity of the sensors, the magnetometer has been designed to operate in negative current-feedback loop. Feedback loop is of a common design with a series sense resistor. Thus the output voltage corresponds to the sensed feedback current, which provides compensating field.

4 MEASURED PARAMETERS

Fluxgate magnetometer with ±50 µT full-scale range has been designed according to Fig. 1 using the PCB IIA and IIB fluxgate sensors.

All measurements were done, as previously stated, with 300 mA p-p pulse excitation current with frequency of 9.6 kHz and 12.5 % duty-cycle.

Open and closed loop parameters in terms of sensitivity and linearity for both IIA and IIB sensors are given in Table 3.

Table 3: Sensitivity and linearity for IIA and IIB, open and closed loop

	Sensor type	**Sensitivity (V/T)**	**Linearity error (ppm FS)**
Open loop	IIA	1 220	5 500
	IIB	2 150	22 500
Closed loop	IIA	92 000	71
	IIB	46 500	714

In closed loop, as this is preferred magnetometer operation, further parameters have been determined – RMS noise Power Spectral Density measured at 1 Hz, RMS of noise power in 0.1-10 Hz band, offset stability and also perming error for ±2 mT shock field. Results for both IIA and IIB sensors are shown in Table 4 and Table **5**.

Table 4: Noise of IIA and IIB, closed loop operation

	RMS noise PSD @ 1 Hz (pT / √Hz)	RMS noise in 0.1-10 Hz band (pT)
IIA	20	116
IIB	63	756

Table 5: Offset stability and perming error for IIA and IIB, closed loop

	3-hours offset stability (nT)	Perming error (±2mT) (nT)
IIA	3.7	125
IIB	19.3	238

5. DISCUSSION OF THE RESULTS

5.1 Sensitivity

It can be clearly seen that the IIB sensor has much greater (open-loop) sensitivity than IIA, in sinewave and also in pulse excitation mode (Table 3). This can be easily explained by the pickup-coil properties – the number of turns is much larger for IIB sensor. On the other hand, the closed loop operation relies on the ability of the pickup (compensation) coil to create magnetic field, there can be seen that the sensitivity of IIA sensor is approx. 2 times better than of the IIB. The main reason is larger number of turns of the compensating coil of sensor IIA, also larger section of the core is covered with the winding.

5.2 Linearity

Open loop-linearity error for sinewave excitation was greater for sensor IIA, because in the 300 mA p-p condition, the sensor is excited with exceedingly large current [6]. However, when pulse-exciting those sensors, the situation is much more clear - the open loop linearity error of IIB sensor is more than 4x larger than IIA. This supports the idea, that for better linearity, the sensor core should be evenly saturated, as for sensor IIA (chapter 2.2).

Closed-loop operation with pulse excitation and gated integrators signal extraction further improved linearity error - 31x for sensor IIB up to 77x for sensor IIA. The IIA sensor is thus clearly the choice for operating in current design.

5.3 Noise

For sensor 3A from the previous generation, in [4] was shown the degradation of PSD from 63 to 710 pTrms/√Hz @ 1 Hz when using pulse excitation instead of sinewave one. For similar sensors IIA and IIB, the noise reduction, which was achieved by our detection technique, is greater than 10x. The resulting noise is then comparable with noise PSD of both IIA and IIB sensors operated in sinewave excitation mode (reduction from 710 to 20 and 63 pTrms/√Hz @ 1 Hz for IIA and IIB respectively, compared with 51 and 62 pTrms/√Hz when the excitation is sinewave). Noise comparison of the signal detection electronics (when the IIA sensor was disconnected) and noise of whole magnetometer (with IIA sensor) is shown in Fig 5

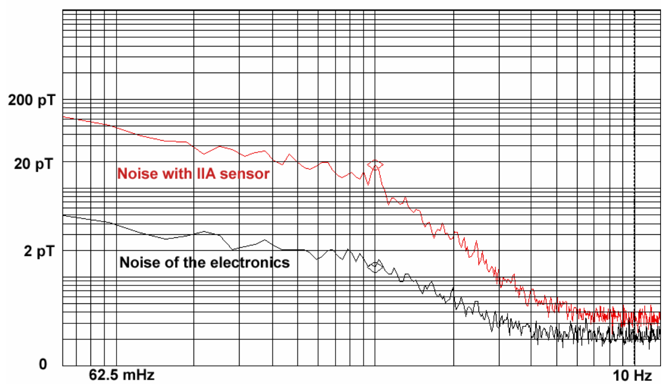

Fig 5. Noise of electronics with, and without IIA sensor

6 CONCLUSION

PCB fluxgate sensors with racetrack core of the 2nd generation IIA and IIB have been manufactured and used in pulse-excitation mode, with new signal extraction technique using differential gated integrators.

The results confirm our expectations of suitability of gated integrators for signal extraction from pulse excited PCB fluxgate sensor instead of using 2nd harmonic detection by lock-in amplifier, in terms of noise suppression. Also, the feedback operation of PCB fluxgate sensors has proven to dramatically improve linearity of the sensors.

Best results have been obtained using sensor IIA, with even distributed excitation and pickup coil around the core, with mutually alternating windings. With this sensor, a magnetometer with ± 50 µT range has been constructed, with sensitivity of 92 000 V/T, linearity error better than 71 ppm of FS, noise PSD of 20 pTrms/√Hz and offset stability of 20 nT within 3-hours.

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Jan Kubík (Ing), born in Pardubice, Czech Republic, in 1979. Graduated from the Faculty of Electrical Engineering, Czech Technical University in Prague, in 2003 from Measurement and Instrumentation and is now pursuing the PhD degree at the same university with the subject of PhD thesis "PCB Fluxgate Sensors". The main field of his research activities are the magnetic field sensors modeling, development and testing and measurement systems. He is the main author or co-author of 12 journal papers, 1 utility design and 19 conference proceedings.

Pavel Ripka (Prof., Ing,, CSc.) was born in Praha in 1959. He received an Ing. degree in 1984, and CSc. (equivalent to PhD.) in 1989, and in Assoc. Prof. degree in 1996. He works at the Department of Measurement, Faculty of Electrical Engineering, Czech Technical University as Prof., lecturing in Measurements, Engineering Magnetism and Sensors. His main research interests are Magnetic Measurements and Magnetic Sensors, especially Fluxgate. He is a co-author of 3 books and > 50 journal papers.

Michal Janošek, born in Varnsdorf, Czech Republic, in 1980. He is a graduate student at the Faculty of Electrical Engineering, Czech Technical University in Prague, with diploma thesis "Magnetometer with miniature fluxgate sensors". His main research activity is implementing and further improvement of differential gated integrator method of fluxgate signal extraction. He is a co-author of 2 journal papers, and 3 conference proceedings.