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► To cite this version:

Didier Robbes, Gilles Allègre, Stéphane Flament, Sylvain Lebargy, Adrian Swinton, et al.. One input - multi output sensors: A relevant concept? . SENSORS, 2014 IEEE, Nov 2014, Valences, Spain. pp.273 - 276, 10.1109/ICSENS.2014.6984986 . hal-01138556

HAL Id: hal-01138556

<https://hal.science/hal-01138556>

Submitted on 2 Apr 2015

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One Input – Multi Output Sensors: a Relevant Concept?

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Abstract—State of the art analogue signal processing allows multi-channel systems to be commonly used to process multi-sensor systems. Nevertheless, specific situations arise where the values from only one input – especially vector physical quantities – are needed, but signal strength and/or efficiency of transducers is not enough to produce sufficient signal to noise ratio, bandwidth, or dynamic range and therefore one output might not be enough. This contribution carefully analyses the case of magnetic flux density vector field sensing where the input consists of 3 wide-bandwidth components (DC to up to 1 MHz) measured around the same space point. The instrument consists of 6 pairs of sensors arranged to obtain the field components estimations around the same sampled point in space. millitesla range measurements were achieved with a noise spectrum of 20 – 50 pT/ $\sqrt{\text{Hz}}$ up to 1 MHz. These observations are discussed to evaluate the relevance of the concept to other physical quantities.

Keywords—Hybrid magnetometer, flux gate, search coil, multi-output system.

I. INTRODUCTION

The framework of our contribution is measuring a physical quantity with large dynamic range and a wide bandwidth that starts from DC. As a matter of fact, analogue to digital signal processing has developed in such a way that converters are now easy to use, and have a very good resolution – routinely 24 bits – so that there are no longer major limitations with the conditioning electronics. Limitations in terms of bandwidth, measuring range and dynamics are now due mostly to the measuring principle rather than the conditioning electronics. Although most large scale applications do not require wide bandwidth or so large a dynamic range, a lot of smaller and more specific applications would benefit from such improved sensing systems. A unique measuring principle that would exhibit workable properties compatible with such extended dynamics is rarely found to acquire vectorial information from a single physical quantity accurately, even at DC. In this instance the use of multiple measuring principles becomes necessary. However this leads to some complications that have to be taken into consideration in the design of the system. The spatial and time reference as well as active volume and response time must remain the same for each chosen measuring principle. Moreover, it should be done along three orthogonal directions whenever the measurand is a vector.

These general issues are addressed in our paper, through the careful analysis of a combined system composed of 3 miniature pairs of search coils complementing 3 pairs of fluxgate sensor heads. It will be shown that these match most of the stated requirements, and, this combined system appears as a textbook case. The paper is arranged as follows. Section II details the target specifications of the system and the approaches that were initially proposed. Section III is dedicated to the design of the miniature pairs of search coils to be combined to the Bartington Instruments fluxgate magnetometer head [3]. Section IV presents our findings and the achieved specification of the hybrid magnetometer described in this study. Section V discusses potential follow-up to our work.

II. HYBRID MAGNETOMETER CONCEPT AND SPECIFICATIONS

A. Magnetic flux and its density, a school case measurand?

Among the many physical quantities magnetic flux density B is a common measurand and important in metrology. We can explain this particular interest from two separate angles: science history and industrial need. The Faraday-Lenz laws of magnetic induction, published in the nineteenth century, state that a change over time of the field B is directly linked to an easily workable output voltage $e_F(t)$ across terminals of an open loop, highly conducting circuit, either a single-turn or multi-turn coil. The expression of Faraday's law is:

$$e_F(t) = - \frac{d\phi}{dt}, \quad (1)$$

where ϕ is the magnetic flux through the coil. The excellent linearity of the response, and the accuracy with which this method can be implemented, made it perfect for use in a simple reliable AC magnetic flux density sensor. Those coil-based sensors are called search coils (SC). They have been used successfully in a wide range of applications [1]. However because of the intrinsic time derivative in (1) they cannot be used for directly measuring DC magnetic flux densities. Coupling SC and non-linear soft magnetic cores overcame that limitation. Coils wound around a magnetic core were used as parametric amplifiers around a pumping frequency [2] and led

to the design of fluxgate magnetometers (FGS). FGS are now considered to be reference vector magnetometers for DC and low frequency measurements by metrologists and industrialists alike. This is mostly due to their very good signal to noise ratio, large dynamic range, excellent linearity, robustness and versatility. However the intrinsic limitation of these sensors is the maximum frequency that can be measured. The bandwidth of a FGS is commonly limited to a few kHz, because of the resonance mechanism that occurs in their coils typically above 100 kHz. In summary, the popularity of the magnetic flux density measurand and the obvious advantages of combining two of its most commonly used sensing technologies led us to select it as a textbook physical quantity in our study.

B. FGS – MSC hybrid magnetometer specifications

As presented in A, SC and FGS are based on the Faraday–Lenz laws. However FGS coils cannot be used as SC sensors because frequency lines associated with the FGS parametric amplification mode create strong perturbations in the SC working frequency band. Therefore the FGS and SC sensors have to be 2 separate physical assemblies and the performance of each should not be degraded by the other. The target specification of this hybrid magnetometer can be formulated as follows with specific technical considerations. The hybrid magnetometer should provide the magnitude of the three orthogonal components of the B field vector, its origin being at the geometric centre of the active volume. Both sensors should use the same origin and same active volume. The magnetometer shall measure B field variations from DC to 100kHz with no gaps in its frequency band. The FGS and SC will have to overlap, implying that the search coil should work from a few hundred Hz. The third requirement is that the magnetometer should measure the B field up to 1mT with the full bandwidth RMS noise at least 5 to 6 orders of magnitude smaller than the full scale range. Both sensors will have to achieve this requirement over their own frequency range. The fourth is that interference between the two sensors should be negligible and should not affect the hybrid magnetometer performance.

C. Proposed designs around the FGS head

To meet the specification, the three FGS are fitted orthogonally so as to share a single crossing point in the centre of the active volume. The point of insertion of one of the FGS can be seen as pairs of boreholes on Fig. 1 (left hand side). These drawings also show two proposed approaches for the design of the SC around the FGS setup, in such a way that their outputs easily lead to an estimation of the 3 components of field \mathbf{B} in the same active volume

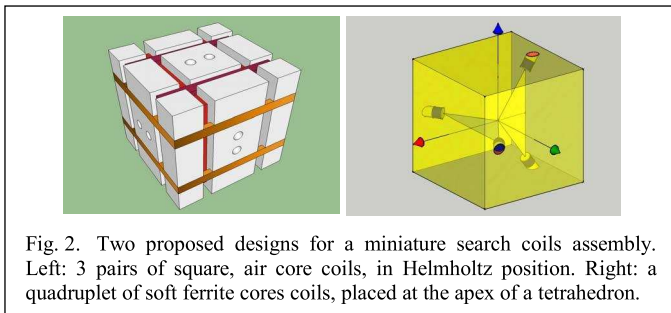


Fig. 2. Two proposed designs for a miniature search coils assembly. Left: 3 pairs of square, air core coils, in Helmholtz position. Right: a quadruplet of soft ferrite cores coils, placed at the apex of a tetrahedron.

The air core coil approach (Fig 2) makes good use of the Helmholtz position and symmetry. Summing and integrating the induced voltage (1) for each pair gives a total flux estimate from which the corresponding \mathbf{B} component is deduced. Once the effective capture area S_{cap} is defined, each component is easily computed from geometric properties of their associated SC, namely the turn number N times the mean side a_m of the cubic envelopes of each winding. Choosing these parameters will depend on the signal conditioning circuitry used. There are two classical operation modes of any SC: the voltage reading mode as a direct application of (1) and the current reading mode where the coil is shorted at a virtual ground, making good use of the Lenz law. We will see in section III that only a combination of these operation modes leads to the fulfilment of the specifications.

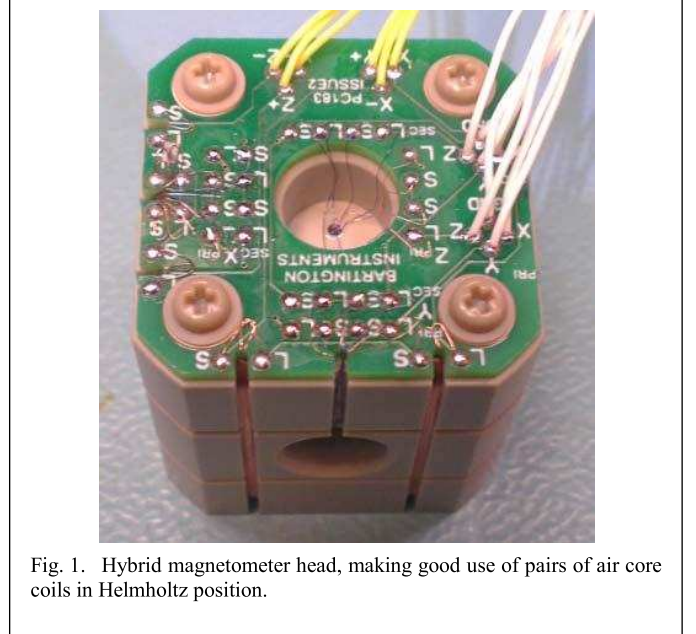


Fig. 1. Hybrid magnetometer head, making good use of pairs of air core coils in Helmholtz position.

The soft ferrite core coil approach was envisaged as an alternative, in order to minimize both the number of windings (6 to 4), and to take advantage of the availability of low-cost, off-the-shelf parts. In this configuration, the 4 axes of the coils quadruplet are aligned along those of a regular tetrahedron. These axes are crossing each other at the centre of the active volume as shown Fig. 1 (right hand side). Using simple geometry transformations, an estimate of the 3 components of field \mathbf{B} can be calculated.

III. ORTHOGONAL PAIRS OF MSC'S, DESIGN AND ELECTRONIC CONDITIONING.

A. Combined voltage – current readout scheme

There are two common readout schemes used to carry out signals from SC. Both have limitations and cannot alone fulfil our requirements. The high impedance readout uses voltage amplification and a pseudo-integrator stage to restore a flat frequency transfer from (1). Such a pseudo integrator stage using reactive components around linear integrated amplifiers (Op Amp) rarely works over more than 4 decades of frequency. In order to get sufficient margins with respect to the SC's bandwidth specifications (II B), at least 5 decades are required. The current readout scheme on the other hand does not suffer

from the effects of the coil self-resonance because of the short to a virtual ground [4]. However it cannot be used as shorting the coils terminals, even to a virtual ground of an Op Amp, leads to induced currents as a result of Lenz's law that circulate in the coils and change the magnetic flux and its density B . This would lead to interference being measured by the FGS. To circumvent this impediment, terminals of each pair of coils were connected to a passive network, thus adjusting the impedance of each SC at high and low frequencies. This network is composed of a resistively shunted capacitor (C_s, R_p), in series with a resistor R_s as drawn in Fig. 3. It acts as a frequency shaper of the upper range of the bandwidth. In the low frequency domain, values of $R_p + R_s$ must be much higher than R_L (DC resistance of the SC), while, in the high frequency domain, the impedance of the capacitor must be much lower than R_p . The crossover between these 2 regimes should occur at a frequency f_c slightly greater than the upper frequency of the FGS bandwidth, to avoid most of the induced currents in the pickup coils. Because in the high frequencies, a current like readout is physically obtained, without needing to connect to a virtual ground, the voltage drop across the R_s resistors just reflects the field B sensed by the pair of coils. Its frequency dependency is flat, and calculating the value required for setting the measuring range and achieving the right output voltage leads to the right components choice.

B. Physical model and transfer parameters

Using the combined readout scheme suggested above, two circuit topologies employed for connecting a set of SC to the frequency shaper circuitry, either in series or in parallel. That choice is dependent on the way the front hand pseudo-integrator stage is designed. Although not detailed in this paper, we had such a stage built around 3 Op Amps, namely the INA163, that demonstrated a very good frequency behaviour at up to 6 decades with a gain as high as 10^4 in the low frequency domain. With this design, a parallel setup was necessary to get realistic coils used, particularly as single reactive elements have an impedance of $R_L + jL_L\omega$. In this instance, common mode choke coils were used replacing the usual resistor gain of INA163.

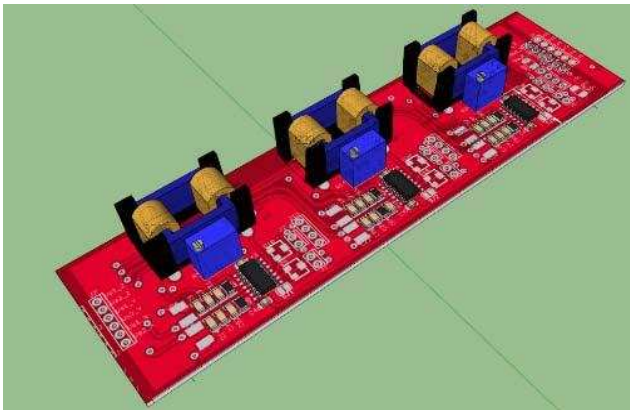


Fig. 4. View of the SC conditioning unit. It explicitly shows the use of common mode choke as frequency variable gain components around the INA163 instrumentation integrated amplifier.

As seen in Fig. 4, a very easy setup is obtained, allowing very simple rules to maximize the dynamics, given a set measuring range. The voltage mode readout has to work at least over 3 decades, up to f_c , giving the maximum value of R_L . Above f_c the INA163 gain quickly goes down to 1, its noise being then limited by its output stage ($60nVHz^{-1/2}$). Values of the supply voltage together with the chosen measuring range dictate the overall transfer T value and the input referred as noise B_n . For example, 1 mT range and $\pm 5V$ supply gives $T = 5VmT^{-1}$ and $B_n = 12pTHz^{-1/2}$ (noise was measured using our shielded room facility), which matches the required condition. Below f_c , INA163 circuit noise is dominated by the input contribution. Maximising dynamic range in that domain dictates the R_L value in order to produce a Johnson noise just of the order of the amplifier noise.

Once these values are chosen, all the other values can be deduced, given the active volume. Detailed results will be given elsewhere, but standard classical results are used to compute all of the introduced inductances, capacitances, and other component values, that appear in Fig. 3.

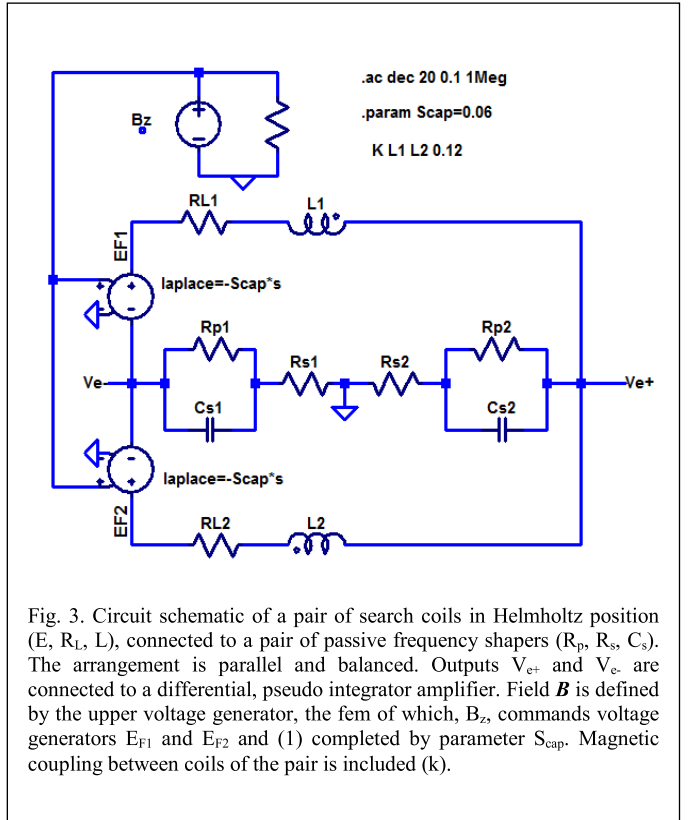


Fig. 3. Circuit schematic of a pair of search coils in Helmholtz position (E, R_L, L), connected to a pair of passive frequency shapers (R_p, R_s, C_s). The arrangement is parallel and balanced. Outputs V_{e+} and V_{e-} are connected to a differential, pseudo integrator amplifier. Field B is defined by the upper voltage generator, the fem of which, B_z , commands voltage generators E_{F1} and E_{F2} and (1) completed by parameter $Scap$. Magnetic coupling between coils of the pair is included (k).

IV. HYBRID MAGNETOMETER, MAIN RESULTS

The plots in Fig. 5 are taken from data collected to characterize the hybrid magnetometer, on a wide bandwidth from 1 Hz to 1 MHz. They clearly show that the two sensing technologies, SC and FGS, can be operated simultaneously, in the bandwidth 2 Hz–2 kHz. In particular, the measurements taken from the random noise source show how highly coherent all the outputs are.

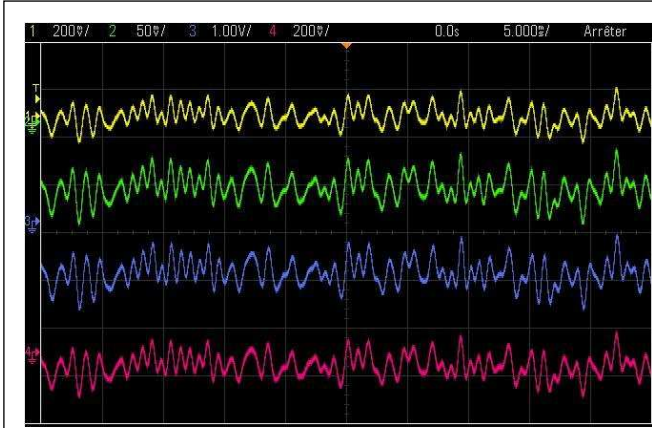


Fig. 5. Scope traces when collecting data to characterize the hybrid magnetometer. The yellow and green curves are MSC outputs and the others are FGS. The upper set is obtained using the random noise source of the vector analyser while the lower corresponds to the chirp source.

Fig. 6 shows that a very flat response from the SC can be obtained, after a well-defined adjustment process which is too long to be described here.

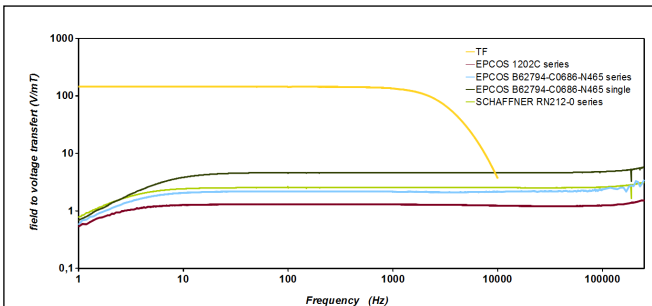


Fig. 6. Hybrid magnetometer field to voltage transfers. Yellow plot corresponds to a FGS, the others to MSCs during trials of various coils in the pseudo integrator stage.

Furthermore, we show that when both sensing technologies are used together, the SC do not degrade the FGS' noise performance. Moreover, even if frequency lines from the AC pumping in the FGS are visible in the SC noise spectra, the

associated rms value in the full system bandwidth was typically 80 dB below the full scale range. Therefore, most of the requirements described in section II A.

Despite these very encouraging results, drawbacks in the temperature sensitivity of the system were highlighted. The pseudo integrator coil exhibited a strong susceptibility to temperature due to the magnetic material of its core. Its high inductance value (100 to 400 mH) would necessitate post processing correction to be added to the design. Alternatively, a solution that avoids the use of these particular coils should be implemented, while keeping the concept of a combined voltage–current readout scheme.

V. DISCUSSION AND OPENINGS

Returning to a key theme of the paper, let us discuss why we consider this work to be a textbook study.

This paper shows that even if maximizing the dynamic range of a measuring instrument is usually difficult, it can be done entirely on the basis of a “simple” law such as Faraday–Lenz laws of induction by combining two sensing technology implementing the concept of one physical quantity input to provide 2 complementing sensor outputs.

It also demonstrates a concept that can be extended to other measurands. For instance, as electromagnetism follows the general action–reaction principle and if the concept of search capacitors [5] can be helped by the design of a charge gate sensor that would be similar to the FGS, then the same principle could apply in electric field sensing.

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