Optimized Mini Search Coil Magnetometer Suited To Large Bandwidth Applications

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***Abstract*— In the framework of a collaborative work with industry aiming at the development of a robust small size (1 cm^3) large bandwidth magnetometer, a theoretical and experimental comparison of optimized search coils based magnetometers, operating either in the Flux mode or in the classical Lenz-Faraday mode, is presented. The improvements provided by the Flux mode in terms of bandwidth and measuring range of the sensor are detailed.**
A compact original flux mode differential magnetometer is presented and detailed in terms of measurement range, bandwidth and transfer. Theory, SPICE model and measurements are in perfect agreement.

Keywords-search coil sensor; differential magnetometer; transimpedance amplifier; biomedical and geomagnetic measurements; non destructive evaluation

I. INTRODUCTION

This research work takes place in the context of an industrial contract aiming at developing a robust small size (1 cm^3) large bandwidth magnetometer. We investigated benefits provided by using search coils operating in the flux mode, instead of the classical Lenz-Faraday mode. This paper consists in a theoretical and experimental comparative study of sensors specifications (bandwidth, sensitivity, measuring range) depending on the operating mode. To meet the industrial constraints, we fixed a budget (ie we selected a search coil and a low noise differential instrumentation amplifier). The obtained results are providing new solutions for applications requiring large bandwidth like pulsed eddy current non destructive evaluation [1], biomedical or geomagnetic measurements in the [1Hz-1MHz] bandwidth, for which Lenz mode magnetometers are not well adapted.

We present in the Section II the main characteristics of the sensors for the two operating mode. In Section III, we discuss how to optimize the signal conditioning so as to obtain low noise and large bandwidth magnetic field sensors. We show that using search coils in a Flux mode enables a large enhancement of both bandwidth and measuring range of the sensor without reduction of its sensitivity. Section IV is devoted to the study of a coupled search coils sensor in Flux mode and the design of a small size differential magnetometer.

II. SENSORS CHARACTERISTICS AND ELECTRICAL EQUIVALENT MODEL IN FLUX MODE AND LENZ MODE

In the Lenz mode, the search coil generates a voltage signal proportional to the flux time derivative not to the field density B and is connected to a voltage instrumentation amplifier. In the flux mode, the short circuit current, proportional to the field density, is measured. In that case the coil has to be connected to an infinite input admittance transimpedance amplifier [2]. Thus, search coils sensor can be considered as voltage or current source depending of the mode they are being operated. Their Thevenin equivalent voltage generator E_{Th}, Thevenin impedance Z_{Th}, Norton equivalent current generator I_N and Norton equivalent admittance Y_N (Fig. 1) can be calculated as a function of both the flux density B_e to measure and the coil features: inductance L_b, noisy resistance R_b, parasitic capacity C_b and flux equivalent surface S_{eq}, which is defined as the ratio of the collected flux to the flux density and experimentally determined. One gets:

$$E_{Th} = \frac{e_{nRb} - j\omega B_e S_{eq}}{(1 - L_b C_b \omega^2) + j\omega R_b C_b}$$

$$Z_{Th} = \frac{R_b + j\omega L_b}{(1 - L_b C_b \omega^2) + j\omega R_b C_b}$$

$$I_N = \frac{e_{nRb} - j\omega B_e S_{eq}}{R_b + j\omega L_b} \quad \text{and} \quad Y_N = \frac{1}{Z_{th}},$$

where e_{nRb} stands for the Johnson voltage noise source of R_b.

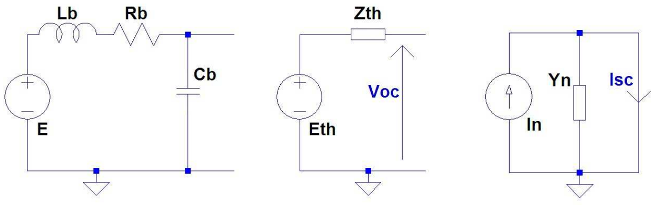

Figure 1: Electrical equivalent circuit of a search coil (a) operating in Lenz mode (b) or Flux mode (c). In Lenz mode the magnetic flux is related to the open circuit voltage Voc whereas in Flux mode, the flux density is related to the short circuit current Isc.

The transfer functions $T_V = \frac{\partial E_{Th}}{\partial B_e}$ and $T_I = \frac{\partial I_N}{\partial B_e}$ and the intrinsic magnetic noise sensitivity, defined as the input noise flux density ($T/\sqrt{Hz}$) that produces a voltage (or current) equal to the contribution of the Johnson noise of the resistance R_b, are plot as a function of the frequency in Fig. 2. One deduces from these figures that in the Lenz mode the bandwidth is intrinsically upper limited by the coil resonant frequency and that the measuring range is inversely proportional to the frequency, whereas in the flux mode the bandwidth is larger, since not affected by the coil resonant frequency, and the measuring range is constant above a low cut off frequency equal to $\frac{R_b}{2\pi L_b}$ [3]. The magnetic sensitivity in the Lenz mode decreases as the frequency and is thus better at high frequency than in the flux mode. In this latter case, the sensitivity is constant over the bandwidth sensor.

As a brief conclusion, intrinsically, the flux mode sensor is well suited to applications requiring a large bandwidth and frequency independent measuring range whereas the Lenz mode magnetometer is rather adapted to applications in limited frequency range and provides in that case a better sensitivity than the Flux mode magnetometer.

Signal amplification is different depending on the operation mode of the search coil. The signal has to be amplified for the Lenz mode by a voltage amplifier, with as high as possible input impedance Z_i, and for the Flux mode Lenz mode by a transimpedance amplifier, with as large as possible input admittance Y_i. These amplifiers can be replaced by their equivalent noisy quadripolar model as shown on Fig. 3 and 4. Such models are very useful for calculating the effective sensitivity of the sensor taking into account the noise due to the amplifier stage and more generally to state the required characteristics of both search coils and amplifier for given sensor specifications in terms of bandwidth and sensitivity.

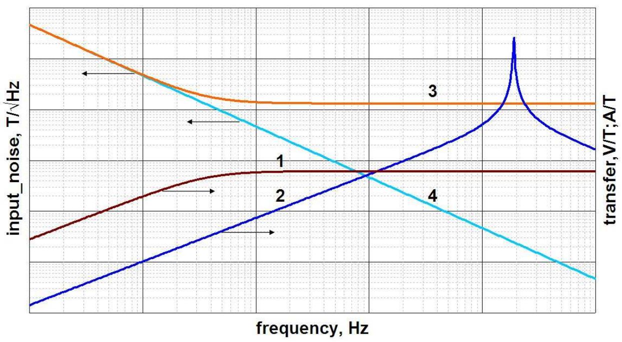

Figure 2: Transfer function and intrinsic sensitivity of search coil magnetometer in Lenz mode (2 & 4) and Flux mode (1 & 3) as a function of the frequency.

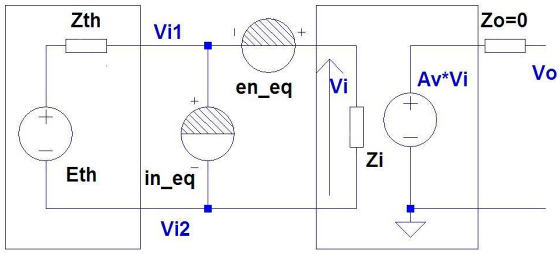

Figure 3: Equivalent electrical model of the Lenz mode magnetometer. Av is the voltage Gain and Z_i the input impedance, which has to be as large as possible.

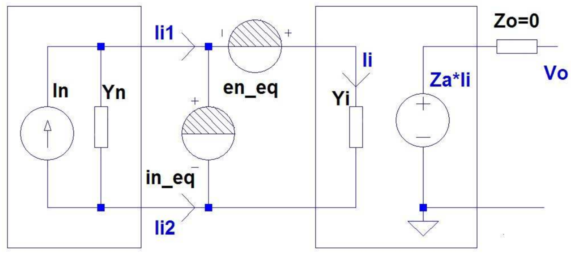

Figure 4: Equivalent electrical model of the Flux mode magnetometer. Za is the amplifier transimpedance and Y_i is the input admittance, which has to be as large as possible.

For signal conditioning, we selected an instrumentation amplifier structure (like the one included in the INA 163 integrated circuit) that we configurated so as to operate either as a voltage amplifier (for the Lenz mode) or as a transimpedance amplifier (for the Flux mode), as shown on Fig. 5 and 6.

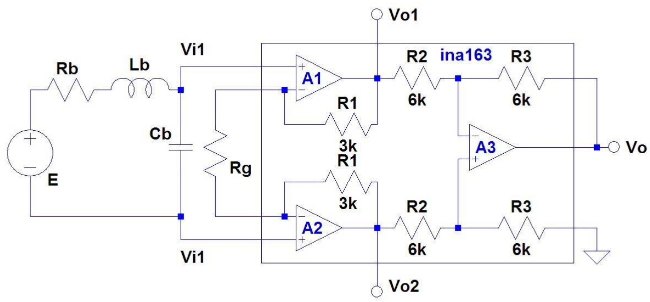

Figure 5: Signal conditioning for Lenz mode magnetometer. Rg is the gain-set resistor.

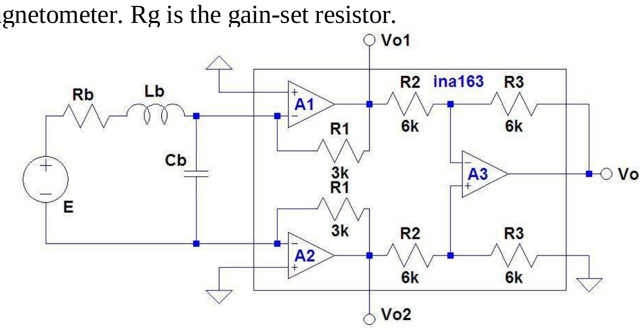

Figure 6: Signal conditioning for Flux mode magnetometer

III. SEARCH COILS SENSORS OPTIMIZATION

The classical Lenz mode magnetometer, which is rather a magnetic flux derivative meter, can be converted into a B field meter by using an integrator output stage [4]. We designed a solution with the integrator embedded inside the amplifier (Fig. 7). The transfer function T_{Lenz} of this Lenz mode B field meter is in that case given by:

$$T_{Lenz} = \frac{\partial V_o}{\partial B_e} = \frac{j\omega\, S_{eq}}{1 - L_b C_b \omega^2 + j\omega R_b C_b}\left(1 + \frac{2R_1}{Z_g}\right)$$

$$\text{where } Z_g = \frac{R_{g1} R_{g2}}{R_{g1} + R_{g2}} \cdot \frac{1 + j\omega\, \tau_{g1}}{1 + j\omega\, \tau_{g2}}$$

$$\text{and } \tau_{g1} = \frac{L_g}{R_{g1}} \;, \qquad \tau_{g2} = \frac{L_g}{R_{g1} + R_{g2}}$$

The magnetometer low cut off frequency can be adjusted by proper choice of integrator parameters. Nevertheless, the magnetometer bandwidth is still limited by the search coils resonance and the measuring range is not enlarged by the integrator stage.

For the standard Flux mode magnetometer, the low cut off frequency is fixed by the search coil parameter. This low cut off frequency can be significantly reduced by including a compensation stage in the transimpedance amplifier as described in Fig. 8.

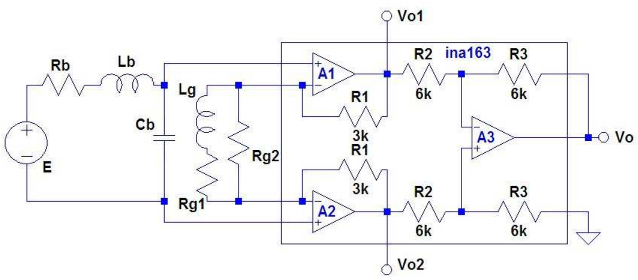

Figure 7: Lenz mode B field meter with embedded integrator stage (Lg, Rg1 and Rg2), which replaces the gain-set resistor Rg in Fig. 5.

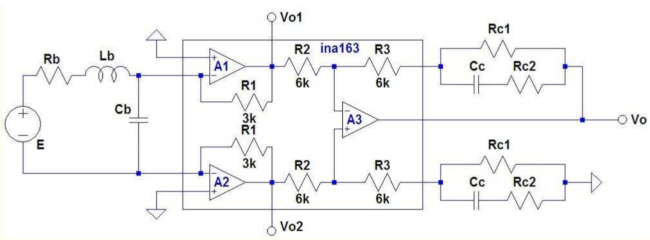

Figure 8: Flux mode magnetometer with compensation stage (Rc1, Rc2 and Cc) for bandwidth enhancement at low frequency.

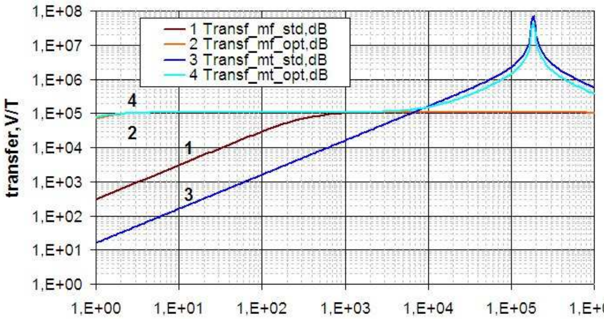

Figure 9: Transfer function of standard (std 1 &3) magnetometer and optimized (opt 2 & 4) magnetometer.

The function transfer T_{Flux} writes:

$$T_{Flux} = \frac{\partial V_o}{\partial B_e} = \frac{j\omega\, S_{eq}}{R_b(1 + j\omega\, \tau_b)} \cdot \frac{R_1}{R_2} \cdot \left(R_3 + \frac{R_{c1}(1 + j\omega\, \tau_{c2})}{(1 + j\omega\, \tau_{c1})}\right)$$

$$\text{where } \quad \tau_b = L_b / R_b \;, \quad \tau_{c1} = C_c\left(R_{c1} + R_{c2}\right), \quad \tau_{c2} = C_c R_{c2}$$

Using the compensation stages described ahead, whatever is the mode of the magnetometer, one can obtained the same cut off low frequency and the same transfer value in the magnetometer bandwidth. The Lenz mode magnetometer bandwidth stays nevertheless limited by the search coil resonant frequency.

IV. DIFFERENTIAL MAGNETOMETER BASED ON COUPLED SEARCH COILS

A significant reduction of common mode signals as well as parasitic signals sensed in connecting wires is usually achieved by the use of a differential structure. An original flux mode differential magnetometer is presented in Fig. 10. The Norton equivalent model and the transfer function of this magnetometer can be calculated as follows:

$$I_N = \frac{\left(e_{nRb1} + e_{nRb2}\right) - 2 j\omega B_e S_{eq}}{2\left(R_b + j\omega\left(L_b + M\right)\right)}$$

$$\frac{1}{Y_N} = \frac{2\left(R_b + j\omega\left(L_b + M\right)\right)}{\left(1 - \left(L_b + M\right) C_b \omega^2\right) + j\omega R_b C_b}$$

$$T_{Diff} = \frac{\partial V_s}{\partial B_e} = \frac{2 R_1 R_3}{R_b R_2} \cdot \frac{p S_{eq}}{1 + \tau_{bd}\, p}$$

$$\text{where } \tau_{bd} = \frac{L_b + M}{R_b} \quad \text{and} \quad M = k\sqrt{L_{b1} L_{b2}}$$

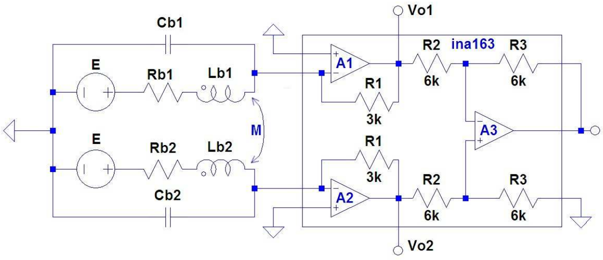

Figure 10: Flux mode differential magnetometer structure

The low cut off frequency can be significantly reduced by including the compensation stage described in Section III. The theoretical study was compared to experimental measurements and calculations using a SPICE simulator. All results are in very good agreement as shown on Fig. 11.

The search coils coupling leads to correlation of the voltage noise sources of the two input amplifiers A_1 and A_2 of the instrumentation amplifier and thus to noise reduction of the sensor [5]. The coupling allows also a significant size reduction of the magnetometer since the coils can be wounded together on the same magnetic coil. In order to check the validity of the theoretical study, experimental measurements and calculations using a SPICE simulator were performed. All results fits very well as shown on Fig. 12.

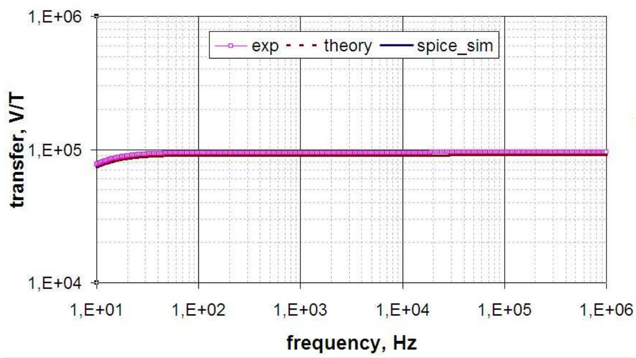

Figure 11: Transfer function of the differential Flux mode magnetometer. Theoretical, experimental and SPICE simulation curves are in very good agreement. Search coils features are: $R_{b1} = R_{b2} = 45$ohms, $L_{b1} = L_{b2} = 4.7$mH, $Cb_1 = Cb_2 = 60$pF, $S_{eq} = 0.152\text{m}^2$, Volume = 0.83 cm^3, intrinsic search coil transfer equal to 28A/T and search coil low cut off frequency equal to 1,5kHz. The compensation stage of the magnetometer (see Section III) was designed so as to obtain an 8 Hz low cut off frequency.

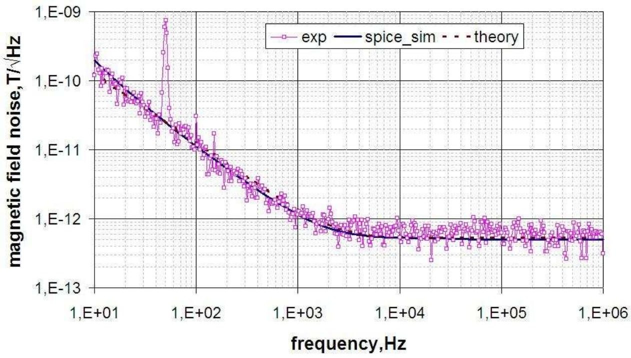

Figure 12: Flux noise sensitivity of the differential Flux mode magnetometer. Theoretical, experimental and SPICE simulation curves are in very good agreement. Search coils features are the same as in Fig. 11.

V. CONCLUSIONS AND PERSPECTIVES

A detailed comparison of transfer function and noise sensitivity of search coils magnetometer operating either in Lenz mode of Flux mode was presented. We explained how to optimize both magnetometers and showed that the Flux mode provides a transfer function, which can be set constant over a bandwidth ranging from 1 Hz to 1 MHz, larger than what can be achieved in Lenz mode. The Flux mode also provides a constant measuring range over the full bandwidth, which is not the case for Lenz mode magnetometer. Such features are very interesting for applications requiring a large bandwidth and a good sensitivity over the whole bandwidth. An original differential flux mode magnetometer, which is much more compact than classical Lenz mode search coil differential magnetometer, was proposed and studied in details, namely in terms of transfer function and noise. Theoretical analysis, SPICE simulations and experimental measurements are in very good agreement.

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