On the dependence of even harmonics with excitation currents in fluxgate magnetometers

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Abstract

In fluxgate magnetometers, the external magnetic field is generally measured by the second harmonic induced voltage of the pick–up coil. However, if the excitation waveform is not symmetrical, due to a DC component in the waveform from the excitation circuit or from a strong external magnetic field, the amplitudes of the following higher order even harmonics (4th, 6th, 8th, ...) can become larger than the 2nd harmonic. In this case, it is not the 2nd but the higher order harmonics that turn out to be more sensitive, depending on the operational place in the hysteresis loop. Yet, the best sensitivity of the sensor is obtained in a region of the hysteresis curve where the 2nd harmonic component predominates. Since this region depends on the amplitude of the excitation, it is necessary to calibrate the excitation amplitude in order to get the highest 2nd harmonic amplitude. When the amplitude of the excitation current is changed, the best operational place in the loop also changes. Depending on how much it is changed, the magnetometer will operate below its optimal sensibility. The same behavior is observed when the core is changed and tests should be carried out to verify how much the core has been saturated so that the amplitude and the frequency are adjusted for the magnetometer's best performance.

Introduction

A fluxgate magnetometer is a solid state device composed of a sensor connected to a processing electronic system. The sensor has a core of soft ferromagnetic material and basically has an excitation and a pick-up coil (Figure 1). It is used to measure DC and low frequency AC magnetic fields for several applications. The fields are measured from the second harmonic induced voltage in the pick-up coil (Ripka, 1992). Nevertheless, studies based on computer simulations have found that the fourth harmonic could provide greater sensitivity than the second harmonic, mainly at weaker fields (Cruz and Trujillo, 1999). Because at the low latitudes over Brazil the geomagnetic field has smaller values, it was decided to investigate the relationship between the even harmonics and the amplitude and frequency of the excitation currents to verify the above results.

To accomplish this objective, a computer simulation of a fluxgate circuit was applied for situations in which the higher-order even harmonics components of the induced voltage could attain larger amplitudes than the 2nd harmonic component, even in fluxgate magnetometers with feedback. The simulations were done with the computer program PSPICE (Microsim Corporation, 1992). Studies that use software simulations to evaluate magnetometer performance are very common (Moldovanu et al., 1996, 1997; Trujillo et al., 1999; Salceanu et al., 2000).

The same experiment was also carried out with a three-axis fluxgate magnetometer of high quality, that was constructed at INPE for space flights (Kabata, 2000).

Computer Simulations

Circuit models, like the one shown in Figure 1, are used to generate the excitation currents (Acuña, 1974), but they depend on the output transistors behavior of (V1) to generate a non-symmetrical wave.

Even when using a good excitation source to obtain a well-behaved current waveform, as observed in Figure 2, the difference between the rising time and fall time and the distinct saturation levels in positive and negative peaks of the transistors output, the signal becomes non-symmetrical, and smaller even harmonic components appear in the pick-up coil, including zero field conditions.

In this simulation, the core is modeled using the Jiles-Atherton model (Jiles and Atherton, 1986) provided by a PSPICE computer program, which takes into account wall motions, including flexing and translation. We have used a simple transformer core (K3019PL-3C8) with 100 turns in the excitation and pick up windings.

As shown in Figure 3, the simulated circuit is a transformer core excited by a sinusoidal AC voltage source (V1) that provides the necessary current to saturate the core. Observations of the excitation current waveform are done at (R1) of Figure 3.

The output voltage sampled in the pick-up coil was analyzed with a Fast Fourier Transform (FFT) provided in the PSPICE program.

The DC voltage (V3) produces the non-symmetrical excitation waveform, making an excitation current with a DC value different from zero, like in real circuits, where different saturation levels of the transistor supply the non-symmetrical signal. This DC value can be due to the non-symmetrical excitation waveform or the external magnetic field in cores with non-compensation coil or with low compensation.

The transient analysis in PSPICE was run with print steps of 2ns and final time of 1.000.000 us. With this model, in a first test, the frequency was fixed at 10Hz, the excitation current was changed and the amplitude of the even harmonics was measured. The results are shown in Table 1. Hystereses curves were also plotted to show the saturation levels of the core.

Table 1 shows that when the excitation current increases, the 2nd harmonic amplitude follows the excitation, also increasing its value, until it reaches a maximum value. Then it starts to decrease as the excitation current continues going up. The other important thing to be observed is that all the other even harmonics have the same behavior. They start to increase until reaching a maximum value, and after that, they start to decrease, as shown in Figure 4. The maximum peak of each harmonic curve shifts to the right, at higher excitation amplitudes, but lower harmonic amplitude.

Such results indicate the occurrence of three groups in Table 1. In the first group (V1 smaller than 0.6 V), the 2nd harmonic amplitude is larger than the other even harmonics. In the second group (V1 from 0.7 to 1.0 V), is the 4th harmonic amplitude that is larger than the other even harmonics. In the last group (V1 larger than 2.0 V), the 6th harmonic amplitude is larger than the others even harmonics, and so on.

In each of the above situation, it was observed that the hysteresis curve, and the amplitude of the even harmonics depend on how much the core was saturated. In figure 5 it can be noticed in the hysteresis loop that the B x H curve is saturated but not deeply saturated, since there is a small gap. In this range, the 2^{nd} harmonic amplitude is larger than the other harmonics.

The hysteresis curve of Figure 6 shows that the core is strongly saturated, and under this condition, Table 1 shows that the 8th harmonic has the largest amplitude of all the results in this experiment.

Tests with a fluxgate magnetometer

A three-axis fluxgate magnetometer, constructed at INPE to collect data of the terrestrial magnetic field for geophysical studies (Kabata et al., 2003), was also used for the tests. This magnetometer is a second-harmonic sensor with a ring core made of high permeability material, 6-81 molybdenum permalloy, similar to the MAGSAT magnetometer. The excitation frequency is about 8.0 kHz. Its real excitation current waveform is shown in Figure 2.

The magnetometer was placed in a three layer u-metal shield with a magnetic field of 1000nT parallel to the x-axis. The output voltage of x-coil of the detector was sampled at a rate of 90kHz. The collected data was processed with a FFT in order to get the harmonic amplitudes. The results are plotted in Figure 7.

Discussions

The tests with the INPE’s magnetometer confirmed the results indicated by the computer simulation in which the changes in the excitation level produced even harmonics with distinct amplitudes, and the optimal excitation current at which the 2nd harmonic response on the detector coil is the largest, depending on the level of the excitation current. Thus, the magnetometer should be calibrated at this level of excitation current. Otherwise, the magnetometer will be operated in a condition where other even harmonics might have larger amplitudes than the 2nd harmonic.

In fluxgate magnetometers, both the non-symmetrical excitation and the external magnetic field can provide an asymmetrical hysteresis curve. As a result, depending on the amplitude and the frequency of the excitation current, the magnetometer will be working under conditions that either the 4th, 6th or other higher harmonics will have a larger amplitude than the 2nd harmonic in the pick up coil. In this situation, the magnetometer should be adjusted so that the amplitude of the 2nd harmonic becomes larger than all other even harmonics.

Even when using a good excitation source and a good current waveform, the difference between the rising time and fall time and different saturation levels in positive and negative peaks of the transistors output of the excitation circuit, it is possible to have non-symmetrical signals. In this case, small even harmonic components appear in the pick-up coil, including zero field conditions.

Conclusions

From the computer simulation, and confirmed by the magnetometer experiment, the following conclusions were reached for the relationships between the even harmonics and the excitation currents:

(1) as the excitation current is increased, the core becomes more saturated and higher even harmonics amplitudes tend to be larger than the lower even harmonics;

(2) the condition where the 2nd harmonic has the largest value should be the goal of the magnetometer calibration;

(3) tests should be carried out in order to verify how saturated is the core and determine at which amplitude and frequency the magnetometer operates at its best;

(4) with the same amplitude excitation, as the frequency is increased, the core becomes less saturated and the effect will be opposite the one described in the first observation above; an increase in the excitation frequency should be accompanied by an increase in the excitation amplitude, in order to maintain the same operational optimal conditions;

(5) when the core is supersaturated, the magnetic signal might be shared with other higher even harmonics;.

Also, it is necessary to investigate the frequency variations of the excitation current, because the amplitude of the excitation current should be adjusted to each different frequency, a topic that will be treated in detail in another article.

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Table 1. Harmonic amplitude as a function of the sinusoidal AC voltage (V1) provided to generate the excitation current.

V1 (V)	2nd Harmonic (mV)	4th Harmonic (mV)	6th Harmonic (mV)	8th Harmonic (mV)	10th Harmonic (mV)
0,1	15,1	2,8	0,36	-	-
0,2	40,8	12,2	5,0	2,4	1,3
0,3	55,9	25,5	13,5	5,9	4,5
0,4	53,5	37,9	26,1	16,4	9,1
0,5	47,5	40,8	31,2	25,0	17,8
0,6	42,0	40,8	32,1	28,1	23,0
0,7	37,5	39,2	32,0	28,9	25,4
0,8	33,9	38,6	31,6	28,5	26,4
0,9	30,9	37,1	31,2	27,8	26,5
1,0	28,2	35,5	30,7	27,0	26,1
2,0	15,4	24,1	25,5	23,1	20,5
3,0	10,6	17,7	20,8	20,5	18,4
4,0	8,2	14,1	17,4	18,3	17,5
5,0	6,8	11,7	14,9	16,4	16,0

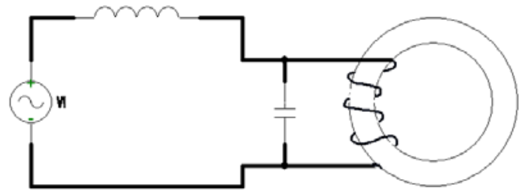

Figure 1. Circuit model used to generate the excitation current in a fluxgate magnetometer

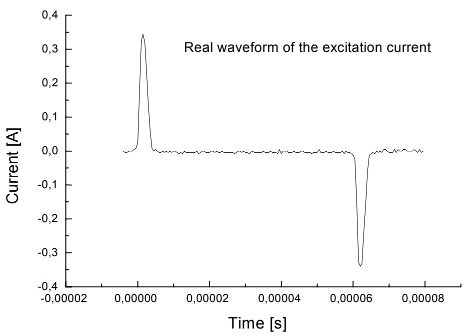

Figure 2. Well-behaved waveform generated by a good excitation source.

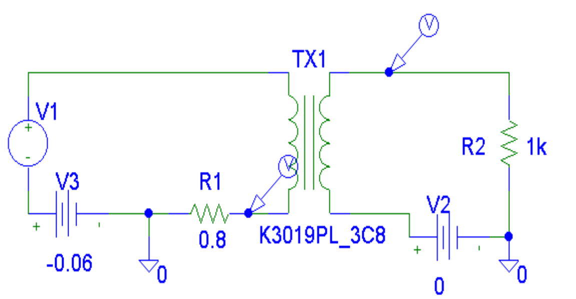

Figure 3. Simulated circuit used in the computer simulations of the excitation currents.

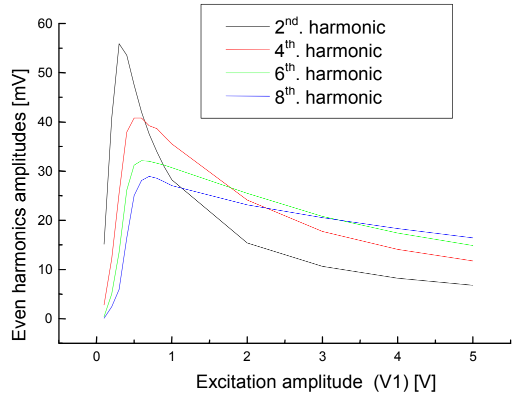

Figure 4. Amplitude variation of each harmonic using the data of Table 1.

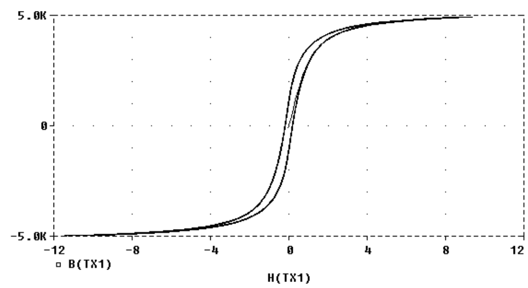

Figure 5: B-H curve for V1 = 0,6V and V3=-0,06V. Example of saturated core.

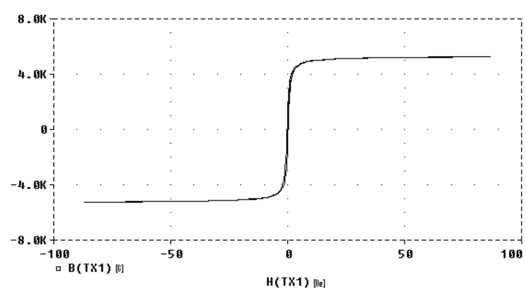

Figure 6: B-H curve for V1=5V and V3=0V. Example of strongly saturated core.

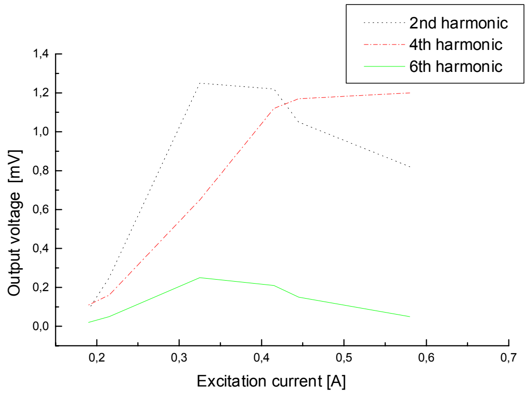

Figure 7. Variations of harmonic amplitude in a real magnetometer.