Crossfield effect at Fluxgate

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Abstract

The magnetic field transverse to the sensing axis may affect the performance of magnetic sensors. In the case of fluxgates, this effect is not as dramatic as it is for AMR sensors, but it still may cause errors up to 40 nT in the Earth's field. We performed measurements on voltage output fluxgate sensors of various constructions. Ring-cores are the most susceptible, showing around 10 nT error for 50 μT perpendicular field, while Vacquier-type (bar-core) sensors suppress the crossfield by their shape anisotropy. Racetrack fluxgates are the best candidates for crossfield resistant low-noise sensors.

Keywords

Magnetometer, fluxgate sensor, crossfield effect, linearity

Introduction

Most of the vector magnetic field sensors are sensitive to magnetic fields perpendicular to their sensing direction (”crossfields”). We do not consider the basic (stable) deviation of the sensing direction from the geometrical axis, which may easily be corrected. The crossfield effects may appear as the change of sensitivity, decrease of linearity, change of the offset and change of the sensing direction caused by a perpendicular field. The crossfield effect is dramatic in anisotropic magnetoresistors: large transverse fields in the sensor plane even cause "flipping" i.e. complete reversion of the response. This effect is nonlinear and at low field levels has a large hysteresis [1]. In general, the crossfield effect may be suppressed by shape anisotropy; or by total compensation of the measured field, not only the component in the sensing direction.

Crossfield The crossfield effects in much smaller scale wasere also observed on fluxgate sensors. This effect became one of the fluxgate mysteries as it is difficult to identify, and it may cause more than 10 nT error [2]. Primdahl analyzed calibration data from several fluxgate magnetometers and flight data from magnetometers on board of spinning rockets and satellites. His analysis indicated that crossfield effects cause a third harmonic component in the spinning magnetometer data stream. The large magnitude was the result of basic sensor non-linearity [3]. Brauer et al. made a theoretical analysis of current-output ring-core fluxgate sensor response to a perpendicular field [4]. They had shownshowed that a variation ofin magnetic susceptibility along the core may result in non-linear transverse field response. ; tThe shape of the derived curve well fittedfit the experimental data well. They also compared it with the calibration model derived by Acuna for the Magsat satellite magnetometer. It should be noted that the Magsat model was derived from the data measured on complete 3-axis magnetometer consisting of three orthogonally mounted single-axis sensors (each of them with its own compensation winding), while Brauer et al. measured on single sensor. This may explain why the linearity deviation from linearity oof the transverse response was 25 nT for the Magsat magnetometer and 8 nT for the Brauer sensor. We do not ascribe this discrepancy to the fact that Magsat sensor was working in the voltage-output mode, with a tuned pick-up coil and second-harmonic detection, while Brauer used current output and an all-even-harmonics detector. TWhile the Magsat data were collected by D.C. measurements atin a large non-magnetic testing facility, and Brauer et al. measured in a noisy laboratory environment.; they They used 1.25 Hz sinewave perpendicular field and extracted the response from the magnetometer output using the spectrum analyzer. We performed a similar experiment in the Dejvjice laboratory using lock-in amplifier and 120 cm Helmholtz coil.: uUnfortunately, we have founddetermined that the non-linearities caused by ferromagnetic parts of the building construction resulted in unacceptable errors.

It should be noted, that the total solution of the crossfield effect on three-iaxial magnetometers was suggested by Primdahl [5]: he used a spherical three-axials compensation coil system with three single-axis fluxgate sensors mounted inside. The sensors were therefore positioned in magnetic vacuum. However, in some cases (such as cost-sensitive or size-limited applications) this approach cannot be used.

We have concentrated onemphasized the conditions in which work where the sensors operate measuring in the presence of the Earth’s field. Our magnetometers always work in the feedback mode.

2. The tested sensors

a) #9 and #10: Ring-core sensors made by the Department of Measurement CTU. The sensor core consists of 8 rings of 18/22 mm diameter etched from 50µm Molybdenum79-permalloy [a].
b) Ring-core sensor manufactured by Billingsley Magnetics. 17 mm diameter, bobbin made of anodized aluminum, 3 wraps of 3 mm wide and 20 µm thick tape. Excitation coil: 220 turns, 0.2 mm dia. [b].
c) Pick-up coil length 15 mm, 1500 turns.
d) Race-track sensor made by Billingsley Magnetics. Core length 2.67 cm,
e) Vacquier-type sensor made by Billingsley Magnetics. Core length 2.34 cm
f) Triheree-axial sensing head made of sensors type a
g) Triheree-axial sensing head made of sensors type b

All tested Billingsley sensor cores are made of pre-anealled amorphous 2714A Mmetglas alloy tape.

The symbols and terms used

H ... direction of the horizontal component of the Earth’s field
h ...horizontal direction perpendicular to H
Z ... vertical direction
Ba... magnetic field component in the sensor sensitivity direction
Bp ... crossfield perpendicular to Ba in the plane of ring (“perpendicular” direction)
Bt ... crossfield in the ring axis (“transverse” direction)

The testing sites:

a) Brookeville: magnetic testing facility of Billingsley Magnetics [c]. The system uses a "closed loop" stable triaxial fluxgate magnetometer to reject outside homogenous field changes such as the variations of Earth's field to levels below 1 nT. The system is calibrated periodically against thea Proton magnetometer standard. Field changes are generated by (3) Electronic Development Corp. model 520 current sources that bias the control magnetometer (coils wrapped tightly around each sensor) to generate offset fields which are then cancelled by the control amplifiers feeding currents to the overall 2.2 m triaxial Helmholtz coil system.
b) Pruhonice: magnetic testing facility of Institute of Geophysics, Czech Acad. Sci. Close to Prague, Czech Republic. 3 m square coil system similar to the one described in [4], magnetically clean building in a magnetically quiet location. Stable current sources for compensation of the Earth’s field, but no active compensations of field variations. Precise current steps generated by Fluke 5100 calibrator.
c) Dejvice: laboratory in the main building of the Faculty of Electrical Engineering, CTU Prague. 120 cm and 50 cm diameter Helmholtz coils. Thermostatted room, but lot of with considerable interference caused byalso in gradient and iron parts of the building construction.

In aAll of our measurements of the magnetometer outputs were monitored by HP 34401 voltmeters. The measurements, which required very high resolution or which were performed in noisy conditions, were made repetitively and an average of 10 or 100 was calculated. The voltmeters were simultaneously triggered when necessary; for critical measurements the integration time was extended to 100 PLC (= 2 s).

4. Basic crossfield response

The basic cross-field effect is observed as a non-linear change of in a sensor output of the sensor whichthat is subjected to a perpendicular or transverse field. Fig. XX shows the values measured for Billingsley sensor head having 3 orthogonal sensors of type (b). The maximum error was 6 nT for perpendicular field up to 80 000 nT (the field in the sensing direction was zero). The same curve was measured for sensors #9, #10 is shown in Fig. XXb. If we When the subtract linear part of these plots are subtracted, as it was done for results shown by Brauer [a4], the curves look very similar up to 50 µT. For The deviation at higher crossfield values the deviation dramatically increases. We have no explanation for such behavior.

The crossfield effect may be understoodcould be described as a as the change ofin the sensor's sensing direction (usually measured as direction for zero sensitivity) with a crossfield applied. Fig. Xxc shows such measured alignment errors of this type for (a) and (b) sensors . While the perpendicular field caused a maximum alignment error of 0.025 °deg (sensor #9, 80 μT), the worst-case response to a transverse field worst-case response was only 0.003 deg°. These results prove that the expected behavior that the race-track sensor is much considerably more resistant to the perpendicular fields than the ring-core sensor. : iIt's maximum error was 0.004 deg°.

5. Sensitivity

In general, Wwe observed in generala decrease of thein sensitivity with crossfield. The may is could be understand the resultfrom the point of finite loop gain, non-homogeneous field ofin the compensation coil andor sensor nonlinearities. so that wWe feel believe that these factorsthat it maycould be present, even if the core was perfectly homogenous.

Fig. YY shows the sensitivity change for ring-core (a) sensors #9 and #10 and race-track (b) sensor as a function of the perpendicular field. We explain the high sensitivity change of the race-track sensor by the lack of a homogenous compensation field. fact that its The race-track's pick-up coil which covers only 70 % of the core length, is also used for the feedback., so the compensation field in the core location was nonhomogenous. The sensitivity change for the transverse field was below thelower than system resolution.

As a result, weWe therefore repeated this measurement on (a) sensors in Pruhonice laboratory. Three sensors were mounted in the same direction in order to suppress the influence of external fields. We observed sensitivity changes of 27, 28 and 30 ppm for individual sensors subjected to transverse field of 40 μT

6. Linearity

Fluxgate sensors are in general are very linear devices. It is believed that the linearity of 10 ppm may be achieved even in cases that where the pick-up coil is also used for the feedback. We feelbelieve that the measured non-linearity of the fluxgate magnetometers, which is typically 25 to 50 ppm, is mostlprimarily caused by the electronics. For example, the LT1028 operational amplifier, which is popular for fluxgate technology because of its low noise and high speed , has 0.02 % THD (total harmonic distortion) at 30 kHz and still 0.001% THD at very low frequencies (both with afor the gain of 1000) [k]. Other sources of non-linearity are the detectors (which behave non-linearly during the switching period) and A/D converters.

We have tested the race-track sensor linearity in the presence of transverse and perpendicular fields. The measurements performed in the Brookeville laboratory had sshowedn that the linearity error curve (Fig. ZZ) changes with crossfield, but in general the overall linearity error remainedis still 30 ppm FS (except the case of 80 μT crossfield, where the error was 40 ppm).

Additional Another tests were performed on sensor head consisting of 3 fluxgate sensors made of etched rings.: The response in sensing direction, to field steps of 10 000 nT in sensing direction was measured while changing the perpendicular field from 0 to +/-25 000 nT. The magnetometer output was monitored by 3 simultaneously triggered HP 34401 voltmeters, while another voltmeter monitored the coil resistance stability by measuring voltage drop by constant current. The sensitivity was calculated as an average of 100 current steps of both polarities to suppress the variations caused by AC interference and DC field variations. The sensitivity changes were maximally 50 ppm (0.5 nT) for perpendicular fields in the plane of the rings and 20 ppm (0.2 nT) with the transverse field (perpendicular to thise plane of the rings). The sensitivity results between large perpendicular field variations were very irreproducibleunrepeatable. The relative sensitivity of, while with stable perpendicular fields the relative sensitivity was measured with 2 ppm with short-term stability.

Stability and temperature effects

We have studied the short-time stability and temperature dependence of the crossfield response of ring-core (a) sensors in the Pruhonice laboratory. The measured results indicated that the time stability at constant temperature is very good (the stability for 20 μT perpendicular field was 2.5 ppm/hour, while for 40 μT transverse field we observed a linear drift of 1 ppm/min). No significant change ofin the crossfield response was observed after mechanical and magnetic shocks. The temperature variations caused changes ofin the crossfield response as high as 40 nT/ 20°C. In most cases, we observed a strong response to rapidfast temperature changes. which indicates A pthat the possible source of the variation warase the internal stresses in the sensor structure. These stresses can be caused by temperature gradients and/or different temperature dilatation of used materials leading to shape distortion.

Conclusions

In principal, Tthe crossfield effect is in principle very low at in sensors having large shape anisotropy such as Vacquier-Foerster design [d]. The temperature stability of the zero offset is very comparable to ring-core sensors. However, these sensors have other limiting parameters characteristics, such as higher noise level and they require more drive power. and temperature stability of the offset worse than the ring-core sensors.

In general, our measurements on ring sensors confirmed the Brauer's description [a4], which was derived for a current-output sensor and which assumes nonhomogenous susceptibility of the core. We did not observed a substantial improvement ofin the crossfield response withat etched rings over the cores made of wound tape.: tThis indicates that the role of tape ends is not asso important as we expectedpreviously thought.

We will concentrate on further development of race-track sensors.: tThey are the most difficult to manufacture, and their feedthrough cannot be easily suppressed as in the case of ring or rod sensors., but t They have the are best potentially for both crossfield resistancet and low-noise. Our studies indicatedWe found that it will be necessary to use a separate feedback winding which is longer than the core.

Acknowledgments

This work is partly supported by the Grant Agency of The Czech Republic, grant No. 102/96/1251

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Figure captions

Fig. 1

Fig. 2

Fig. 3