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Flugate sensor with pulse feedback

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Fluxgate sensors have typically only 100 µT range, which sometimes limits their applications. Main obstacle for increasing the measurement range power dissipated in their feedback coil. Until now the feedback was always continuous. We suggest to use pulse excitation only for the active part of the period, in which output signal is present. In this paper we show for the first time that if the sensor is excited by short pulses, the feedback need not be continuous, but it can be formed by pulses slightly wider than the excitation pulses. We have shown that in our case the feedback current duty cycle can be only 17.25 %. This means that for the same power we can increase maximum feedback current and thus the range by the factor of three. We show that this can be done without compromising the sensor performance.

***Index Terms*—Fluxgate sensor, electric current sensor, magnetic sensor**

I. INTRODUCTION

FLUXGATE SENSORS measure small magnetic fields from 0.1 nT to 100 µT. Some applications such as current sensing [1,2] or non-destructive evaluation [3] require to extend this range while keeping the high sensitivity and resolution of fluxgate compared to other types of magnetic sensors [4]. It is generally known that if the sensor works without compensation it saturates in case that the measured DC external field is larger than the peak value of the AC excitation field. Thus the first way how to increase the sensor range is theoretically increasing the excitation field. The other possibility is to reduce the effective external field by increasing the demagnetization factor of the sensor core and/or by external magnetic shielding [5]. Another possibility is to use core material with higher saturation magnetization; this brought only 50% increase of the fluxgate range to 120 µT [6]. However in most cases the fluxgate sensors work in the compensated mode using magnetic feedback. The feedback strongly improves the sensor linearity and also stabilizes the open-loop sensitivity, which strongly depends on temperature. The magnetic feedback also increases the sensor linear range. The limiting factor here is the power needed for generation of the DC compensation current (important for battery powered devices) and often also the self-heating of the compensation coil (important for integrated fluxgates). While the power consumption is traditionally an important parameter for battery powered sensors, in our case the limitation was different: we were developing techniques for application in integrated fluxgates, in which the power should be limited to avoid sensor overheating.

In this paper we examine three approaches how to increase the measuring range of the fluxgate sensor and simultaneously keep the power consumption low. While increasing the excitation amplitude of the uncompensated sensor or biasing its excitation are traditional approaches, the third technique is new.

In this study we show for the first time that the compensation field need not to be present permanently. By using pulsed compensation we save power and allow further increase of the sensor range.

II. PULSE EXCITED RACETRACK FLUXGATE

We used PCB fluxgate described in [7] with 2-layer race-track amorphous core etched from Vitrovac 6025 foil of 25 µm thick. The core is 30 mm long and 8 mm wide, the track width is 1.8 mm. The 84 turns excitation coil was formed by PCB tracks and vias, therefore it has relatively large resistance of 1 Ω. Due to this the excitation amplitude cannot be increased by tuning with external parallel capacitor, as the quality factor of the excitation LC resonance circuit would be low [8]. The sensor was therefore excited by 1.16 µs 2.5 A_{p-p} pulses with repetitive frequency of 16 kHz, thus the excitation duty cycle was only 3.2%, which is half of the value used in [9]. Exciting the sensor by short pulses allows to use high excitation current peaks, which were shown to reduce perming effect and reduce the sensor noise similarly as excitation tuning which is routinely used for sensors wire-wound excitation winding [10]. Pulse excitation and processing by gated integrators is prospective for the design of integrated fluxgate sensors [11-14].

For the laboratory experiments we used NI PXIe-6124 multipurpose card and home-made H-bridge made of IRF7105 HEXFET transistors and ADuM1233 isolated MOSFET drivers. The excitation current waveforms were measured by Tektronix P6021 current probe. With this excitation the open-loop range was 200 µT. Fig. 1 shows the waveforms of the excitation current and output voltage for several values of the measured field. In order to understand the sensor operation we divided the pick-up coil and wound separate half on each of

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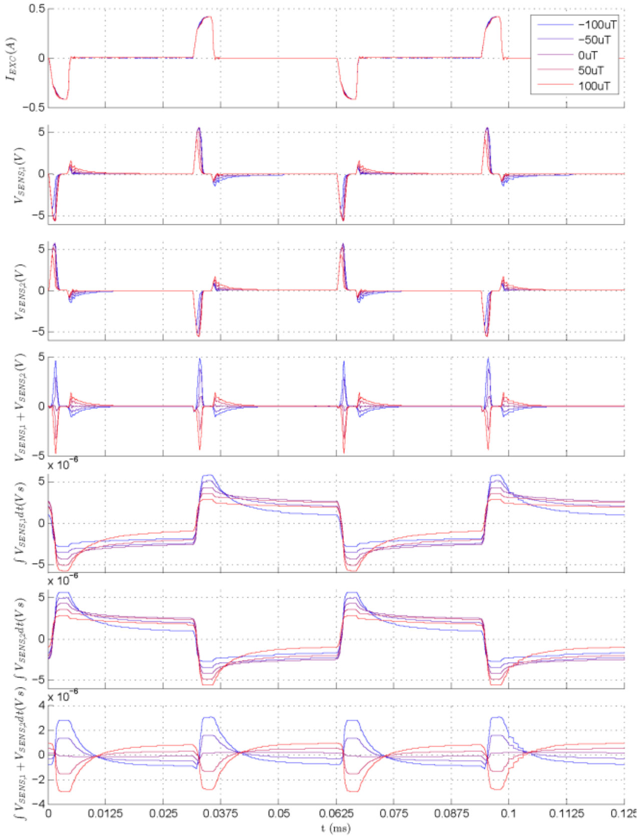

Fig. 1. Waveforms of the pulse excited racetrack fluxgate sensor. From the top: (a) excitation current, (b) and (c) voltages induced into individual pick-up coils wound around left and right track, (d) sum of b and c, i.e. voltage induced into the pickup coil around both tracks for five values of the external field, (e), (f) and (g): integral of (b),(c), (d), which is proportional to flux through the core halves and total flux.

the sensor tracks. By integration of the induced voltage we received waveforms of the flux in each track. By adding the two voltages induced into the individual arms we received voltage induced into the conventional pick-up coil which is wound around the whole core and by integration the total core flux as seen by this coil.

It is clear that the sensor response to the measured field is limited to short time interval and for the rest of the working cycle the sensors is inactive.

The sensor output was therefore processed by Signal Recovery 4161A box-car averager, which has integration window with adjustable width and delay.

Fig. 2 shows the sensor characteristics as a function of the excitation current amplitude for the constant pulse width of 25 %. While for the sine-wave or squarewave excited sensors one would expect that the field range strongly depends on the excitation level as was theoreticaly derived in [15], in this case the field value for maximum output is independent of the excitation amplitude. This shows that the existing fluxgate theory does not sufficiently describe operation under pulse excitation and it should be amended. However, by increasing the excitation level the linear range is clearly increasing.

Fig. 3 shows characteristics for the reducing the excitation width and simultaneously increasing the pulse amplitude. Again the benefit for increasing of the open-loop dynamic range is negligible.

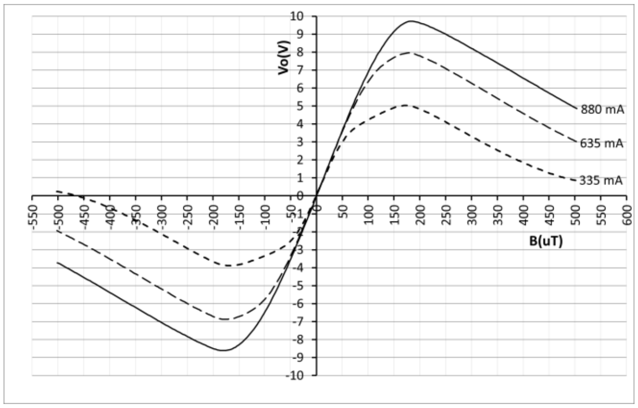

Fig. 2. Sensor characteristics as a function of excitation amplitude, constant pulse width

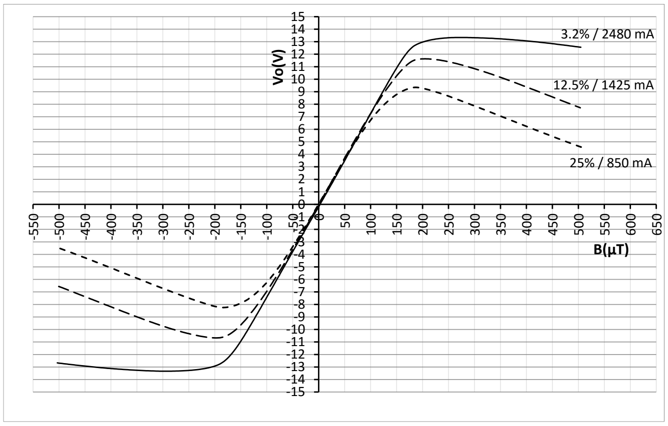

Fig. 3. Sensor characteristics as a function of pulse with and amplitude, constant rms power

With 70 mA max. DC compensation current into the pick-up coil the field range was increased to 0.5 mT.

III. BIASED EXCITATION

First idea was to extend the field range by adding DC component into the excitation winding as was already used in [14]. This should be made with proper polarity respecting the fact that the direction of the excitation field and sensed external field is different in each track of the core. The DC excitation current bias was therefore introduced by applying DC voltage to the middle point of the winding as shown in Fig. 4.

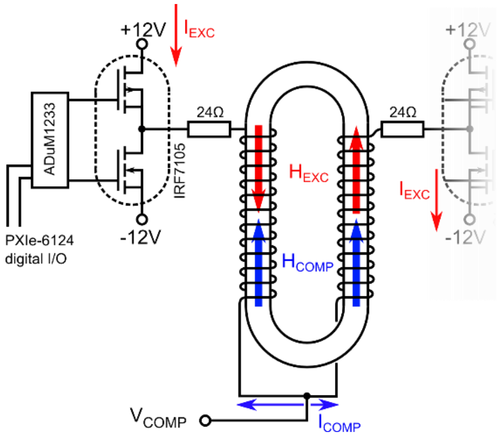

Fig. 4. Principle of excitation bias compensation technique. The right part of the electronics is shown only partly (shadowed), as it is mirror image of the left part.

As the number of turns is low and cross-sectional area of the PCB is technologically limited, this technique allowed for the field range only 15 µT. The resulting sensor characteristics is shown in Fig. 5. Poor linearity and a decrease in range clearly make this technique unfavorable. The reason is that the biasing pulses have exactly the same width as excitation pulses, which is too short. For satisfactory operation the biasing pulses should be significantly wider so that sensor is biased well before the excitation pulse appears. However, achieving this would require complicated circuit solution if it is possible to avoid short-circuiting of the switching transistors at all.

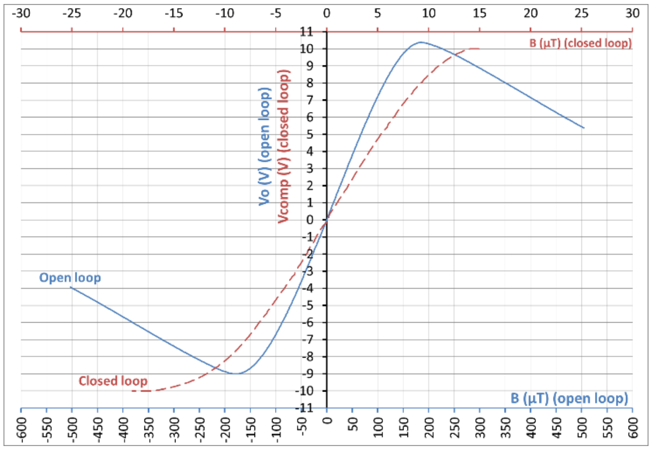

Fig. 5. Racetrack sensor with excitation bias. Notice different axes (top, red) for closed loop operation and open loop operation (bottom, blue)

IV. Pulse Feedback

It has been shown in the previous section that simple excitation biasing is not practical. Thus, standard compensation path through the sensing coil was used. The new idea here is that the sensor need not to be compensated continuously but only for wide enough time interval. As shown in Fig. 6 we used an FPGA module (NI PXI-7851R) to control the excitation bridge and, synchronously, the demodulation timing. Boxcar averager (4121B) is used to integrate pulses at the sense coil of the fluxgate proportional to measured field. It is believed that the compensation needs to be effective at the times the sensor is being excited and output signal processed. Therefore, we apply the compensation before the excitation pulse and keep it on as long as the integration window of the boxcar integrator is open. After this point, compensation no longer affects output of the boxcar averager and, consequently, it is not necessary.

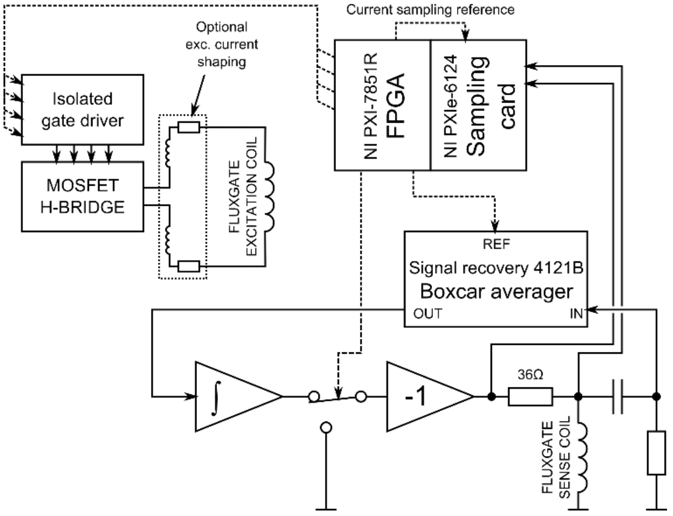

Fig. 6. Diagram of the experimental setup

Fig. 7a shows sensor characteristics for three values of the feedback duty factor and Fig. 7b shows the corresponding linearities. Small degradation of the linearity is acceptable for most application.

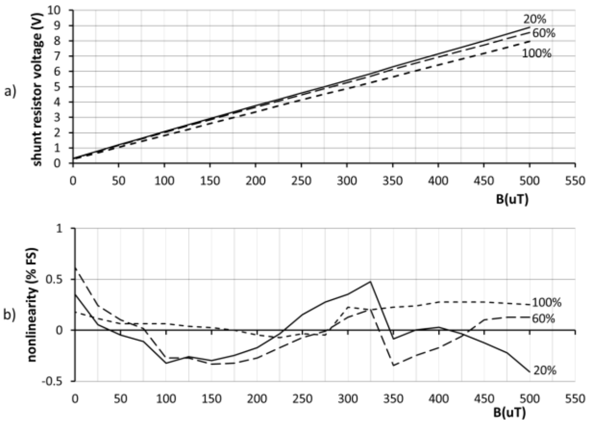

Fig. 7. Characteristics of the sensor with pulse feedback

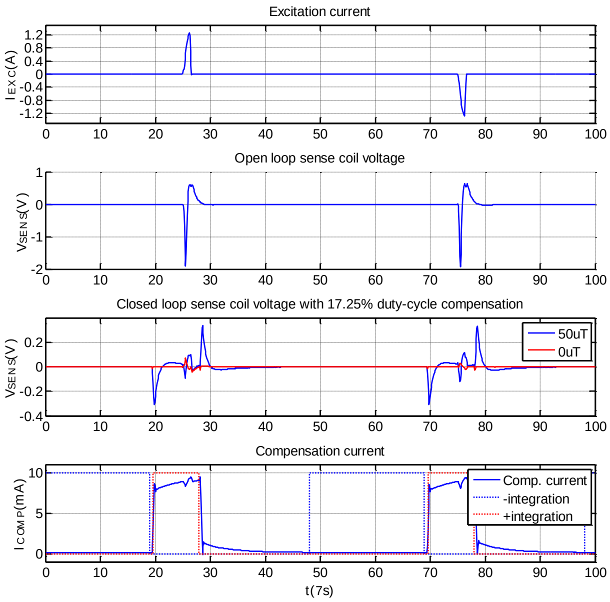

Fig. 8. Waveforms of excitation current, sense voltage and compensation current in our pulse-feedback magnetometer, compensation duty cycle 17.25%

Waveforms shown in Fig. 8 and noise depicted in Fig. 9 (summary in Tab. 1) were obtained with a setup, where boxcar averager was replaced by gated integrator made in-house. One unit was used for demodulation of sense coil voltage and one for sampling of compensation current. In noise measurements, output of a respective integrator unit was processed with Agilent 35670A spectrum analyzer. Excitation parameters for this experiment were changed to 10 kHz/2.5 App. The frequency was selected so that the period is as long as possible while maintaining acceptable open-loop noise of the magnetometer. Compensation duty cycle used was obtained by adjusting left and right edge of the compensation pulse to get a minimum RMS current. Further narrowing of the compensation pulse led to increase in pulse amplitude so that the power is no longer decreasing. Fig. 9 shows the sensor noise for open-loop operation, continuous feedback and pulse feedback. Noise of electronics measured in open loop mode with excitation switched off is one order of magnitude below the open loop noise. It is clear that switched operation does not affect the sensor noise if the phase is properly adjusted.

It should be noted that the sensor is operated with short excitation pulses, i.e. optimized for low power, not minimum noise. This minimum noise for the sensor of this type is 30 pT, when power is not limited.

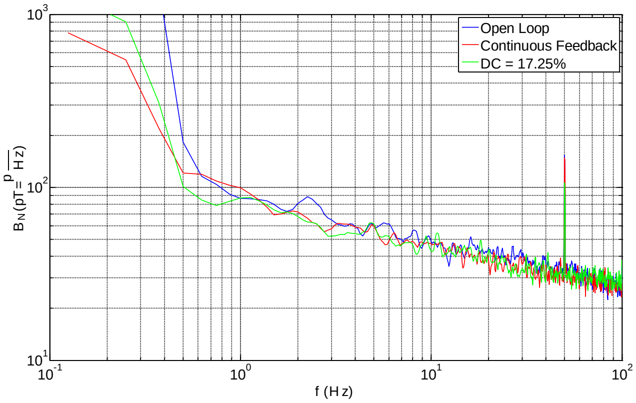

Fig. 9. Noise of the sensor with pulse feedback vs open loop and continuous compensation

Tab. 1. Comparison of pulse feedback and conventional modes of fluxgate operation

	Noise (pT/√Hz)		Comp. current RMS (mA)
	1 Hz	10 Hz	
Open loop	86	49	-
Closed loop (continuous feedback)	100	47	7
Closed loop (DC=17.25% feedback)	87	43	3.75

V. CONCLUSION

Theoretical concepts of extending the linear range by increasing the open-loop range of the fluxgate sensors or by the excitation bias are not effective.

However we have proved that the compensation current can be in the form of the square-wave with 17.25 % duty cycle without compromising the sensor performance. As most of the compensation power is dissipated in the resistance, it is proportional to I^2. It means that pulse feedback in this case allows to decrease the excitation power to one third or to increase sensor range 3-times. It is vital for the future development to investigate the mechanisms which prevent further shortening of the compensation pulse.

It is possible to further reduce power by keeping the width of the excitation pulse constant and reducing the repetitive frequency, which would allow to further reduce the compensation duty cycle. However, this leads to increase in noise. We should point out that this is not connected with change in sensitivity due to the process of signal processing which provides sensitivity independent of repetitive frequency.

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