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TECHNICAL PROCEDURES TO SELECT BASIC PARAMETERS OF A FLUXGATE MAGNETOMETER

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ABSTRACT. In fluxgate magnetometers, the external magnetic field is generally measured from the second harmonic induced voltage in the pick-up coil. Thus, to improve the performance of a fluxgate magnetometer design, careful considerations should focus on some operational parameters and how to calibrate them to attain an optimal performance with a minimum intrinsic noise at the output. Basically, two main factors are considered: i) the output dependence on variations of the even harmonics amplitudes with the excitation current; and ii) adjustments for a perfect timely match between the core saturation and the time-width of the sampling. The best sensitivity of the magnetometer is obtained in a portion of the hysteresis curve where the 2nd harmonic component predominates. Since this region depends on the amplitude of the excitation, it becomes necessary to calibrate the excitation amplitude in order to get the highest 2nd harmonic amplitude in the pick-up coil. When the amplitude of the excitation current is modified, the amplitude of the even harmonics also changes, and consequently the magnetometer will operate below its optimal sensitivity, depending on how much the current has changed. Similar result is observed when the core is built with a different inductance (different number of wraps) which requires operational tests to be carried out to verify the level of the core saturation by adjusting the amplitude and the frequency to get the best performance from the magnetometer. Changes in the amplitudes of the excitation current generally occur with changes in the excitation current waveform, affecting the timing of the core saturation. To avoid bad synchronization between the excitation current and the sampling, the phase shift circuit is locked with the excitation current circuit in order to work together and variations on the excitation current phase is automatically corrected in the sampling circuit. In summary, finding the moment when the 2nd harmonic has its greatest value, adjusting the time-width of the synchronous detector and avoiding phase's shifts between excitation and detection circuits can produce a magnetometer performing at its lowest noise output.

Keywords: magnetometer, fluxgate, magnetic noise, *vitrovac*, computer simulations.

RESUMO. Nos magnetômetros tipo *fluxgate*, o campo magnético externo é geralmente medido utilizando-se da tensão do segundo harmônico induzido na bobina de detecção. Assim, para melhorar o desempenho de um magnetômetro *fluxgate*, deve-se observar com cuidado alguns parâmetros operacionais e o modo de calibrá-los, com o objetivo de colocá-los num ponto ótimo de operação. Basicamente dois fatores são considerados: i) a dependência das variações do segundo harmônico com a corrente de excitação; e ii) o ajuste perfeito entre a saturação do núcleo e a janela de amostragem. A melhor sensibilidade é obtida em uma porção da curva de histerese onde o segundo harmônico é predominante. Visto que essa região depende da amplitude da corrente de excitação, torna-se necessário calibrar esta amplitude para se obter a maior amplitude do segundo harmônico na bobina de detecção. Quando a amplitude da corrente de excitação é modificada, as amplitudes dos harmônicos pares também mudam e consequentemente o magnetômetro pode estar operando abaixo de seu ponto ótimo. Resultados similares são observados quando o núcleo é construído com diferentes indutâncias (diferentes em números de camadas) requerendo testes para verificar o nível de saturação e ajustes na amplitude da corrente de excitação para melhorar seu desempenho. Mudanças nas amplitudes da corrente de excitação geralmente provocam mudanças na sua forma de onda, afetando o tempo de saturação do núcleo. Para evitar uma sincronização errada entre a excitação e a amostragem, o circuito de correção de fase deve ser amarrado ao circuito de excitação, de modo a trabalharem juntos, e as variações de fase na corrente de excitação são automaticamente corrigidas no circuito de amostragem. Em resumo, encontrando o momento em que o segundo harmônico tem o seu maior valor, ajustando-se a janela do detector síncrono e evitando-se deslocamentos de fase entre os circuitos de excitação e detecção, obtém-se um magnetômetro que trabalha em seu melhor ponto de operação.

Palavras-chave: magnetômetro, *fluxgate*, ruído magnético, *vitrovac*, simulação.

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INTRODUCTION

The Earth's magnetic field permeating its solid part and geospace originates from electric currents, mainly associated with its dynamic metallic fluid outer-core, but also with the magnetosphere, ionosphere and oceans. A very small but important component of the geomagnetic field comes from magnetized rock material rich in iron oxides found in the crust, constrained by their Curie temperatures, and from currents flowing in lithospheric conductors. Thus, appropriate measurements of the Earth's magnetic field components, gathered at the ground, and on board land, sea, atmosphere and space vehicles, can provide a wealth of magnetic information to the present knowledge of the geospace and the interior of the Earth. Accurate measurements are usually conducted by fluxgate triaxial magnetometers to obtain directional components whereas the magnetic magnitude is commonly measured by other types of scalar magnetometers.

Research on ground-based fluxgate magnetometer has been conducted at INPE for several years to provide vector measurements of the magnetic field for regional studies of crustal magnetization (Kabata et al., 2004), and electrical currents flowing in the lithosphere and geospace (Vitorello et al., 2007), as well as in technological systems such as electrical power transmission lines (Trivedi et al., 2007).

Fluxgates are magnetometers with cores made up by materials possessing high magnetic permeability that can be easily saturated. Pulses of an excitation current are used to bring the core in and out of saturation causing a drastic reduction of the core permeability during the saturation time interval. Thus, the fluxgate operation is based on the time variation of the core permeability and the external natural magnetic signal is then measured with a sensor coil (pick-up coil) enclosing the first set made up by the core and the excitation coil.

Nowadays, many scientific researchers make their own cores using amorphous tapes (like *vitrovac*), and generally are confronted by some design options that will impact the performance of the magnetometer to be constructed. These options are, for instance, the possible number of tape wraps around the core, and so is need to find the best excitation current waveform to this new arrangement.

In this paper it will be discussed some technical aspects in the design of fluxgate magnetometers and the procedures used to obtain the basic parameters that can yield an improved fluxgate performing close to its optimal operational condition. To achieve this, the design should consider a careful planning, where all parameters of the project should conform to prior specifications, including the mechanics, electronics and details of cable assemblages. It also should have the necessary follow-up adjustments that provide the parameters under which the magnetometer can operate close to perfection.

To accomplish the objective of enhancing the knowledge about the operational behavior of any new sensor, a computer simulation of a simple fluxgate circuit is applied for situations in which the higher-order even harmonics components of the induced voltage would attain amplitudes larger than the ones obtained for the 2nd harmonic component, even in fluxgate magnetometers with feedback. The simulations are carried out with the computer program PSPICE (Microsim Corporation, 1992) also used in other articles (Moldovanu et al., 1996; Trujillo et al., 1999).

Finally, some prior tests have shown that changes in the excitation current amplitudes generally occur with changes in the excitation current waveform, affecting the timing of the core saturation. To investigate this effect, tests of excitation current amplitude variations were accompanied by corrections in the time-width of the sampling.

In order to perform the proposed tests, a set of three ring cores constructed with metallic glass ribbon and a special fluxgate magnetometer kit are used to facilitate the substitution of the different cores and introduce changes in the parameters, necessary for the tests. Measurements of the intrinsic noise are obtained under different excitation current values and under different widths of the sampling time, in order to get a 2nd harmonic signal with a lower noise.

COMPUTER SIMULATIONS OF AMPLITUDE VARIATIONS

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

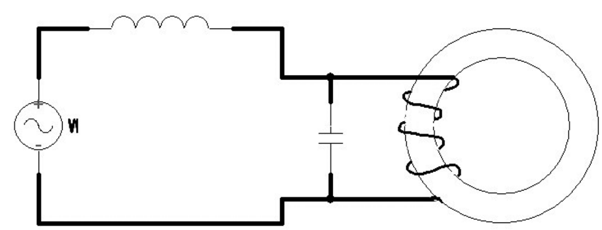

Figure 1 – Circuit model used to generate the excitation current in a fluxgate magnetometer with ring cores.

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. The former is related to the current excitation waveform that could be non-symmetrical, due to a DC component from the excitation circuit or from a strong external magnetic field.

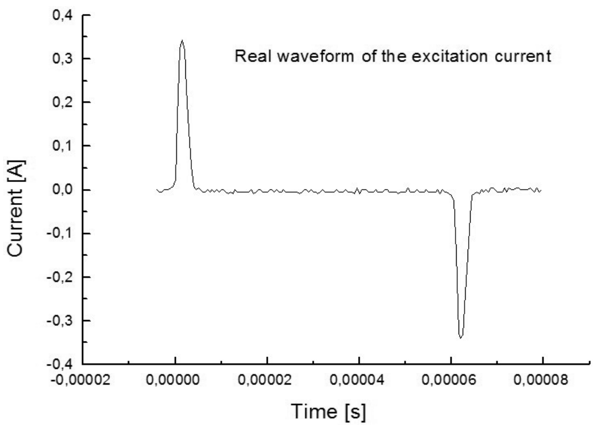

Figure 2 – Example of a well-behaved waveform generated by a good excitation source.

In this simulation, the core is modeled using the Jiles-Atherton model (Jiles & 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 made at (R1) of circuit in Figure 3.

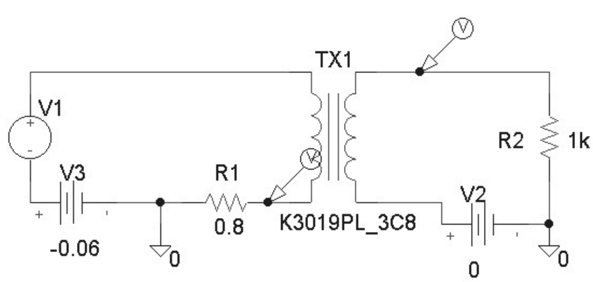

Figure 3 – Simulated circuit used in the computer simulations of the excitation currents.

The output voltage sampled in the pick-up coil is 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 is run with print steps of 2ns and final time of 1,000,000μs. With this model, in a first test, the frequency is fixed at 10 Hz, the excitation current is changed and the amplitude of the even harmonics is measured. The results are shown in Table 1. Hysteresis curves are 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 while the excitation current continues going up. It is noteworthy that all the other even harmonics have the same behavior, as shown in Figure 4. The amplitudes of every harmonics have a sharp increase until reaching a maximum value, after which they start a slow decrease. However, the maximum peak of each higher harmonic curve shifts to the right, at higher excitation amplitude, but at lower harmonic amplitude.

Based on the results presented in Table 1, it is possible to define the occurrence of three groups: i) in the first group, where V1 is smaller than 0.6 V, the 2nd harmonic amplitude is larger than the other even harmonics; ii) in the second group, where V1 varies from 0.7 to 1.0 V, it is the 4th harmonic amplitude that is larger than the other even harmonics; iii) in the last group, where V1 is larger than 2.0 V, the 6th harmonic amplitude is the one larger than the other even harmonics. At higher voltages, similar results are expected for the other higher even harmonics.

In each of the above situation, it is observed that the hysteresis curve and the amplitude of the even harmonics depend on how much the core is saturated. It can be noticed in the hysteresis loop shown in Figure 5 that the B$\times$H curve is saturated but not deeply saturated, since a small gap is present in the curve. In this range, the 2nd harmonic amplitude is larger than the other harmonics.

The hysteresis curve of Figure 6 shows an example of a strongly saturated core. Under this condition, Table 1 shows that the 8th harmonic is the one that has the largest amplitude compared with others harmonics.

TESTS WITH A REAL FLUXGATE MAGNETOMETER

A three-axis fluxgate magnetometer, constructed at INPE to collect data of the terrestrial magnetic field for geophysical studies (Kabata et al., 2004), is 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 9.5 kHz.

Table 1 – Harmonic amplitudes as a function of the sinusoidal AC voltage source (V1) generating the excitation current, in mV.

V1 (V)	2^{nd} Harmonic (mV)	4^{th} Harmonic (mV)	6^{th} Harmonic (mV)	8^{th} Harmonic (mV)	10^{th} 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

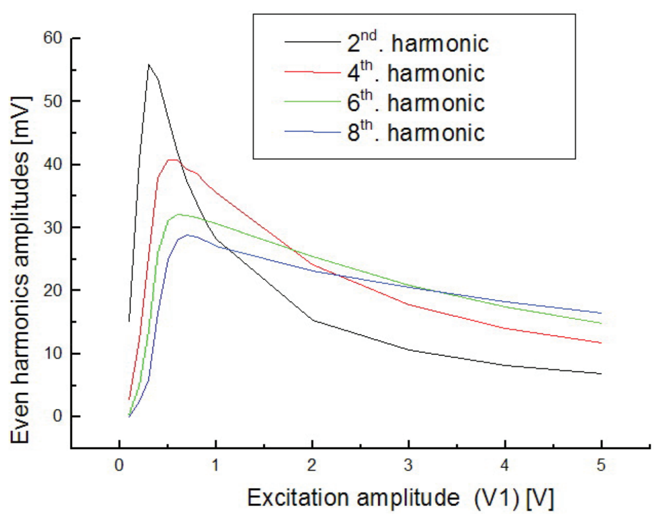

Figure 4 – Amplitude variation of each harmonic using the data of Table 1.

The magnetometer is placed in a three layer mu-metal shield with a magnetic field of 1000 nT parallel to the x axis. The output voltage of the x-coil of the detector is sampled at a rate of 180 kHz. The collected data is processed with a FFT in order to get the harmonic amplitudes. The resulting amplitude variations are plotted in Figure 7.

CHANGES IN THE SAMPLING TIME-WIDTH

High phase stability is desirable in fluxgate magnetometers for most magnetic applications. Phase shifts can occur due to the offset voltage in electronics, shifts in the synchronization of the core saturation and the sampling time, changes in the size of the sensor and in the feedback current in the pick-up coil. Generally, the circuits used in fluxgate magnetometers follow the general block diagram shown in Figure 8.

The stability of the synchronous detector to sample the magnetic signal at the exact optimal moment depends on several factors: i) the stability of the resonant circuit of the current excitation; ii) the phase shifter; iii) and the offset voltages of the operational amplifiers.

In this project (Fig. 9), the phase shift circuit is locked with the excitation circuit in order to synchronize the time of the magnetic sampling that follows the variations of the excitation current.

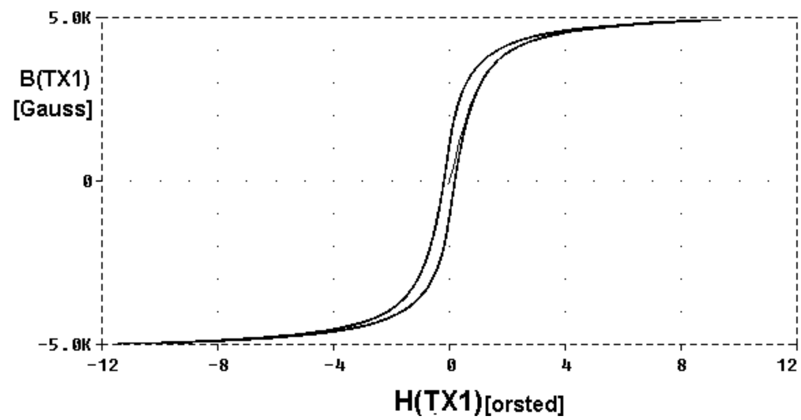

Figure 5 – Example of a hysteresis curve of a saturated core. B-H curve for V1 = 0.6V and V3 = –0.06V, according the circuit shown in Figure 3.

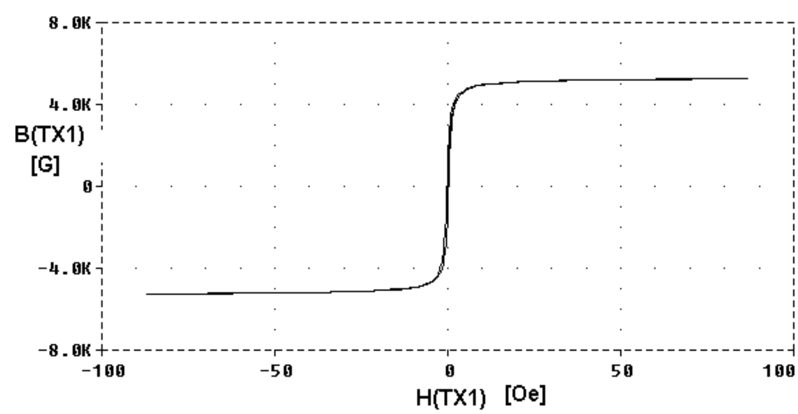

Figure 6 – Example of a strongly saturated core. Hysteresis B-H curve for V1 = 5V and V3 = –0.06V.

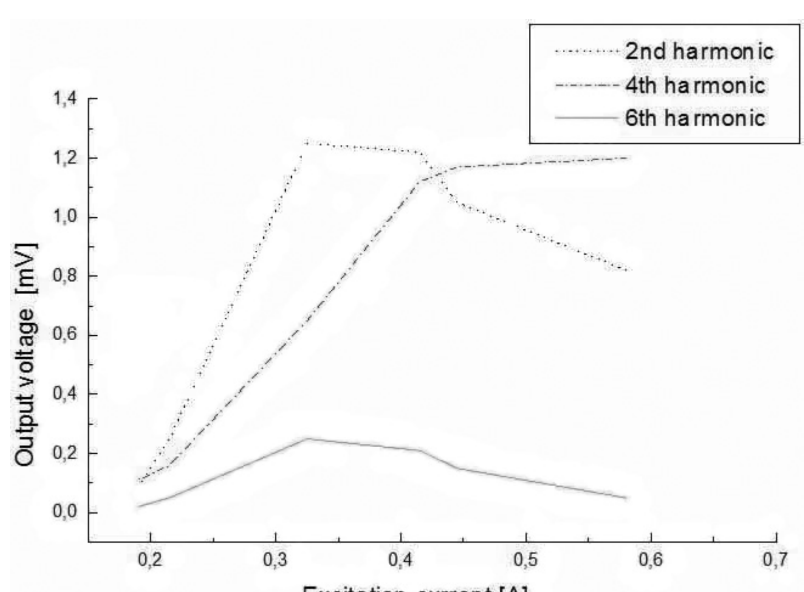

Figure 7 – Variations of harmonic amplitude of a real fluxgate magnetometer.

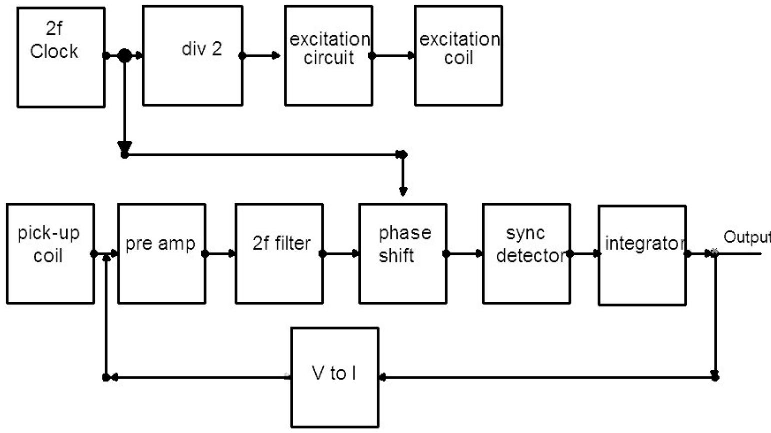

Figure 8 – General fluxgate block diagram: the excitation coil involves the highly permeable core; the external field is generally measured from the induced voltage in the pick-up coil, enclosing both the core and the excitation coil.

The detected time is delayed and has its width controlled and sent to the synchronous detector. Variations in the tank circuit components can change the saturation moment, but the locked circuit acts correcting the sampling time. This arrangement acts automatically and permits phase adjustments just once, whatever is the temperature (Kabata & Vitorello, 2007).

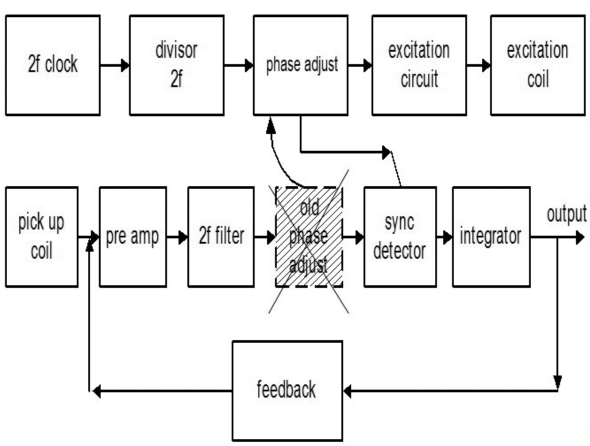

Figure 9 – Block diagram of the tested magnetometer in this study highlighting the phase circuit.

MAGNETIC NOISE RELATED TO CHANGES IN THE EXCITATION CURRENT AND SAMPLING TIME-WIDTHS

To make a comparative study of the intrinsic noise in fluxgate sensors, a set of three amorphous cores made of *vitrovac* 6025 was provided. These sensors are supplied with a ring core support wrapped with a metallic glass ribbon, about 0.02 mm^2 in cross section for each wound, and each sensor with 11, 20 and 40 wraps of the ribbon, respectively.

A kit of magnetometer is provided in order to facilitate changes in the amplitudes of the excitation current, tuning, phase shift and precise changes in the window of the sampling time. To measure the noise, the sensor is placed in a mu-metal three layer shield. The noise results are estimated with a power spectral density analysis of the sampled data (Snare & McPherron, 1973).

The study, carried out with magnetometers having cores with different number of turns, show the behavior of the magnetic noise when the excitation current and the width of the sampling pulse vary.

The kit of the magnetometer is controlled by the 4 MHz crystal oscillator which delivers, through a divider, 8 kHz square wave to the excitation circuit and 16 kHz to the detection circuit. The circuit also permits the tuning of the excitation current.

A phase and a width adjustment circuitry permit to change the phase and the width of the sampling window. The goal of this experiment is to estimate the correct phase and the best width of the sampling window in order to get the lowest magnetic noise. Tables 2, 3 and 4 show the variations in the measured noise with different excitation current amplitude in cores having 40, 20 and 11 wraps, respectively.

Table 2 – Noise measurements of a core having 40 wraps, sampling time-width of 16μs, and subjected to increasing excitation currents.

Excitation current [A]	Noise [pT]
0.106	38.9
0.149	17.9
0.253	11.6
0.298	26.5
0.383	39.3

The overall behavior of the detected noise, shown in the above tables, demonstrates that the noise decreases as the excitation current is increased to a point where this tendency is reversed and the noise starts to increase as the excitation current continues to increase.

Table 3 – Noise measurements of a core having 20 wraps, sampling time-width of 25μs, and subjected to increasing excitation currents.

Excitation current [A]	Noise [pT]
0.076	46
0.094	25
0.170	23
0.290	24
0.370	19
0.410	25

Table 4 – Noise measurements of a core having 11 wraps, sampling time-width of 15μs, and subjected to increasing excitation currents.

Excitation current [A]	Noise [pT]
0.10	57
0.17	39
0.23	21
0.27	17
0.30	25

Furthermore, as the current is increased, the width of the excitation current pulse becomes narrower and this fact reflects on the selection of the sampling time-width. To investigate the relation between the width of the excitation current pulse and the selected second harmonic sampling time-width of the synchronous detector, noise measurements are carried out in a core having 40 wraps and subjected to increasing excitation currents but variable sampling time-widths.

The results presented in Table 5 show that the level of noise decreases when there is a match between the sampling time-width and the width of the current excitation. Thus, a simple comparison between noise levels in magnetometers that are excited with different excitation current can mask the results due to the very different waveforms that the excitation current can take. As a consequence, large differences are observed between the time of the core saturation and the width of the sampling time.

RECOMMENDATIONS AND CONCLUSIONS

When the core is strongly saturated, the amplitudes of the subsequent higher order even harmonics (4^{th}, 6^{th}, 8^{th}...) can become greater than the 2^{nd} harmonic. In this case, it is not the 2^{nd} but the higher order even harmonics that turn out to be more sensitive, depending on their operational position in the hysteresis loop. Yet, as a consequence, the variations of the excitation current amplitude and the time-width of sampling require detailed investigations. The sampling time-width of the 2f signal in the synchronous detector is adjusted in order to match it with the time of the core saturation.

For instance, cores with a different number of turns of *vitrovac* 6025 show that a close match between the saturation time of the core and the window sampling the second harmonic in the synchronous demodulator produces a smaller noise than cores where such match does not occur.

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 conditions by which the 2^{nd} harmonic has its 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 with 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.

Tests show that there is a close relationship between the time-width of the excitation current and the window that sampling the second harmonic in the synchronous demodulator. The results show that there is a good point to find where the noise is smaller than anyone and this point is found if you sweep the time window of the synchronous demodulator with different width.

Table 5 – Magnetic noises (in pT) of a core having 40 wraps and subjected to increasing excitation currents (I in A) with various sampling time-widths (in μs).

I[A]	Sampling time-widths of the synchronous detector [μs]										
	11	12	13	14	15	16	17	18	19	20	21
0.106					54.5	38.9	20.9	18.9	14.7	15.4	29.2
0.149					25.0	17.9	11.6	11.0	14.1	15.0	
0.213			29.4	26.7	16.3	11.6	20.4	22.6			
0.298	35.3	28.6	25.6	28.7	37.1	26.5					
0.383	37.5	30.7	29.8	28.1	35.4	39.3					

Thus, there is a need to correct the time of sampling in the synchronous demodulator in order to match with the time that the excitation current saturates the core to obtain a smaller total noise.

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