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CROSSFIELD EFFECT IN COMMERCIAL FLUXGATE AND AMR SENSORS

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Crossfield effect often seriously limits the accuracy of magnetic sensors. However, this effect is only rarely discussed by sensor manufacturers and users. In the case of bulk fluxgates, crossfield error in the Earth's field can be suppressed by proper design below 3 nT p-p for the race-track and rod fluxgates and also for carefully designed ring-core sensors. Crossfield for miniature fluxgate can be significantly higher mainly due to imperfections in the geometry– for PCB fluxgate we measured 60 nT error.

In case of AMR crossfield sensitivity is inherent. Typical high-sensitive sensor has 1000 nT p-p error in the Earth's field. Feedback compensation of the measured field can effectively suppress this error. If feedback compensation is not possible, we suggest new methods for effective compensation of the crossfield sensitivity such as advanced processing of the flipped sensor output.

Keywords: fluxgate, AMR, crossfield

1 INTRODUCTION

Crossfield effect is unwanted sensitivity to field which is orthogonal to the sensing direction of magnetic sensor [1]. This effect is nonlinear and it is common to all magnetic sensors containing ferromagnetic material. It may cause serious errors of sensor systems, e.g. navigation devices or multichannel gradiometers for location and recognition of ferromagnetic objects. We discuss the origin of this effect and methods how to suppress or compensate it. We concentrate on fluxgate and AMR sensors as these are presently the only practical candidates for precise vectorial magnetometers for navigation, security, and military applications and for geophysics and space research [2].

In the case of fluxgates, which are the most precise vectorial magnetic sensors, crossfield error in the Earth's field can be suppressed by proper design below 15 nT p-p for ring-core sensors. We show that the crossfield error of the race-track and rod fluxgates is very low – without optimization the measured error was 3 nT p-p. We also show that similar results can be achieved for ring-core sensors designed for high homogeneity of the core.

In case of AMR the situation is more serious. Crossfield sensitivity in AMR is natural feature of these sensors. Typical high-sensitive sensor has 1000 nT p-p crossfield error and efforts to suppress this value by better design lead to degradation of the sensor's performance. The typical error patterns confirm our simplified theoretical explanation of crossfield mechanism. We also discuss new methods for effective compensation of the crossfield sensitivity such as advanced processing of the flipped sensor output.

2 CROSSFIELD IN FLUXGATE

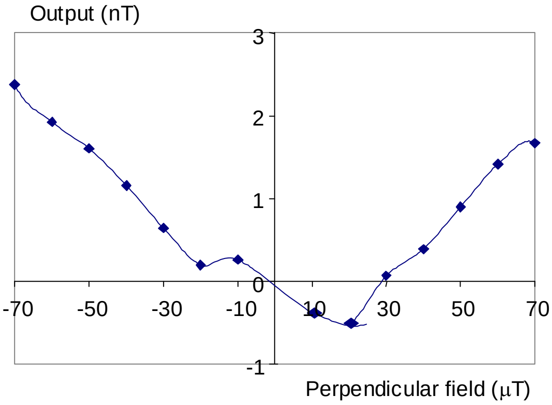

Fig. 1. Crossfield response of a Billingsley racetrack sensor, [12]

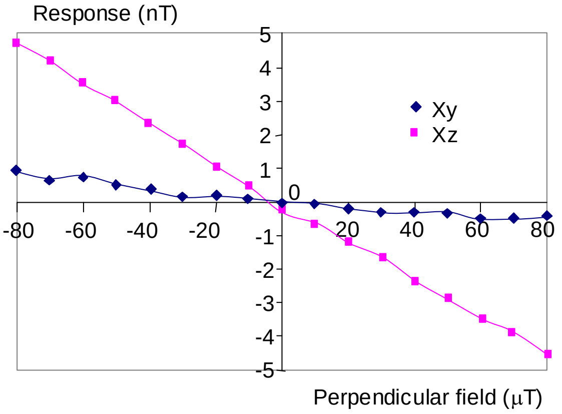

Fig. 2. Crossfield response of a Billingsley Billingsley rod sensor for two directions of the crossfield, [12]

The origin of crossfield in fluxgate was attributed to core non-homogeneity [3]. Crossfield error was shown to be a main source of 50 nT p-p non-linearity of legendary Magsat sensors. Later, it was reduced to 15 nT p-p for Oersted sensors and up to 5 nT p-p for Billingsley 3-axial sensor [4]. We found that crossfield is significantly lower for race-track (Fig. 1) and rod (Fig. 2) sensors due to their higher demagnetization factor, compared to ring-core sensors. We also found that fluxgate sensors remain sensitive to crossfield even when the measured field is zero.

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The fluxgate crossfield error measured for the feedback compensated ring-core sensor (Fig. 3) is very similar as for the sensors working in the open loop (Fig. 1 and Fig. 2). This is very different for AMR sensor.

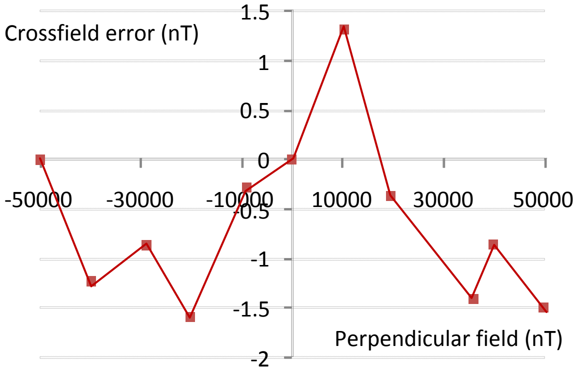

Fig. 3. Crossfield error of the feedback compensated ring-core Billingsley fluxgate sensor.

3 CROSSFIELD IN PCB FLUXGATE

Crossfield effect in PCB race-track sensors was found to be significantly higher: the observed crossfield sensitivity was 60 nT/20 µT (Fig. 4). We believe that this can be fully explained by geometrical imperfections of the pickup and compensating coils which have low number of turns [5]. In wire-core fluxgate sensors the crossfield effect can be very strong due to Matteucci effect – a 5% crossfield sensitivity was observed in [6]. However, some results presented in literature indicate, that high apparent crossfield sensitivity was mainly caused by bad adjustment of the sensor direction during the measurement [7].

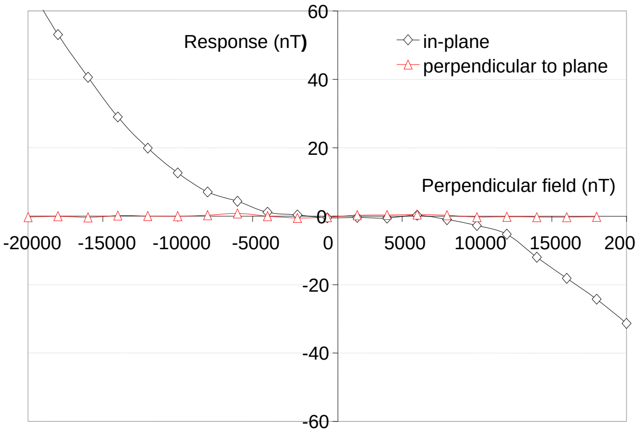

Fig. 4. Crossfield response of a PCB race-track fluxgate for two directions of the crossfield

It should be noted, that our measurements were made on feedback-compensated fluxgate sensors, as this is the typical working mode of fluxgate sensors. The power spent by compensation is small compared to excitation and also the circuit complexity makes no difference. On the other hand, AMR sensors consume much less power when they work without compensation and flipping. It is therefore desirable to investigate the AMR crossfield error in uncompensated mode and find power-efficient methods to reduce it.

4 SMALL CROSSFIELD IN AMR SENSORS

Crossfield effect in AMR is due to the anisotropic character of these devices. The simplified formula for output voltage V1 was derived in [8]:

$$V_1 \approx \frac{H_y}{H_x + H_0} \tag{1}$$

where H_y – is the measured field
H_x – is the crossfield
H_0 – is the effective anisotropy field

From (1) we clearly see the most effective way how to suppress the crossfield effect: cancel H_y by feedback compensation. This method is very effective even if the compensation field is non-homogenous, but cannot be always used as it requires power and slows-down the sensor response.

When the sensor is flipped, *ie* the magnetization of the ferromagnetic sensing strip is remagnetized into the opposite direction, the sensor characteristics is reversed

$$V_2 \approx \frac{H_y}{H_x - H_0} \tag{2}$$

Flipping the sensor and averaging the output readings V_1 and V_2 reduce the crossfield error approximately 10-times. The shape of the error response roughly follows the values predicted from the previous simplified equations (Fig. 5, and Fig. 6). This residual error may have serious consequences: Fig. 7a shows the calculated AMR compass error caused by crossfield: for 20 µT horizontal field the maximum azimuth error is 1 degree [9]. The calculation is in a good agreement with the measurement performed using non-magnetic theodolite (Fig. 7b).

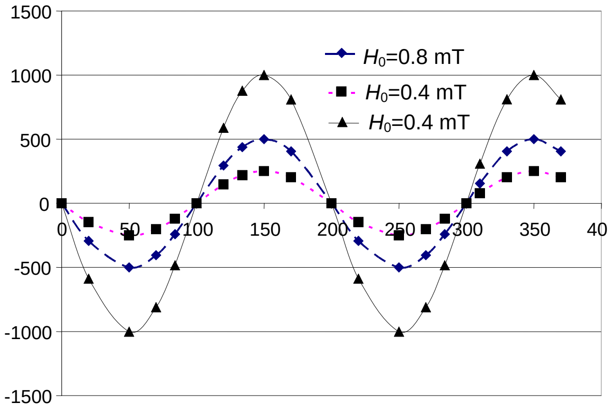

Fig. 5. The effect of H_0 on crossfield error. Simulated rotation in the field of 20 µT, [12]

More advanced methods of numerical compensation of the crossfield error in AMR sensors theoretically result in smaller errors [10]. These methods include separate processing of V_1 and V_2 and also correction methods for mul-

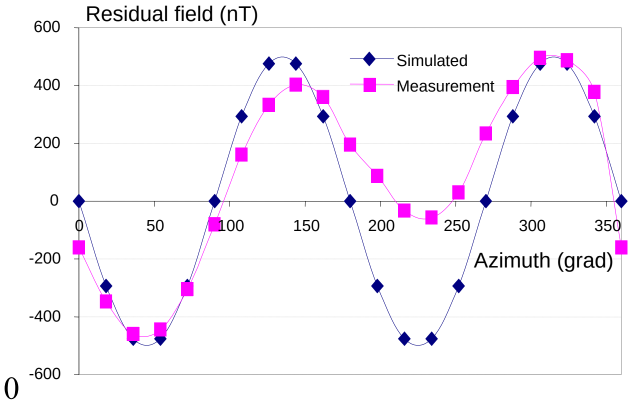

Fig. 6. Crossfield error of flipped HMC 1001 (rotated in 20 μT horizontal field): measured and simulated [12].

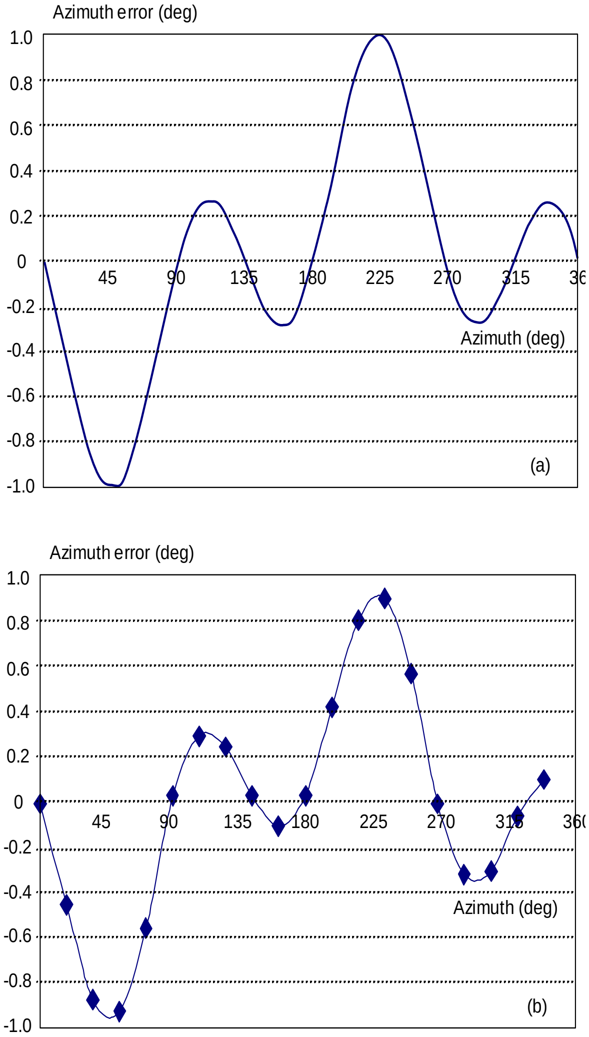

Fig. 7. Azimuth error of AMR compass caused by crossfield error, for unflipped HMC 1001, in central Europe: (a) - prediction from simulations [9], (b) - measured values, [12]

tisensory systems. However, the efficiency of these methods always depends on the accuracy of the used formulae: we can use simplified formula (1) only in case that the external field H is much smaller than the anisotropy field: $|H_x|$, $|H_y| << |H_0|$. A general requirement is also a single-domain state of the magnetic sensing element, which also remains only in the low-field region.

4 LARGE CROSSFIELD IN AMR SENSORS

When the AMR sensor is subjected to large magnetic field, the linear model presented in Part III is no longer valid.

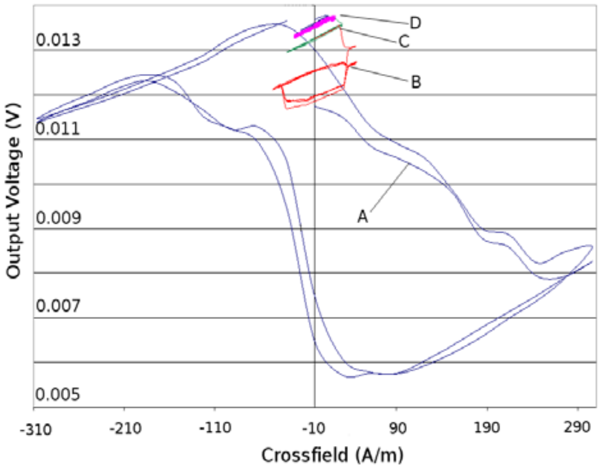

Fig. 8. Large field crossfield response of unflipped HMC 1001. Measured for the sensing field of 50 A/m. [12]

Large field crossfield response of unflipped HMC 1001 is shown in Fig. 8. The characteristics are measured for the sensing field of 50 A/m. After the sensor was magnetized by 300 A/m in crossfield direction (after cycle A), three measuring cycles were performed: cycle B for crossfield in ± 20 A/m range, cycle C for ± 30 A/m range and cycle D for ± 40 A/m range.

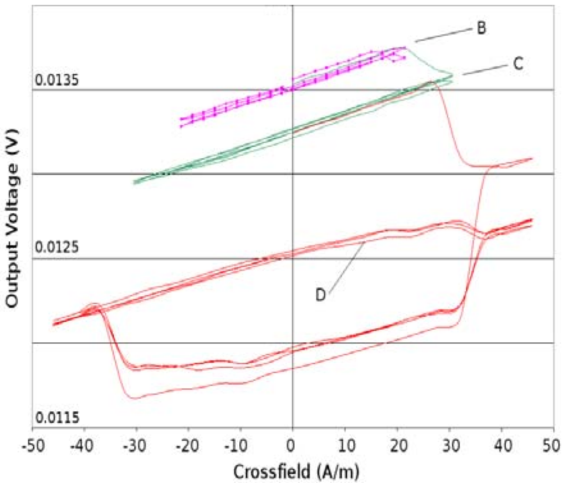

Fig. 9. Large field crossfield response of unflipped HMC 1001, for the sensing field of 50 A/m. The detail of the measuring cyc les. [12]

The detail of the measuring cycles is shown in Fig. 9. It is evident, that for the crossfield larger than 20 A/m the sensor magnetization is irreversibly changed, which means that the sensor is broken into several domains. This effect was described as dispersion of anisotropy in [11]. For the field of 50 A/m hysteresis in the crossfield characteristics clearly appears. This is in contradiction to the datasheet presented by the manufacturer, which claims that the sensor is safe to fields of 80 A/m. When proper flipping is employed, hysteresis disappears as shown in Fig. 10.

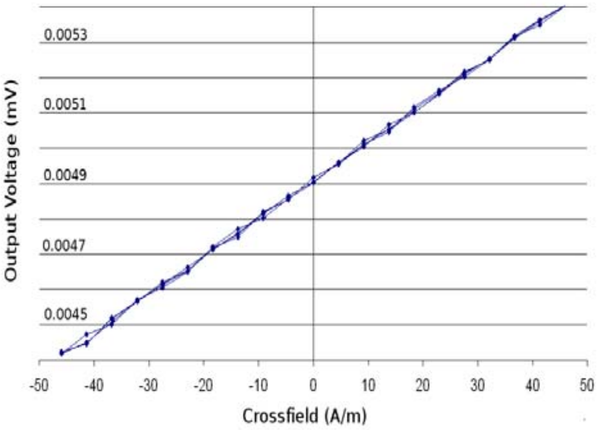

Fig. 10. Large field crossfield response of flipped HMC 1001. Measured for the sensing field of 50 A/m. [12]

5 CONCLUSIONS

The crossfield in classical fluxgate sensors is typically below 5 nT for the Vacquier and race-track sensors, and below 20 nT for ring-core sensors, all these values measured within the Earth's field range. For PCB and wire-core fluxgates the crossfield effect is more dramatic [6].

The situation for AMR sensors is more serious. These sensors are very sensitive to crossfield and even within the Earth's field range the sensor's magnetization can be irreversibly changed. We therefore do not recommend to use these sensors without periodical flipping. Although the flipping increases the power consumption, it defines the sensor magnetic state and makes the sensor offset independent to precious magnetic history. The most efficient technique to suppress crossfield error in AMR sensors is combining feedback compensation and flipping: Possible reduction or compensating schemes were theoretically discussed in [10], but still did not fully verified.

We believe that crossfield effect also exists in GMR and SDT sensors, but we are not aware of any study on this topic.

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