COMPARISON OF MAGNETOMETERS EFFICIENCY FOR ELF BAND

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ABSTRACT

The flux-gate and search-coil magnetometers are the most widespread nowadays for component measurements of weak magnetic fields. Their utilization areas are from DC to very low frequency oscillations for flux-gates and from low frequency to about 1 MHz for search-coils. But there is some intermediate frequency band - extremely low frequency (ELF) one - where the magnetometers choice is not so obvious. The purpose of the report is to give recommendations for optimal choice of magnetometer type using noise level as the optimization criterion and sensor dimensions as main restriction factor. Theoretical study and experimental tests allowed to obtain the deviation of manufactured magnetometers from the calculated ones within ±15%.

1. INTRODUCTION

The investigations of magnetic fields were always an important part of both scientific and applied activity. Especially great interest is paid to the study of Earth’s magnetic field and its fluctuations. For low frequency range - from DC up to about 1 MHz - best combination of parameters have flux-gate magnetometers (FGM) and search-coil magnetometers (SCM). In spite that concurrent methods of magnetic field measurement are constantly perfectioning (e. g., Kerr effect transducers, Josefson effect, Hall effect, magnetoresistive ones etc.), the FGM and SCM application area has the tendency to become even greater.

It is natural that in correspondence with their physical operation principle the SCM’s sensitivity is proportional to the measured signal frequency. That is why they are mostly used for the investigation of magnetic fluctuations with frequencies within higher part of the mentioned band. The FGM sensors sensitivity is practically constant starting from DC to few tens of hertz what determines their application for the measurement of DC or very slowly fluctuating magnetic fields.

But there is some intermediate band - approximately from 0.01 to 10 Hz - where the magnetometer type choice is not so easy as it could be seen. Namely this band - extremely low frequencies (ELF) - recently draws the attention of the scientific community, first of all because the electromagnetic oscillations in this band were often found to be seismic hazards precursors.

The most important parameter characterizing magnetometer quality - threshold sensitivity or own noise level (NL) of either FGM or SCM - is dependent from practical limitations of weight and size (and sometimes of power consumption) in different way. The present work is an attempt of the systematic approach to the optimization of such choice.

2. THEORETICAL APPROACH

May be the best way in order to look for the magnetometer for the given frequency band, including ELF one, is to use the NL as the optimization criterion for the proper choice. For this generalized NL characteristics for FGM and SCM as a function of their geometric and electric parameters were introduced. As a result following semi-empirical dependencies for NL's of FGM (h_F) and of SCM (h_S) correspondingly were proposed:

$$h_F = C_F \, [1 + (f_0 / f)^{0,8}] \cdot l^{-3}, \tag{1}$$

$$h_S = h_0 \, [1 + A / (l^5 \cdot f^2) + B / (l^5 \cdot f^4)] , \tag{2}$$

where $C_F \approx 5 \cdot 10^{-28}\ T^2 \cdot m^3 \cdot \mathrm{Hz}^{-1}$; $h_0 \approx 10^{-28}\ T^2 / \mathrm{Hz}$; l - sensor core length (or ring diameter - for FGM ring core); f - investigated signal frequency; $f_0 \approx 1$ Hz - corner frequency, $A \approx 30\ \mathrm{m}^5\ \mathrm{Hz}^2$; $B \approx 10^{-4}\ m^5\ \mathrm{Hz}^4$.

Some comments have to be made to these expressions. As to the FGM NL, there are different opinions about its dependence from the sensor core volume V_F and its length. Our opinion is that the dependence $h_F \equiv V_F^{-1}$ is valid only for FGM sensor constructions where additional disturbing factors are not influencing. Such factors are mainly mechanical stresses in the core and its vibrations during operation. It is very difficult to delete them, especially in relatively thick cores made from many layers of very thin material. Because of this in most cases the NL of the sensors using short and thick core is greater as of the sensors with elongated cores or thin ring cores with the same V_F.

Also the opinion is widespread that the FGM NL frequency dependence in the infrared noise band is $h_F \equiv f^{-1}$. It means that the more is observation time the greater are FGM output signal fluctuations, growing infinitely according to the well known relation: integral from f_{min} to f_0 for function $1/f$ is striving to infinity when $f_{min} \rightarrow 0$. Practically it is not so and our opinion confirmed by empirical investigations is that as given in the expression (1), $h_F \equiv f^{-0.8}$.

By this the known conditions to provide the lowest possible NL are assumed to be accomplished. For FGM they are the following [1]: best possible thin (no more than 20 mcm) magnetic materials for the core has to be used and deep saturation mode of the core (more than 1000 A/m) assured. By this electronics practically should not introduce additional noises. Only with these conditions best noise parameters according to the expression (1) could be achieved.

For the SCM NL the composition of the expression (2) is at first look controversial to the physical considerations: it appears that the minimal h_S value corresponding to $f \rightarrow \infty$, does not depend from the core length l. But it is necessary to recall that NL minimum is always near SCM sensor own resonance frequency which is sharply decreasing when l is increasing. As a result, h_S in the lower part of the SCM operation frequency band is determined by frequency-dependent terms in the expression (2). First of them is physically clear, but the second one has f^{-4} dependence which has to be explained. It determines the influence of the MDM preamplifier noise power increment at extremely low frequency. Even for best possible preamplifiers it is proportional to f^{-1} starting from some frequency and together with the sensitivity drop and $h_S \equiv f^{-2}$ dependence this gives $\equiv f^{-4}$ value.

So, let us underline that this expression is valid only for lower part of the SCM operation frequency band because it does not take into account the NL increase at higher frequencies, but for our low frequency optimization problem it is well acceptable.

All these results are also valid only for properly made SCM [2]. First, its core has to be made from the magnetic material with as high as possible relative magnetic permeability (no less than 20000) and optimal relations of its dimensions have to be considered. The winding has to be properly made with turns number assuring best possible matching with the modern type MDM or chopper preamplifier. If these recommendations are not considered, it may happen that, especially for SCM's with $l \leq 300$mm, the NL at lower frequencies is much greater as calculated from the expression (2).

3. INVESTIGATION RESULTS

The comparison of calculated NL's using the given relations and of measured ones of the known magnetometers of both types manufactured by best known companies gave following results.

For FGM's the comparison was made for LEMI type magnetometers having the sensors with race-track cores with longer axis of 20 mm and 50 mm. About 5 pieces of magnetometers were tested and all obtained experimentally results ranged within ±15% around calculated by expression (1) values.

The comparison of the calculated results using the expression (2) with the published NL parameters of SCM's manufactured by EMI company showed that their low frequency NL is greater as theoretical one. Two main causes of this are possible:

- in order to reach wide operation frequency band the optimal noise matching of the system "sensor-preamplifier" is made for the mean part of this band and not for the lower one;
- for the same purpose the constructed preamplifiers use FET-transistors at the input, which have very good noise parameters at mean frequency. But at very low frequencies their NL is much greater as for MDM-type preamplifiers.

That is why the NL estimation using expression (2) has to be considered as theoretically lowest NL in the very low frequency band, which is possible to achieve only for SCM's with the upper operation frequency about few tens of hertz.

NL curves for FGM with core length from 15 to 150 mm (curves 1,2,3) and low-frequency optimized SCM with core length from 150 mm to 1.5 m (curves 4,5,6) are given on Fig. 1. It is seen that frequency, for which NL's of FGM and SCM are equal, changes from ~5Hz (for FGM and SCM with the same core length) to ~0.002 Hz (for SCM core length 100 time bigger than FGM one).

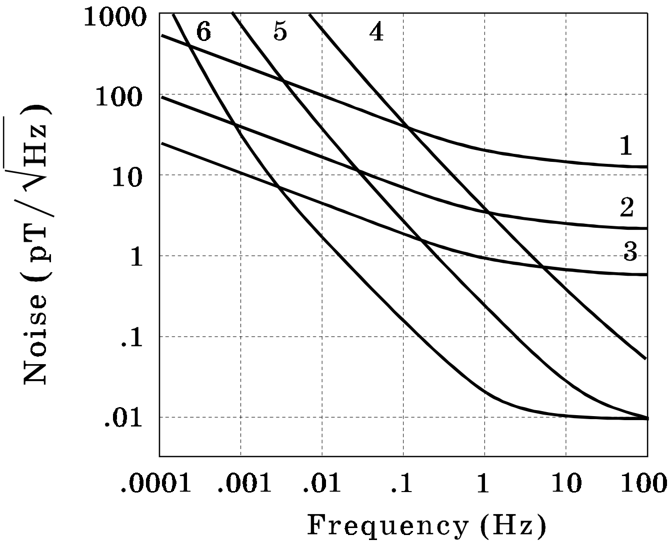

Fig. 1

4. CONCLUSION

The presented results allow to make the proper magnetometer type choice according to the investigation problem. Given NL estimation formulae really can have wide practical applications. But it is necessary to realize that the close coincidence of the calculated and experimental NL parameters can be obtained only when all known recommendations as to the design of FGM or SCM are taken into account. At any rate, these expressions allow to estimate the theoretically lowest possible NL of these magnetometers in the ELF band when given core length restriction is imposed.

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