LOW POWER PORTABLE DC MAGNETOMETER

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The paper describes a low-power consuming portable DC field magnetometer which employs a relatively new sensor. Saving of power is due on one hand to the selection of a thin ferromagnetic amorphous material for the sensor core. On the other hand, the fact that the sensor core excitation current consists of a square wave-form carrier whose amplitude modulation by another square wave permits an on- and off-operation, leads to economic utilization of power in the electronic circuitry. The magnetometer is operated by six cells type AA 1.5V connected to supply ± 4.5V. The power consumption is 60 mW, from this two thirds are supplied to the excitation coils of the sensor. The sensitivity of the magnetometer is 1nTs for a 0.2 Hz bandwidth. It seems that the sensitivity of the present magnetometer can be further increased to 0.1nTs with 1 Hz bandwidth by using sensors with relatively thin core of properly heat treated MuMetal or MolyPermalloy.

Introduction

A relatively new method for constructing low frequency magnetometers has been described recently [1]. Guidelines for analysis and design are also presented in reference [1]. The heart of the magnetometer is a sensor constructed of a thin ferromagnetic strap which serves as a core for a system of two excitation coils and one or two pick-up coils (Fig. 1). The excitation current in the cases studied so far is a sinusoidally amplitude modulated sinewave. A voltage signal at the relatively low modulation frequency would appear between the pick-up coils terminals if the core senses a DC external magnetic field along its axis. This phenomenon is caused by the odd nonlinearity of the magnetic characteristic of the material. The size of the low frequency pick-up signal is a measure for the intensity of the external magnetic field. The present paper deals with ways of selecting the magnetic core of the sensor and designing the electronic unit of the magnetometer in order to obtain a relatively compact instrument with low power consumption and of relatively light weight. The latter features are achieved without reducing the sensitivity of the instrument.

Design considerations

Decrease in the power consumption of the magnetometer was in the first place obtained by reducing the eddy-current losses in the sensor core, with an attempt not to affect the sensor performances. It was shown [1] that the transduction gain $T[V_{pp}/Oe]$ of the sensor itself depends on the ratio $2\delta_o/c$ (δ_o is the penetration depth of the magnetizing fields generated by the excitation coils, evaluated according to the carrier frequency, and c the thickness of the sensor core) and reaches a maximum for $2\delta o = c$. Furthermore, $\delta o = \sqrt{(Ho/\pi \, fo\sigma Bo)}$ (this evaluation assumes an ideally step characteristic of the core magnetization curve [2]) where H_o is the amplitude of the excitation magnetic field of carrier frequency f_o, B_o is the core magnetic induction at saturation, and σ is the electrical conductivity of the core material. Therefore, in order to obtain good results with regard to the transduction gain of the sensor but with the aid of small excitation currents, (a) the sensor core is a thin (0.04 mm thickness) strap of amorphous ferromagnetic material, and (b) the carrier frequency of the excitation current is only 2 KHz.

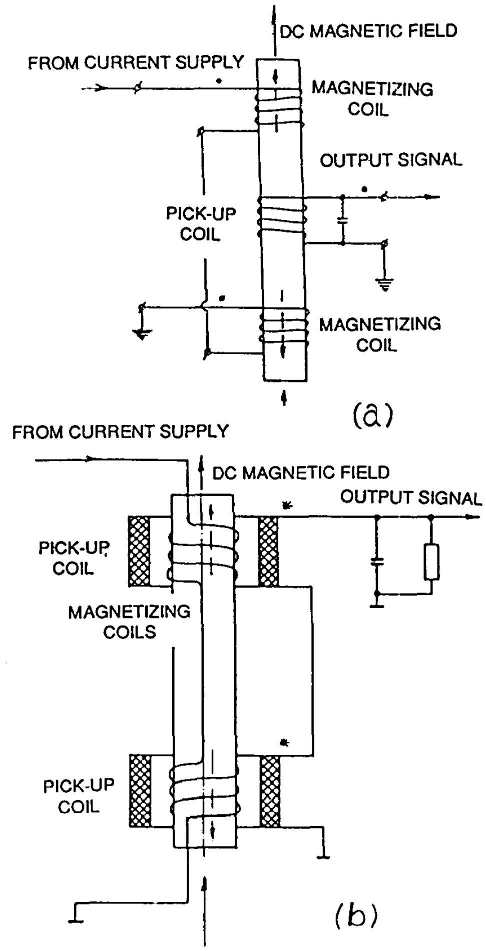

Fig. 1. Some practical configurations of the magnetometer sensor. (a) Transducer with only one pick-up coil. (b) Transducer with two pick-up coils.
<— — — — direction of high-frequency magnetizing fields.
< ———— direction of measured DC magnetic field.

The present magnetometer consists, apart from the sensor, of the electronic unit. The electronic unit which is operated by six cells type AA 1.5V connected in order to supply ± 4.5V, provides the amplitude modulated current to drive the sensor. At the same time, it processes the pick-up signal at the modulation frequency by employing a band pass preamplifier tuned to the modulation frequency, a variable phase shifter 45° - 135° and a synchronous detector. The synchronous detector itself consists of two units: a phase sensitive detector followed by an RC low pass filter. The simple design of the electronic circuitry (Fig. 2) also contributes towards saving of power. The carrier wave here is a rectangular one, and an efficient amplifier operating alternatively in cutoff and in saturation is employed to supply the excitation current. The rectangular carrier wave

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multivibrator (carrier oscillator) consists of three 1/4 CDB 4011 B quad two input COS/MOS NAND gates. The excitation amplifier consists of 1/4 LM324 low power quad operational amplifier. It was found that the performance of the magnetometer is improved if the frequencies of the carrier and the modulation wave which characterize the excitation current are synchronized. The lack of synchronization is a source of a small (equivalent to several nTs) disturbing signal at the output of the magnetometer. Moreover, the replacement of the sinusoidal modulation wave used in previous experiments [1] by a synchronized rectangular wave simplify the system further. The 100% amplitude modulation of the carrier [1] is obtained now in a simple way by an analog switch (modulator) connected across the input terminals of the excitation amplifier and driven by the rectangular modulation wave. The rectangular modulation wave of 250 Hz is actually obtained from the carrier wave by binary division. The binary division by eight, and a fixed phase shift of the rectangular modulation wave by 90° are obtained with the aid of two dual CD4013A flip-flops.

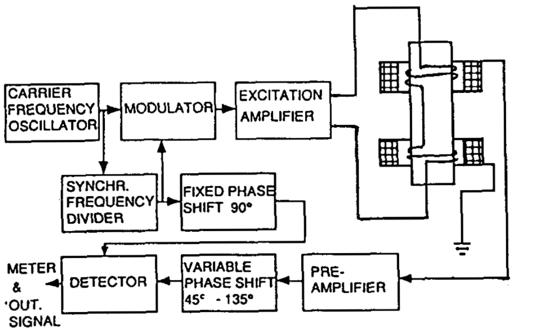

Fig. 2. Block diagram of the magnetometer.

It seems that a substantial reduction in power consumption can be obtained by correctly matching the

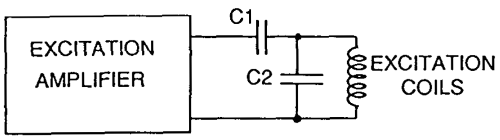

Fig. 3. The excitation system for the "trial and error" optimization procedure.

load of the excitation coils to the excitation amplifier. However, a theoretical analysis of the problems associated with their matching is relatively cumbersome: the sensor has a highly nonlinear ferromagnetic core, the single core-sensor is magnetized by two short excitation coils connected in a way that their magnetizing fields oppose one another, and eddy currents whose influence is beneficial for the sensor operation take part in the process. As a result, experimental measurements were performed and different variants of the excitation system were checked in a way that leads to optimizing the ratio between the transduction gain T[V_{pp}/Oe] of the sensor itself [1] and the DC current I[mA] supplied by the cells to the magnetometer. It is worth mentioning that it has also been observed that in the operating region, the signal to noise ratio is somewhat larger for larger values of transduction gain. Several matching methods were checked by experimenting with various connections of series and parallel capacitors and their combinations (Fig. 3). Furthermore, the amplifier was sometimes (type A circuits) connected directly to the network as if it were a voltage source. In other experiments (type B circuits) a series resistor was added to provide a current feedback (this current feedback does not assure an operation of the system as a strictly true current source, since the system operates in a quasi-switching mode). The experimental results are presented in the following section.

Experimental results

The sensor (Fig. 1a) used in experiments comprises a thin ferromagnetic amorphous strap of 240 mm length, 25 mm width, and 0.04 mm thickness. The samples were donated by Hirst Research Centre of GEC Research Ltd., U.K. According to our measurements, the electrical resistivity of the sample is 1.23×10^{-6} Ωm and its magnetic induction at saturation is 0.45 Ts. The two excitation coils of 30 mm length and respectively the two pick-up coils of 40 mm length and 3,000 turns each one, are placed around the core, with a distance of 120 mm between their centers. Several excitation coils of different turns numbers N were employed. Some experimental results are as follows:

a) Circuit type A; C1 is short-circuited, C2 is omitted.

N [turns]	I[mA]	T[V_{pp}/ Oe]	T/I[V_{pp}/Oe mA]
60	121	5.2	0.042
80	96.8	6.2	0.064
300	24.6	6.8	0.276

It is seen that the ratio T/I increases as the turns number N of the excitation coils is larger. However, the current value I for N = 300 turns changes with the change in the DC measured field value and the sensor indications are unstable.

b) Circuit type A; C1 is changed; C2 is omitted.

Circuit data	N [turns]	I [mA]	T [V_{pp}/Oe]	T/I [V_{pp}/Oe mA]
C1=0.9μF	60	13.8	4.0	0.29

The experiments performed with this circuit for N = 300 turns show that the current value I changes with the DC measured field value, and the sensor indications are unstable.

c) Circuit type A; C1 is changed; C2 is changed.

Circuit data	N [turns]	I [mA]	T [V_{pp}/Oe]	T/I [V_{pp}/Oe mA]
C1 = 11.5μF C2 = 1μF	60	10.7	6.2	0.58
Ca = 1μF C2 = 0.6μF	300	13.2	6.5	0.49

d) Circuit type B; C1 is short circuited, C2 is omitted; R is the current feedback resistor connected in series with the excitation system.

Circuit data	N [turns]	I [mA]	T [V_{pp}/Oe]	T/I [V_{pp}/Oe mA]
R = 57Ω	60	19.0	4.8	0.25
R = 57Ω	300	9.5	4.4	0.46

e) Circuit type B; C1 is changed; C2 is omitted; R as in case (d)

Circuit data	N [turns]	I [mA]	T [V_{pp}/Oe]	T/I [V_{pp}/Oe mA]
C1 = 2µF R = 57Ω	60	14.0	4.3	0.3
C1 = 0.4µF R = 33Ω	300	10.2	6.5	0.64

It is seen that the best result according to the ratio T/I was obtained in the case (e) with the excitation circuit type B, N = 300 turns, R = 33Ω, C = 0.4 µF: I = 10.2 mA; T = 6.5 V_{pp}/Oe; T/I = 0.64 V_{pp}/Oe mA.

However, our principal aim was to obtain a magnetometer with a good transduction gain but with as low as possible power consumption. As a result, the excitation system shown in Fig. 4 which permits the lowest power consumption and also a fair transduction gain was actually employed in the present magnetometer: circuit type B, N = 300 turns; R = 200 Ω; C1 = 1µF; I = 6.47 mA; T = 3.3 V_{pp}/Oe; T/I = 0.51 V_{pp}/Oe mA. Fig. 5 shows experimental results of low magnetic field measurement obtained by the present magnetometer. The time constant of the RC filtering circuit in the synchronous detector was 1 sec.

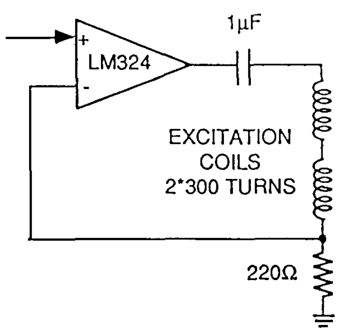

Fig. 4. The excitation system actually employed in the magnetometer.

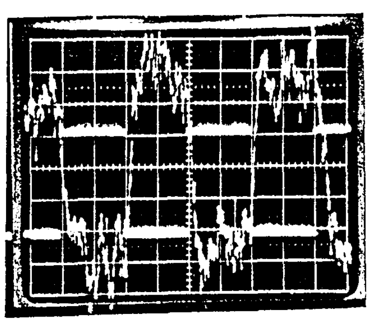

Fig. 5. Experimental results of low magnetic field measurements. Upper trace: output voltage of the magnetometer. X : 5 sec/div; Y: 2 mV/div. Lower trace: measured magnetic field. X: 5 sec/div; Y:3nT/div.

Conclusions

The paper describes the details and the design considerations of a relatively new magnetometer. The main aim of the development has been in constructing a portable instrument of relatively low-power consumption. This was obtained by employing simple commercial electronic modules. The power consumption is 60 mW; from this, two third are supplied to the excitation coils of the sensor. The sensor is connected to the electronic unit by a pair (one cable used for the sensor excitation, and the other for the pick-up signal) of four-meters BNC to BNC coaxial cables. It has been shown previously (Fig. 5) that the sensitivity of the present magnetometer is about 1 nTs for a bandwidth of approximately 0.2 Hz. Moreover it seems that the sensitivity can be further increased by using sensors with core of properly heat treated MuMetal or MolyPermalloy, in place of the present core of amorphous ferromagnetic material [1]. The sensitivity obtained in previous experiments with MuMetal or MolyPermalloy cores was indeed 0.1 nTs for a bandwidth of approximately 1 Hz. However, the main aim here is reduction of power consumption, which was assisted by using a very thin amorphous core; but then it appears that the magnetic characteristic of such a core does not permit a larger signal to noise ratio. As a result, it is expected that a very thin MuMetal or MolyPermalloy core (which we do not possess at the moment) will permit the construction of a similar instrument with sensitivity in the region of 0.1 nTs for a bandwidth of approximately 1 Hz, but with the further advantage of very low power consumption.

It is worth noting that one of the reasons for an expectedly relatively large sensitivity is due to the demagnetizing factor of the sensor core as a whole regarding to the DC measured magnetic field being relatively small.

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