# NEW APPROACH TO THE EXACT DESIGN OF LOW NOISE SEARCH-COIL MAGNETOMETERS

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*Abstract:* It may be shown that for the investigation of the magnetic field fluctuations an optimum set of parameters have inductive, or search-coil sensors (SCS). The proper choice of SCS and matched to it preamplifier parameters is difficult task because a great number of mutually dependent and correlated parameters must be taken into consideration. That's why the optimum version of "SCS/preamplifier" complex cannot be found by simple testing of all possible combinations, even by using computer program. A new methology of SCS design is proposed, based upon introduced "generalized" parameters of SCS - a set of stable combinations, relatively independent from dimensions, number of turns and frequency band variations. A physical meaning and numerical values of four main and three additional generalized parameters are given. Preamplifier is characterized by extended set of 8 known noise parameters. A corresponding PC program is developed which allowed to proceed directly from the search-coil magnetometer (SCM) design to the manufacturing without laboratory models. New versions of super-light SCM construction are proposed, based upon a non-traditional approach.

*Keywords:* magnetic measurements, search-coil, sensor, design

The SCM application has the tendence to extend and the investigated frequency band is as wide as 0,1 mHz ÷ 1 MHz. For relatively narrow-band SCM ($f_{max} / f_{min} < 1000$) it is not very difficult to determine the sensor parameters and the really achievable noise level is close to the theoretical one for given mass and dimensions of a sensor.

For wide-band SCM direct optimum matching of sensor and preamplifier is impossible because of different dependence of sensor output impedance and optimum resistivity of signal source for preamplifier with frequency.

Calculation of search-coil magnetometer noise in dependence from threshold sensitivity, frequency band and weight/dimensions restrictions requires to take into account simultaneously a great number of SCM parameters (for sensor only more than 30 geometric and electric values are described in the known papers). To this some of these parameters are mutually dependent or can be chosen from the restricted range of values (e.g., wire diameter). That is why in spite of as one would think rather simple task, the optimum set of values determination by versions look-over or equations system solution is impossible.

Then, two possibilities are used in practice:

1) the intermediate parameters of sensor and preamplifier which are necessary for calculations are chosen on the base of precedent tests of similar devices and then noise parameters are calculated for a number of sets of values given by the desired construction;

2) the recommended in papers relations between some intermediate parameters are accepted and anothers which are necessary for calculations are set, proceeding from general considerations.

In the first case the look-over of the versions doesn't guarantee the optimum set achievement at any rate, first of all because the selection of versions is executed arbitrarily. In the second one the parameters partly are selected also arbitrarily and the use of known equations without taking into account corresponding limitations, within which they were deduced, can give rough errors. E.g., in one paper the optimum combination of sensor and preamplifier one finds as a search of an optimum SCS for an ideal preamplifier, and then the matching with the real preamplifier is executed by the SCS turns number correction. This procedure gives not absolute optimum combination but the complex of two relative optima, what leads to very incorrect result, especially in high frequency region.

A new approach for the wide-band optimized SCM design is proposed and respective method and computer program are developed. The main peculiarity of this method consists in introduction of "generalized" SCS parameters, which values may be admitted constant for the given core material.

A set of 4 main generalized parameters and 3 additional ones is given in the table 1.

Table 1. SCM generalized parameters

| Parameter | Dimensions | Physical sense and tentative estimation |
|---|---|---|
| $K_S$ | $V/(T*Hz*m^2*turn)$ | Open-circuit sensitivity of SCS with 1 m length and one turn winding at 1 Hz; 1 ± 20 % |
| $K_L$ | $H/(m*turn^2)$ | Inductivity of the same SCS; $2*10^{-7}$ ± 25 % |
| $K_f$ | $Hz/(m^{1/2}*turn)$ | Own resonance frequency of the same SCS; $4*10^7$ ± 25 % |
| $K_R$ | $Hz*m^2$ | Frequency, for which inductive and active resistances are equal for the same SCS; 0.5 ÷ 3.5 |
| $f_F$ | Hz | Frequency, for which SCS Q-factor determined by Fuco currents in the core, is equal to 1; $(5 \div 500)*10^3$ |
| $Q_h$ | - | Q-factor, determined by hysteresis losses in the core; 50 ÷ 200 |
| $Q_0$ | - | Q-factor at the resonance frequency, determined by losses in parasitic capacitances; 3 ÷ 10 |

It is obvious that the dispersion of parameters $K_R$, $f_F$, $Q_h$ and $Q_0$ can be enough wide. But these parameters have relatively weak influence on the total noise level of SCM and only upon separate sections of frequency band.

The use of generalized parameters allows to conceive all the SCS parameters in very simple and physically clear form, for example:

$$S = K_S\, f\, l^2 w \quad (1)$$

$$L = K_L\, l\, w^2\,; \quad (2)$$

$$Q = 1 / [K_R / (f\, l^2) + 1/Q_h + f / f_F]; \quad (3)$$

$$f_{res} = K_f / (l^{1/2}\, w); \quad (4)$$

$$R = 2\pi\, K_R\, K_L\, w^2 / l; \quad (5)$$

where S - sensitivity; l - core length; w - number of turns; L - inductance; Q - main component of q-factor, depends of core and winding losses; f - working frequency; $f_0$ - own resonance frequency, $f_{res}$ - own SCS resonance frequency; R - active winding resistance.

Frequency spectrum of the preamplifier noise is characterized by extended set of 8 noise parameters: minimum noise voltage density $W_{u0}$; corner frequency and angle of elevation at low frequencies $f_{u1}$, $\alpha_u$; corner frequency of additional elevation at extremely low frequencies $f_{u2}$; minimum noise current density $W_{i0}$; corner frequency and elevation angle of the current noise at high frequencies $f_{i1}$, $\alpha_i$; corner frequency at low frequencies $f_{i2}$. Then voltage and current noise densities dependences from frequency may be calculated by the equations:

$$W_u = W_{u0}\,[1 + (f / f_{u1})^{\alpha u} + (f / f_{u2})^2\,] \; ; \tag{6}$$

$$W_i = W_{i0}\,[1 + (f / f_{i1})^{\alpha i} + (f_{i2} / f)^2\,] \; . \tag{7}$$

The equations for the calculation of frequency spectrum of SCM noise are composed according to equivalent SCM diagram on fig.1, where $E_x$ - output e.m.f. of the sensor, $U_r$ - equivalent noise voltage of the active part of the sensor impedance (active resistance - R, hysteresis one - $R_h$ and Fuco losses one - $R_F$), $I_{ro}$ - noise current of the losses ($R_0$) in the parasitic capacitance, $R_i$ - input resistance of preamlifier (all resistors are supposed to be noiseless), $U_n$ and $I_n$ - input noise voltage and current of the preamplifier with densities $W_u$ and $W_i$ respectively, which are characterized by mentionned 8 parameters.

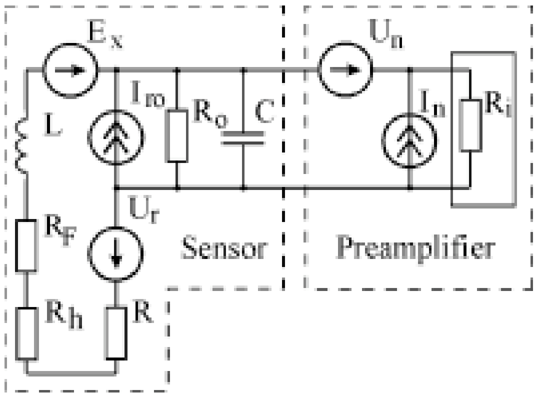


Fig.1. Equivalent noise circuit of SCM.

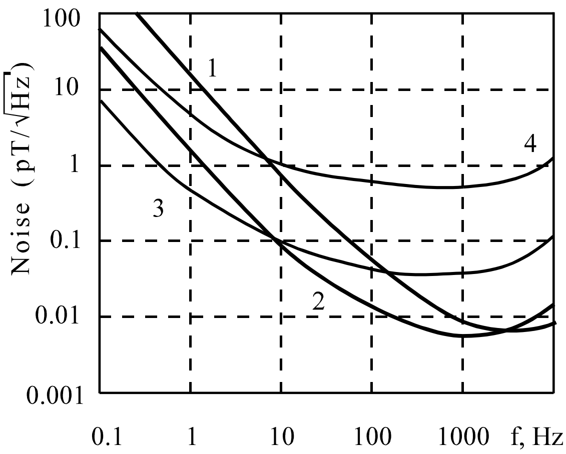


Fig.2. Influence of turns number change on SCM noise level

The resulting expressions for noise calculation are too cumbersome to present them here. On their base the calculation program was created, having developed service part, what allows to present the set of SCM noise characteristics in the form of curves or tables, where some given parameters can change, starting from those of ideal lossless sensor and preamplifier until the versions which are easy to make by simple technical means.

By this procedure it is easy to find the parameters, which influence most significally the noise in the given part of the frequency band. Service part of the program includes a set of values of generalized sensor parameters for a wide range of core materials and core constructions; also a number of input parameters for the different types of preamplifiers are available. A special version of the program is developed which allows to make automatic look-over of possible SCM realizations and alleviates the choice of the version, providing the minimum noise level in the given frequency range.

When all main parameters of the sensor and the preamplifier are taken into account, high precision of final calculation results is guaranteed. Important is, that when given constructive parameters of the sensor are changed, the correction of calculated parameters, which determine frequency properties of the SCM and corresponding changes in noise spectrum, is made automatically.

Fig.2 illustrates the calculation example when SCS winding turns number is varied. It is clearly seen that noise curves are bent and noise minima are shifted to lower frequencies with moderate number of turns increase (curves 1, 2, 3; w3>w2>w1). When an optimum is passed, SCM noise becomes higher for all frequencies (curve 4, w4>w3).

Also the possibility of changing the shape of transfer function of SCM is investigated and its new types, named "extraflat" and "ultralinear", are achieved in SCM LEMI - 102 (fig. 3). For extraflat transfer function with relation $f_{max} / f_{min} > 100\ 000$ the lowest frequency 0.0003 Hz is realized in serial production.

The noise suppression of 60 dB at mains frequency was realized in SCM LEMI-102 using standard notch-filters (see fig.3). For many applications of SCM, for example for geophysical researches near big towns, such suppression is not enough. The new method of noise suppression in narrow frequency band was developed on the base of distributed along the sensor core windings system and additional channel of negative feedback. This method allows to achieve compensation (and even hypercompensation, with control possibility) of external magnetic fields along the main measuring winding volume. As a result the noise suppression at frequencies 50 (or 60) Hz up to 130 dB was realized and very small signals may be measured at high industrial interferencies level.

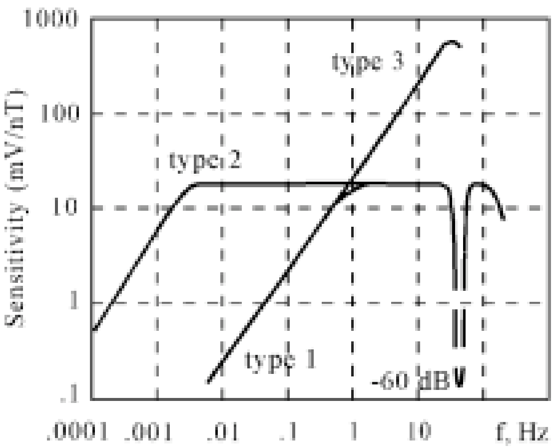


Fig.3. Transfer function types:
1 - normal;
2 - extraflat;
3 - ultralinear.

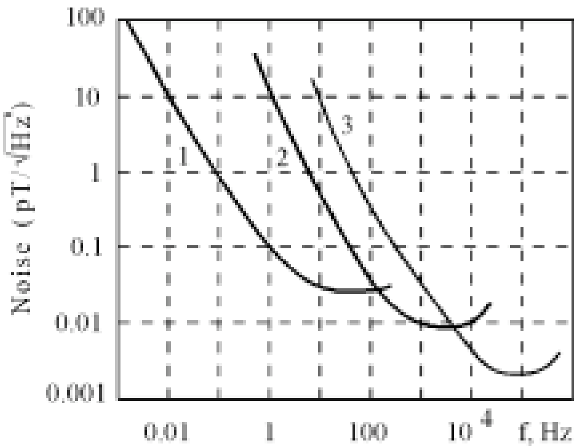


Fig.4. Noise curves of SCMs:
1 - low frequency;
2 - medium frequency;
3 - high frequency.

As a comment, it is necessary to say the following. The choice of a determined combination of generalized parameters means implicitly the choice of SCS materials and construction with determined geometrical sizes relation. That is why the given calculation methodology is especially simple and efficient for the determination of optimum length and turns number of geometrically similar SCS for standard operation conditions (wide frequency band, including infralow part, limited length, cheap magnetic materials). In the specific cases considerable deviation of generalized parameters from the values in table 1 is possible.

E.g., the spacecraft weight limitations demand as low weight as possible of onboard sensors. The attempts to design ultralight SCM however meet also serious methodological and calculative problems.

A new calculation methodology for low mass SCM (without length limitation) was developed. The complete analysis is also too cumbersome for the presentation here. Let's give final results for two SCM versions.

1. Low frequency SCM. The optimum relations for the relative permeability $\mu_S$ of the core shape and the ratio $n$ of outer and inner diameters of the winding are following:

$$\mu_{s\ opt} = 5\ \mu\ ; \tag{8}$$

$$n_{opt} = 1.4\ , \tag{9}$$

where $\mu$ – relative permeability of the core material.

2. High frequency SCM. Calculated noise level changes monotonically with $\mu_S$ and $n$ , that is why:

$$\mu_{s\ opt} \to \infty; \tag{10}$$

$$n_{opt} \to 1. \tag{11}$$

Final dependencies of the own noise level of the SCM with optimal length (for low and high frequency SCM respectively) are:

$$\sqrt{W_b} \equiv 1\ /\ f\ (\mu M)^{5/6} \tag{12}$$

and

$$\sqrt{W_b} \equiv 1\ /\ (f\ \mu M)^{1/2}, \tag{13}$$

where $\sqrt{W_b}$ - noise level of SCM in the units of induction (T/Hz$^{1/2}$).

The obtained results considerably differ from commonly adopted recommendations, especially as to the influence of the parameter $\mu$. Specifically, the decrease of the active material weight can be achieved by the proportional increase of the permeability of the core material. The equivalence of mass M and permeability $\mu$ in particular clearly shows that the use of recommended in literature ferrite cores with low $\mu$ is not efficient in spaceborn SCM.

Of course, the optimum $\mu_{s\ opt} \to \infty$ (even $\mu_{s\ opt} = 5\ \mu$) cannot be realized, because the SCM length will surpass the reasonable limits. But the strongly alongated "wirelike" construction is advisable. This consideration is valid fully only for SCM with minimal mass when the length is not limited. One would think that when such limitations do exist, the published recommendations give better results. However our calculations show that for the same length the decrease of the weight in 8 times when our procedure is used gives (for $\mu$ = 20000) the increase of the noise only in 4 ÷ 35 %. Then, the use of the new metodology of the SCM optimization seems rather reasonable.

The program version for ultralight SCM parameters calculation was corrected by corresponding changes in the generalized parameters table as to admitted value of SCS elongation. Its application to the high-frequency SCM design gave good results (see table 2).

Still one principial limitation exists for the practical realization of extremely light SCM: the existence of the constant outer magnetic field leads to the magnetization of the narrow core and the saturation of the core material is possible with corresponding sharp drop of the sensitivity and of other parameters of the SCM. Then, it is necessary to define the limits of the $\mu_s$ increase in dependence from the outer magnetic field $H_e$ value and admissible accompanying decrease of the sensitivity.

The corresponding equation in common case cannot be solved for any H, but for relatively small and high H the approximative expressions can be used.

The maximum possible $\mu_s$ value, for the decrease of the SCM sensitivity (in the outer field $H_e$ no more than $H_{max}$) was less than the admissible relative $\delta_s$ value, can be presented as follows:

$$(\mu_s)_{max} = \frac{\mu}{\sqrt[3]{\left(\frac{1}{\delta_s} - 1\right)\left(\frac{\pi H_{max}\mu}{2B_s}\right)^2} - 1} \quad ; \qquad (14)$$

where $B_s$ - saturation induction of core material.

Last equation is valid approximately until $\mu_s H_e \leq B_s$.

For the relatively high core saturation ($\mu_s H_e > B_s$) the calculations show that $\delta$ value changes very sharply when $\mu_s$ approaches to:

$$\mu_{smax} = B_s / H_e. \qquad (15)$$

That is why the value of $\mu_{smax}$, determined from the last equation, with the garanteed margin is the obligatory restriction in order do not obtain large errors because of the SCM core magnetization in the constant outer field.

It is necessary to note that the laboratory tests showed very good coincidence of calculated parameters of SCM with the results of their metrological certification on all frequencies, including the domains of sensor own resonance and higher frequencies: the discrepancy was not greater as the parameter differences of some SCM in one batch. The noise level of SCM, close to the theoretically estimated one, was achieved for the frequencies starting from 1 mHz. Main technical parameters of the developed SCM are given in the table 2:

Table 2. Main SCM parameters.

| | Low frequency | Middle frequency | High frequency |
|---|---|---|---|
| Frequency band, Hz | 0.0003 ÷ 200 | 1 ÷ 20 000 | 10 ÷ 600 000 |
| Noise level // at frequency | 0.1 pT*$Hz^{-1/2}$ // 1 Hz | 10 fT*$Hz^{-1/2}$// 1 kHz | 2 fT*$Hz^{-1/2}$ // 50 kHz |
| Length, m | 1.0 | 0.35 | 0.55 |
| Weight, kg | 15 | 0.45 | 0.07 |

Averaged noise curves for all these SCM types are given on fig.4.

In the conclusion the authors would like to mention that this report summarizes the precedent works, partly published in FSU scientific magazines and patents. But because of practically absent knowledge of western colleagues with these papers the authors decided do not refer them here.

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