Low-Power Printed Circuit Board Fluxgate Sensor

Jan Kubík, Lukáš Pavel, Pavel Ripka, *Member, IEEE*, and Petr Kašpar

***Abstract*—A new printed circuit board flat fluxgate sensor with integrated coils and amorphous alloy core was developed and its excitation parameters optimized for low-power consumption. The power consumption achieved with 10 kHz, 300 mA p-p pulse excitation with duty cycle 12.5% was only 3.9 mW, which is three times lower than that for sinewave B excitation. The sensor sensitivity reached 94 V/T. The required excitation bridge supply voltage was only 0.47 V. The low-cost low-power sensor has a temperature offset stability of 120 nT in the -20 to $+70$ °C temperature range and 0.17%/°C open-loop sensitivity tempco due to the use of a new core embedding technique. The perming error due to 10 mT field shock was suppressed below 1.2 μT. The short-time offset stability was 38 nT within 3 h. Thus the developed sensor is more precise and less energy consuming than a periodically flipped anisotropic magnetoresistance (AMR) sensor. The achieved parameters are sufficient for compass with 0.1° error.**

***Index Terms*—Fluxgate sensor, low power, printed circuit board (PCB).**

I. INTRODUCTION

CLASSICAL fluxgates with wire wound coils are expensive and bulky. Recent efforts to minimize production costs and decrease the sensor size resulted in use of printed circuit board (PCB) technology [1], [2] or planar microtechnology [3]. All above-mentioned sensors use electroplating or electrodeposition of core material. The quality (permeability, coercive force) of such materials does not meet the qualities of soft rapidly quenched tapes of amorphous alloys. The wet-etched amorphous alloy core was used to create a new type of PCB fluxgate sensor [4].

The miniaturized fluxgate sensors require a new type of low-power excitation, as classical excitation tuning cannot be used due to the high resistance of the excitation coil and thus low Q-factor of the excitation tank circuit. Excitation by short pulses to reduce the power consumption was already used for fluxgate sensor with flat coils [5]. First experience with pulse excitation of PCB fluxgate was described in [6]. The principal limitation of flat coil design compared to three-dimensional winding is poor magnetic coupling between the flat coils and the core.

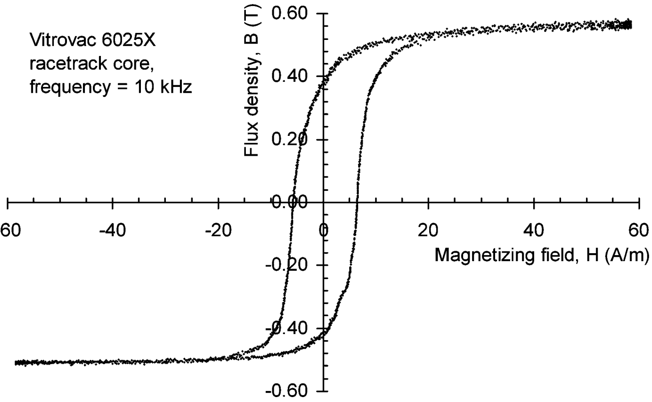

Fig. 1. Vitrovac 6025X racetrack core B-H loop measured at 10 kHz [6].

The proposed pulse-excited flat fluxgate sensor is intended for use in battery-operated precise navigation devices. The sensor is able to measure geomagnetic field with power consumption lower than 5 mW.

II. MANUFACTURING PROCESS

The process consists of separate core preparation and then core embedding into the prepared PCB. At first, the racetrack-shaped core was etched from 25 μm thick Vitrovac 6025 X amorphous alloy sheet. The racetrack core shape was chosen for its high suppression of crossfields and improved sensitivity in longitudinal direction compared to the ringcore shape. The core is 30 mm long and 8 mm wide, and the racetrack width is 1.8 mm. The core's B-H loop measured at 10 kHz excitation current showed a coercive force of 6 A/m and saturation flux density of 0.54 T (Fig. 1). Further measurements on the core samples indicated that the initial permeability (μ_4) was $\sim$26 000, maximum permeability was $\sim$72 000, and maximum differential permeability $\sim$150 000.

The standard four-layer PCB manufacturing technology was used to prepare a sensor frame: three layers of 0.2-mm-thick DURAVER-E-Cu laminate and two layers of 0.065-mm-thick Prepreg solid-state adhesive in between the PCB layers were used. The core-shaped hole was milled into the inner layer of PCB laminate, and the etched core was inserted into this hole before bonding the layers together. Using this design minimizes the transfer of thermal expansion of PCB to the core material [4]. The coils are formed of copper routes on the outer layers of PCB and electroplated through-holes (vias). The sensor has four sections of windings (Fig. 2) to be used as excitation (two round sections, 2 × 15 turns, dc resistance 0.43 Ω), and pickup coils (two straight sections, 2 × 27 turns, dc resistance 0.64 Ω). The excitation coils are connected serially, thus totally 30 turns of excitation winding were used. The pickup coils are connected antiserially, forming 27 turns of pickup coil.

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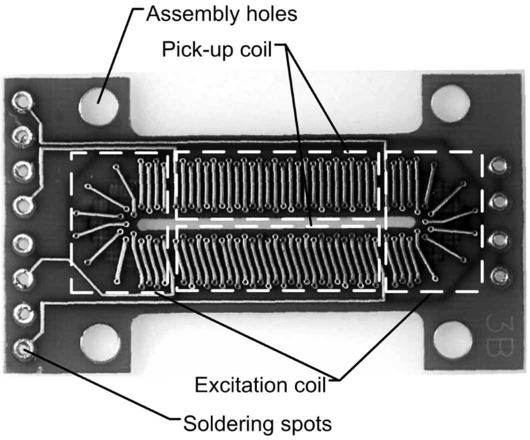

Fig. 2. PCB fluxgate sensor photography [6].

The more detailed description of sensor manufacturing process including cross-section figure of the sensor structure can be found in [4]. The sensor used in further experiments had two layers of embedded core material making the total core thickness 50 μm and is referred to as "double-core sensor" in [4].

III. EXPERIMENT SETUP

At first, the sensor was excited by an Agilent 33120 generator set to sine wave generation, Krohn–Hite 7500 amplifier, and MT-56 R matching transformer. Then the pulse excitation unit described further on was used. The sensor output was measured by a Stanford Research SR830 lock-in amplifier, and the noise at its output was measured by an Agilent 35670A spectrum analyzer set to 95% overlap and 50x root mean square averaging. All the measurements were made on the second harmonic frequency. The phase was adjusted for maximum sensitivity at the 50 μT field and then kept constant. Six-layer permalloy magnetic shielding with internal thermostat was used to measure noise and offset temperature stability. Helmholtz coils with thermostat was used to measure temperature coefficient of sensitivity. The current waveforms were measured by an Iwatsu CP-502 current probe. The sensor power consumption was calculated using N voltage ($V(i)$) and current samples ($I(i)$) acquired by Agilent 54624 A oscilloscope in one excitation period

$$P = \frac{1}{N}\sum_{i'=1}^{N} V(i)I(i). \tag{1}$$

In case of pulse excitation (see Section IV), the voltage samples $V(i)$ were calculated as a voltage difference between two probes connected to both ends of the sensor excitation coil in order to avoid short-circuiting one of the excitation bridge branches by oscilloscope probe grounding.

IV. SENSOR EXCITATION

According to the formulas developed in [7], the amplitude of excitation current to reach maximum sensitivity was calculated to be 160 mA p-p (presuming triangular excitation current waveform). The dependence of sensitivity on the excitation current is given by the time derivative of the excitation field $\mathrm{dH_{exc}/dt}$ in the time interval when the core is not saturated.

First, the sensor was excited by an Agilent generator set to sine wave output and Kron–Hite amplifier to prove the sensor functionality and determine its parameters. The excitation current waveform was not sine wave due to nonlinearity of the inductance of the excitation coil caused by saturation of the core material (an excitation field B was close to sine wave). The experimentally found excitation current amplitude for maximum sensitivity was 300 mA p-p in this "B sine wave" excitation mode. The higher optimum p-p excitation current than that for theoretical triangular waveform is caused by lower $\mathrm{dH_{exc}/dt}$ of the "B sine wave" excitation mode in the time interval when the core is not saturated. The sensor has maximum sensitivity at 200 kHz, but sensitivity itself is not the most important parameter. We have shown in [4] that at lower excitation frequency (5 or 10 kHz for this sensor design), lower sensor noise and better temperature stability can be achieved. The sensitivities of the sensor at these frequencies were 116 and 241 V/T for 5 and 10 kHz, respectively, measured for "B sine wave" excitation mode with 300 mA p-p current. The power efficiency of sine wave excitation is not optimal unless excitation tuning by parallel capacitor is used. Such tuning by parallel capacitor was not possible in case of a PCB fluxgate sensor, which has high winding resistance causing low Q-factor of the LC resonant circuit.

The previous works on fluxgate sensor with electrodeposited core and wire wound pickup coil [8] have shown that the pulse excitation can significantly reduce the power consumption. The pulse excitation circuit with variable duty cycle was designed to investigate the properties of bipolar pulse excitation applied to PCB fluxgate sensor. The pulse excitation circuit is based on 2 IRF7103 HEXFET transistors creating a full H-bridge and 2 ADP3412 MOSFET drivers (Fig. 3). The control part of the excitation unit is based on Complex Programmable Logic Device (CPLD) Altera 3064A producing the transistor–transistor logic driving signals *RIGHT* and *LEFT* and also second harmonic square wave reference signal for the lock-in amplifier. These signals are derived from the CPLD input clock signal by frequency division. The *RIGHT* and *LEFT* signals are the driving signals for MOSFET drivers; the pulse duration t of these signals determines the duration of fluxgate excitation current pulses. The mutual phase-shift of these signals is set to 180° in order to achieve excitation current pulses containing only odd harmonic components. Using external clock instead of fixed crystal oscillator is a flexible solution allowing us to change the excitation frequency simply by changing input clock frequency of the CPLD. The CPLD accepts clock frequency up to 222 MHz, and this corresponds to a maximum excitation frequency of 1.7 MHz. The duty cycle t/T can be adjusted in steps (1.56, 3.13, 6.25, 12.5, 25, and 50 %) by DIP switches on the control part of the excitation circuitry. Fig. 4 demonstrates the sharp peaks of the excitation current of 300 mA p-p while the root mean square (rms) value is kept down at 24 mA. The same figure shows the induced voltage waveforms for the measured field of 0 and 38 μT.

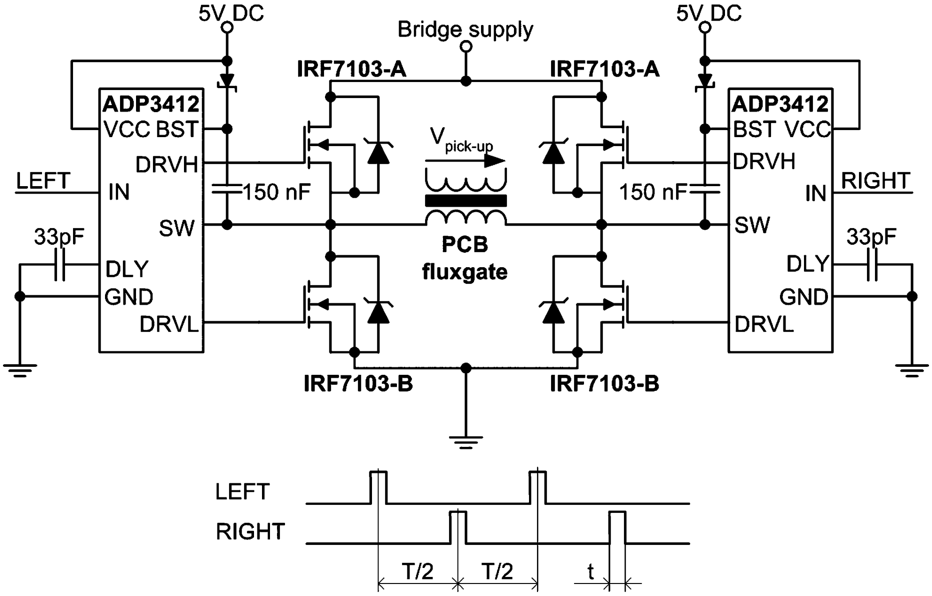

Fig. 3. Power part of the fluxgate sensor excitation circuitry including the HEXFET H-bridge.

Fig. 4. PCB fluxgate excitation current 300 mA p-p, frequency 10 kHz, duty factor of 6.25% (top trace, 100 mA/div), and sensor response to measured field 0 (middle trace, 200 mV/div) and 38 μT (bottom trace, 200 mV/div).

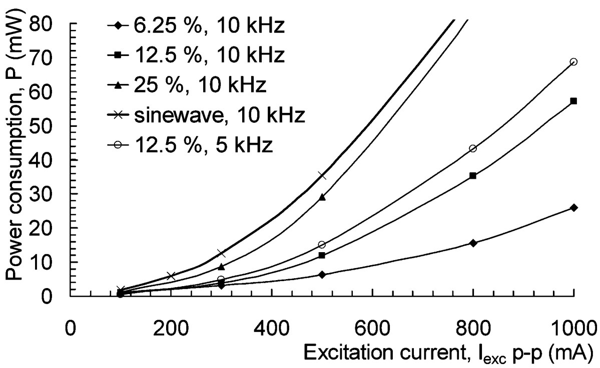

Fig. 5. Power consumption of PCB fluxgate (duty factor of excitation current in percent and excitation frequency are denoted) [6].

V. Measured Results

A. Power Consumption

Theoretically, the excitation power is increasing with frequency due to the frequency dependence of hysteresis and eddy current losses. However, in most cases (excluding the excitation current of 100 mA), we observed that the power consumption at 10 kHz excitation frequency was lower than for 5 kHz excitation frequency (Fig. 5). This is favorable due to higher sensitivity of the sensor at 10 kHz excitation frequency. Similar complex nonlinear behavior in frequency was observed in fluxgate sensors with tuned excitation [10].

The power consumption naturally increased with increasing duty cycle. The power consumption of the sensor including the bridge for sufficient excitation current of 300 mA p-p, 10 kHz reached 3.1 mW (6.25% duty cycle), 3.9 mW (12.5%), and 8.8 mW (25%). The bridge voltage was in the range of 0.76–0.38 V, and the rectified mean current values were in the range of 4–23 mA. It was not effective to use shorter pulses due to highly increasing bridge voltage and instability of excitation current p-p values in such cases.

B. Sensitivity

The sensor full scale linear range was ±100 μT. The maximum sensitivity of 241 V/T reached for "B sine wave" excitation was for the 300 mA p-p excitation current (Fig. 6). The pulse excitation behavior is different: the sensitivity is slowly increasing even up to 1000 mA p-p. The sensitivity is also increasing with increase in the duty cycle of the excitation current. Generally, the sensitivity of a pulse excited sensor is lower than that of a "B sine wave" excited sensor for lower excitation currents below 500 mA p-p. The sensitivity of the pulse excited sensor reached 94 V/T for 300 mA p-p current at 10 kHz with 12.5% duty cycle. The sensor pickup coil tuning did not bring any increase of sensitivity due to low Q-factor of the pickup coil.

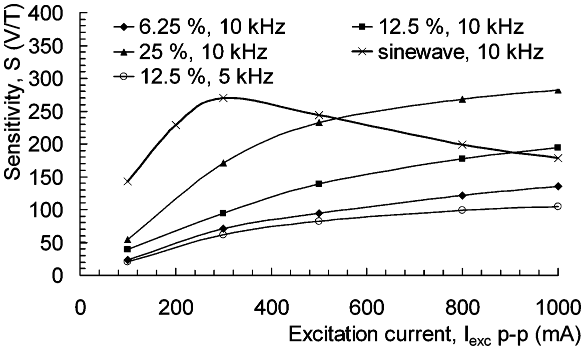

Fig. 6. Sensitivity of PCB fluxgate [6].

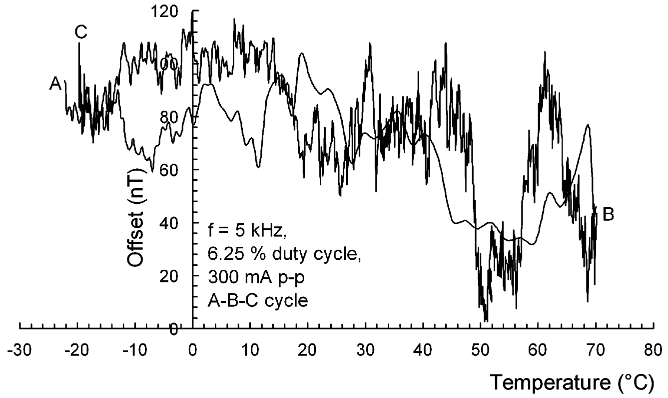

Fig. 7. Offset temperature stability of pulse excited PCB fluxgate sensor [6].

C. Temperature Stability

The offset temperature stability has degraded when using pulse excitation. The "B sine wave" excited (300 mA p-p, 5 kHz) sensor had offset drift in the -20 to $+70$ °C temperature range below 16 nT. The same value for a pulse excited (5 kHz, 300 mA p-p, 6.25% duty factor) sensor was 120 nT (Fig. 7), which is 7.5 times worse than for the same p-p "B sine wave" excitation current. The 120 nT offset temperature drift is still more than 40 times lower than values reported for an electrodeposited core [11]. On the other hand, the temperature coefficient of sensitivity was not affected by pulse excitation. We even observed a slight improvement of the sensitivity tempco from 0.25%/°C when using sine wave excitation to 0.17%/°C when using pulse excitation. (Fig. 8).

D. Noise

The sensor noise increased when using pulse excitation. The noise power spectrum density at 1 Hz was 24 and 710 $\mathrm{pT_{rms}}/\sqrt{\mathrm{Hz}}$ for "B sine wave" mode (300 mA p-p, 10 kHz) and pulse excitation (300 mA p-p, 10 kHz, 6.25% duty cycle), respectively. The noise rms value in the range from 64 mHz to 10 Hz was 0.7 and 3.7 $\mathrm{nT_{rms}}$ for "B sine wave" and pulse excitation. The noise increase for pulse excitation was also observed in [8]. The noise is considerably higher than when using the same sensor with wire wound pickup coil, which could be effectively tuned and noise greatly reduced [9]. However, the achieved noise level is still lower compared to anisotropic magnetoresistance (AMR) sensors and sufficiently low for our application, which is precise compass.

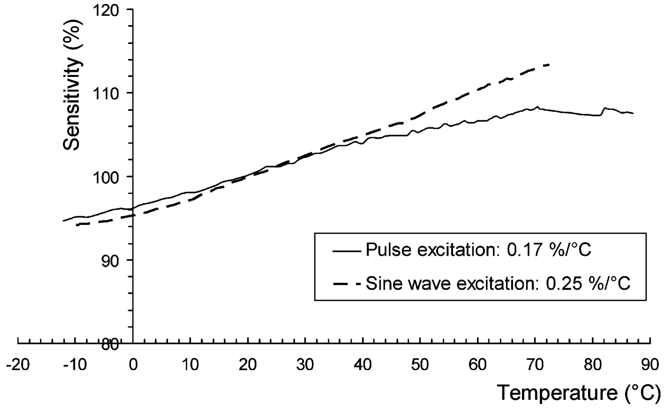

Fig. 8. Sensitivity temperature stability of pulse and sine wave excited PCB fluxgate sensor.

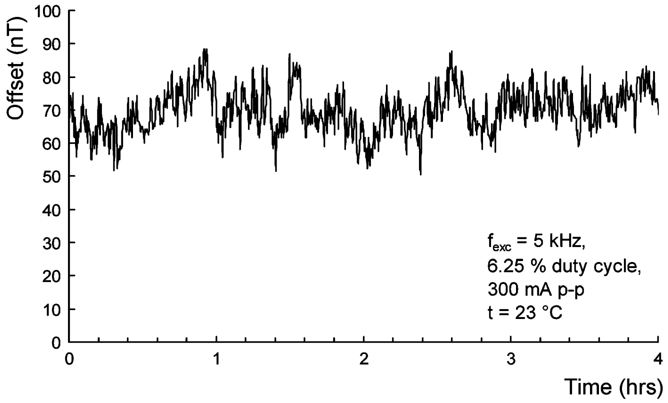

Fig. 9. Offset time stability of the pulse excited PCB fluxgate sensor offset.

E. Offset Short-Time Stability

The short-time stability of the sensor offset (or the ultra-low-frequency noise) was measured within 3 h by sampling the sensor output every 20 s. The p-p offset value remained within 38 nT range (Fig. 9) when using 5 kHz excitation current with 6.25% duty cycle and 300 mA p-p current. This value is significantly worse than 3.5 nT when using "B sine wave" excitation at 5 kHz [4] but still acceptable for many precise applications.

F. Perming

The perming effect (permanent offset change after the applied field shock disappears) was a great concern when "sine wave" excitation showed perming effect of $\sim 5\mu\mathrm{T}$ after a field shock of 10 mT. However, the pulse excitation mode fluxgate appeared to be more resistant to the field shocks: the 10 mT field shock caused only below 1.2 μT offset change when using 10 kHz, 300 mA p-p, 6.25% duty cycle excitation.

VI. CONCLUSIONS

The results clearly show that power consumption lower than 5 mW can be achieved even for 300 mA p-p excitation current (duty cycle $\mathrm{d} = 6.25\%$ or 12.5%, with frequency of either 5 or

10 kHz), whereas the "sine wave" excitation consumes ∼13 mW for 5 or 10 kHz excitation frequency for the same p-p current value. The bridge supply voltage is 0.76 V for 10 kHz, 6.25% duty cycle and 0.47 V for 10 kHz, 12.5% duty cycle, which is low enough for battery-operated devices. This would allow excitation of three serially connected orthogonal sensors using a single supply voltage.

The power efficiency of pulse excitation is even more increasing with increased current amplitude. For example, 500 mA p-p excitation current at 10 kHz requires 35 mW when using "B sine wave" excitation mode but only 6.2 mW when using pulse excitation with duty cycle 6.25%.

The power consumption of only 2 mW was achieved for 300 mA p-p excitation current with 6.25% duty cycle at 5 kHz with sensitivity of 36 V/T.

The offset temperature stability was within 120 nT and sensitivity tempco was 0.17% °C in the -20 to $+70\,^\circ\mathrm{C}$ temperature range. The sensor noise was 710 $\mathrm{pT_{rms}}/\sqrt{\mathrm{Hz}}$ at 1 Hz. The sensor offset short-time stability was 38 nT within 3 h. The sensor perming error substantially improved to $\sim 1.2\ \mu\mathrm{T}$ for 10 mT shock when pulse excitation was used.

Generally, the pulse excitation degraded the noise properties, temperature, and time stability of the sensor offset. However, the tempco of sensitivity was not affected by pulse excitation, and perming error was even four times decreased. Thus the developed sensor is more precise and less energy-consuming than a periodically flipped AMR sensor. The achieved parameters are sufficient for compass with 0.1° error.

We believe that more even distribution of excitation winding around all core length could further improve the perming error and noise due to better magnetization of the sensor core. This will be investigated in the next sensor prototype. Future research will also include investigation of alternative signal extraction method optimized for pulse excited sensor to decrease the noise values and increase the sensor offset stability.

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