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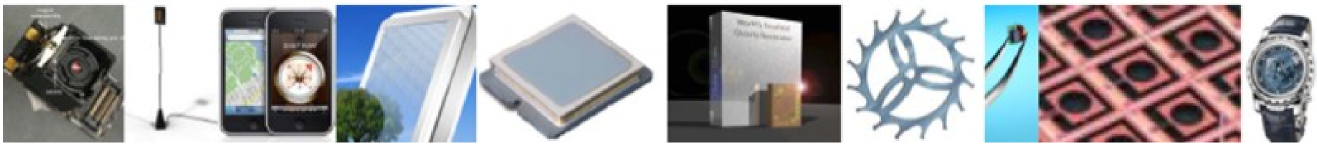

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Induction Magnetometers – Design Peculiarities

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Abstract: Induction or search-coil magnetometers (IM) are widely used in many branches of science and industry. The frequency range and dynamic range of IMs are probably the widest of all existing magnetometers: they are used for the measurement of magnetic field variations in the frequency band from ~10^{-4} till ~10^{6} Hz with the intensities from fractions of femtotesla till tens of tesla. This explains the permanent interest to IM design and the attempts to construct the IMs with best possible parameters. The present paper deals with the peculiarities of IM design. An attempt to re-establish the correctness of priorities in the field is made and the approaches to the IM optimization and their quality estimation are described. *Copyright © 2010 IFSA.*

Keywords: AC magnetic field, Induction magnetometer, Design, Quality factor.

1. Introduction

Induction or search-coil magnetometers (IM) are widely used for the experimental study of natural and man-made magnetic fields variations in the frequency band from ~10^{-4} till ~10^{6} Hz for science and engineering application in land and space conditions. They are probably the most widespread devices used for the magnetic field study. Certainly, different application areas impose different requirements to the main IM parameters. For example, field geophysics needs as low as possible magnetic noise level (NL) of IM and such parameters as length, weight and power consumption have secondary importance. Space research, to as low as possible NL requirement, needs weight and power consumption minimization. And some special types of application require very small IM dimensions and power consumption, still requiring as low as possible NL. This shows that, independently on other requirements, to get as low as possible NL remains the most important demand and at close or equal figures for other parameters the NL may be used to compare the IM quality.

Despite IMs are used probably more than a couple of centuries, the interest to them and to their design peculiarities is still at enough high level, what is proved by a good number of publications in recent few years. There are several reasons which induced the authors to write still one paper devoted to the IM design.

First, this is a desire to re-establish the correctness of the priorities in the field. Unfortunately, Cyrillic alphabet and "iron curtain" caused that the considerable theoretical and experimental groundwork made in Former Soviet Union still remains unknown to the international scientific community. For example, Russian scientist V. Arkadyev was probably the first who showed theoretically and experimentally the role of demagnetization factor for metallic rods [1], whereas the earliest cited work in this field in western papers is attributed to R. Bozorth and D. Chapin [2], which was published 7 years later. The detailed study of the demagnetization factor was executed in a fundamental work of M. Rozenblat [3] published the same year as the paper of K. Warmuth [4], though the first author was never cited by Western authors. And the best known monograph about IM design of Prof. L. Miziuk [5] published in 1964 is not known to the western experts at all, though a great deal of expressions given there are listed again by later authors as original ones.

Next is the desire to put right accents in the development problem of IM. The best found western paper devoted to IM design [6] pays much attention to the sensor (coil and core) design and very little attention is paid to the main problem in the field – *noise matching* of the sensor and amplifier, whereas this is a principle question to get low noise IM [5, 7]. In later publications [8, 9] this problem is omitted completely, as well as in the recent ones, where the necessary probably too complicated calculations are substituted by "intuitive" decision [10] or by very peculiar understanding of what the IM optimization means [11]. We want to stress that, if your goal is to create the IM with lowest possible NL, it is a wrong way to calculate first the sensor parameters and then to find an amplifier to it. Only a complex optimization of sensor-amplifier system according to the selected criterion – weight or length – can give really optimal IM construction with lowest possible NL in the given frequency range [12].

The ways to get low NL when designing IM are shortly outlined below and the attempt to compare the known IM quality is made.

2. IM operation Principle

The IM transfer function may be derived from the Faraday law of induction:

$$u = -n \cdot \frac{d\Phi}{dt},$$

where u is the voltage induced in a coil which has n turns, Φ is magnetic flux. In the case of a sinusoidal flux variation directed along a longitudinal axis of the core $\Phi = \Phi_{\max} \cdot \cos(\omega t)$, where ω is circular frequency.

Taking this into account, the open-loop peak output voltage of the coil wound on the high-permeability core may be presented as follows:

$$U_0 = \omega \cdot n \cdot \Phi_{\max} = \omega \cdot n \cdot S \cdot \mu_0 \cdot \mu_c \cdot H_e = G \cdot H_e, \tag{1}$$

where μ_0 is permeability constant, μ_c is relative permeability of the core, S is cross section of the core, H_e is measured external magnetic field peak intensity, G is IM sensitivity.

According to (1), ideally, the coil output signal has to depend linearly on frequency (U_{0id} on Fig. 1). But due to the sensor winding equivalent resistance R_e, inductance L and capacitance C the dependence $U_0 = f(\omega)$ or $U_0\ (f)$ is more complicated. Inductance L and capacitance C form the resonance circuit the Q-factor of which depends on the resistance R_e and typical frequency characteristic of an induction coil is presented on Fig. 1 by the solid line. So, we see from this figure that expression (1) is valid only for the frequency band lower than the resonance frequency.

IM may be used in a resonance mode with transfer function as shown by solid line on Fig. 1 for the measurement of the magnetic field fluctuations if the frequency range of interest is very narrow or in time domain mode at frequencies lower than resonance frequency. But in case of the measured signal with wide complex spectra it is necessary to have a wide-band induction magnetometer with linear-flat frequency response (see Fig. 1, dotted line). It can be obtained by several ways: 1) output signal integration, 2) using the sensor with current amplifier, 3) using the sensor with transformer coupled negative feedback.

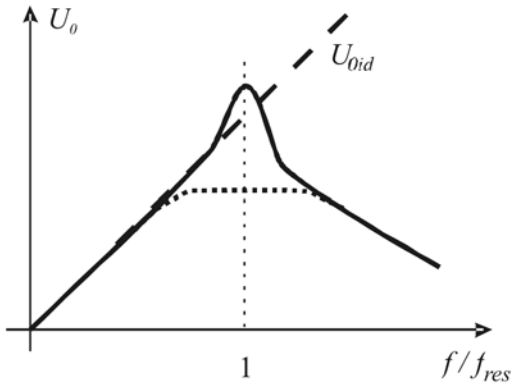

Fig. 1. Solid line – amplitude-frequency response of an induction coil output peak voltage U_0 in resonance mode (f_{res} is a resonance frequency); dashed line – ideal shape of this response; dotted line – typical frequency response of IM.

Each of these operation modes has their own design peculiarities.

1. As it is seen from expression (1) and Fig. 1, the induction coil works as differential section at frequencies lower than resonance frequency. Integration of output signal may make the response linear. In this case IM frequency range is limited at high frequencies by resonance frequency, at low frequencies - by integrator zero drift.

2. In the case of coupling the coil with a current amplifier the coil is loaded by inverting operation amplifier, so it will operate close to short-circuit mode. Frequency response will be linear up to frequency ω_1 =R/L, after that it will be independent on the frequency. The main drawbacks of this circuit are difficulty of its realization at low frequency and higher sensitivity threshold than in the circuit with voltage amplifier.

3. Sensor with transformer coupled negative feedback by the magnetic flux allows obtaining wide-band frequency response, low sensitivity threshold and the main feature of this version is the

possibility to control the flat part of amplitude-frequency response in wide range, up to very low frequencies. So, it is evident that the last solution is the most widespread in practice.

Let us consider the peculiarities of low-noise IM design.

3. Core and Winding Influence on IM Parameters

If to analyze expression (1), it may be seen that the IM output signal is proportional to the winding turns number *n*, core cross-section *S* and core permeability μ_c. We may conclude that to increase IM sensitivity we have to make every of these values as big as possible. Let us see first what is resulting with μ_c increase.

First step to get high μ_c is to use the soft magnetic material with as high as possible relative permeability μ. But because of the demagnetizing field effect [1] the resultant core permeability μ_c is lower than permeability of core material μ and strongly depends on the core shape. It can be calculated as [5]:

$$\mu_c = \frac{\mu}{1 + N(\mu - 1)}, \tag{2}$$

where *N* is the demagnetizing factor. The demagnetizing factor *N* is geometry dependent and, slightly modifying the corresponding expression in [5], we may consider that its value is determined by the ratio *m* of the core length *l* and diameter *d*:

$$N \approx \frac{\ln 2m - 1}{m^2}, \tag{3}$$

It is known that the material permeability μ may change considerably with time and temperature and here *N* plays an important role for the stabilization of the factor μ_c in the expression (1).

It is necessary to mention that the demagnetizing factor *N* according to the expression (3) in reality is valid only for three-axes rotational ellipsoids. N. Feldkeller proposed the simplified expression

$$N = 5S / l^2, \tag{4}$$

which gives enough low error and is widely used for practical calculations [13].

Fig. 2 allows determining lowest acceptable limit of μ at given ratio m in order to keep μ_c constant in wide limits of possible μ changes under the influence of different factors.

As we already stated, the more is μ_c, the higher is IM sensitivity, so elongated wire-like core construction with $m > 50$ is recommended. But as it is seen from Fig. 2, for this case it is necessary to select material with $\mu > 30000$, otherwise its changes may lead to the sensitivity variations, what is not desirable.

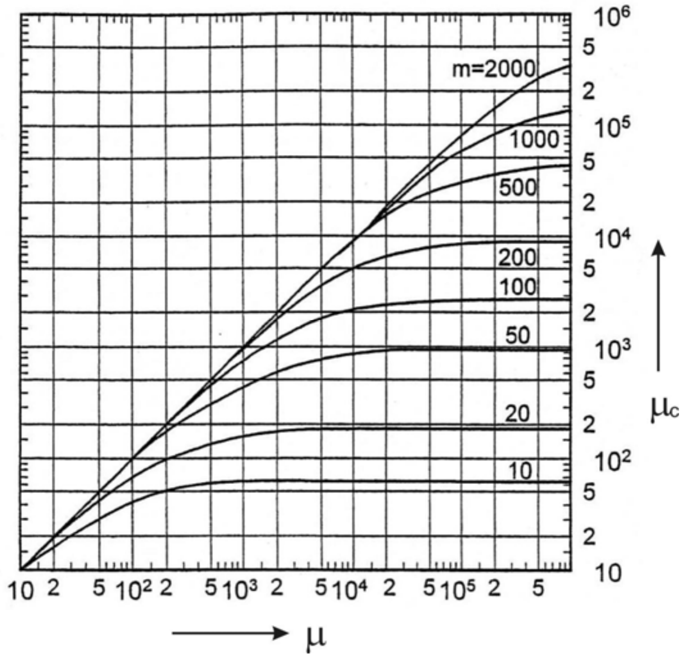

Fig. 2. Core permeability μ_c of cylindrical rods versus the material permeability μ with length-to-diameter ratio *m* of the rod as a parameter, after [2].

It is necessary also to take into account that the existence of a permanent Earth's magnetic field may lead to the core magnetization and core material saturation with corresponding sharp degradation of *G* and other IM parameters. So, for strongly elongated cores the maximal admissible $\mu_{c\max}$ value has to be estimated in order the sensitivity variations in the outer filled $H_e \le H_{\max}$ were below admissible relative error δ. The approximate expression [14] gives:

$$\mu_{c\max} = \frac{\mu}{\sqrt[3]{\left(\frac{1}{\delta}-1\right)\left(\frac{\pi H_{\max}\mu}{2B_s}\right)^2} - 1}, \tag{5}$$

where B_s is the saturation induction of the core material.

This equation is valid approximately until $\mu_c H_e < B_s$. The calculations show that δ value changes very sharply when μ_c approaches to:

$$\mu_{c\max} = B_s H_e^{-1}.$$

That is why the value of $\mu_{c\max}$ determined from the equation (5) with the guaranteed margin is the obligatory upper restriction in order to avoid large errors because of the IM core magnetization in the permanent outer field.

So, at recommended *m* values (50-100), high μ (larger than 50000) allows obtaining μ_c up to 2500 with enough low sensitivity to μ variations (see Fig. 2). Also the moderate value of μ_c guarantees that core will not be magnetized in the Earth's permanent magnetic field.

Considering the core dimensions, let us remind that the core cross-section area S itself also is directly connected with output voltage value – see (1). But, as we showed above, the relation $m = l / d$ is already determined from other considerations and to increase S or, what is the same, d, will reduce proportionally m, then μ_c will decrease too and reduce the effect of S increment. Recently several successful attempts were made to overcome this restriction: the so called flux concentrators are added to both ends of the core, so augmenting S without considerable deterioration of m [10, 11]. It is reported about "threefold" increasing of the IM sensitivity with the ratio of flux concentrator diameter D_c and core diameter $d \approx 5$ [11]. In cited works the sensitivity increment is attributed to the increase of μ_c, named there "apparent permeability", but this postulate is not substantiated, neither theoretically nor experimentally. The reported there mathematical model of the effect of magnetic flux concentration in reality refers not to μ_c increase, but to the increase of the efficient surface S of the core tips. This difference has principal character: if flux concentrators increase μ_c, then they spoil accordingly to Fig. 2 the μ_c stability in time and temperature; if only S is increasing, then no negative effect at all.

Last possibility to raise the IM sensitivity- to increase the winding turns number n, according to expression (1), – is also not so efficient because augmenting n leads to the increase of the winding active resistance R and thermal noise correspondingly. So, it is necessary to increase the copper wire diameter simultaneously, what leads to the copper weight M increase. The theoretical and experimental studies show, that the IM sensitivity threshold W_{BM} depends on the winding (copper) weight M as follows [7]:

$$W_{BM} = \frac{K}{\mu_c \cdot \omega \cdot d \cdot \sqrt{M}}, \tag{6}$$

where $K = 8 \cdot \sqrt{k \cdot T \cdot \Delta f \cdot \rho \cdot \gamma}$. So, IM sensitivity depends mainly on copper weight M and the turns number is selected mostly for the optimal matching of the coil and preamplifier, what relates to the optimization problem of IM design discussed further.

Before to proceed with the IM optimization, let us make still one objection as to the winding influence on IM sensitivity. It is evident that in majority of IM constructions the coil is not wound on the core itself – a special reel is used. So, the coil wound on the reel has internal D_i and external D_e diameters and following relation is valid: $D_e > D_i > d$.

It is also known that the greater is this inequality, the lower is IM sensitivity G [7]. So, we may state that G is inversely proportional to coil mean diameter $D_m = \frac{D_e + D_i}{2}$. Simple physical considerations allow us to ascertain this to the efficient value of μ_c reduction, if a system "core-coil" is considered: $\mu_c \equiv D_m^{-3/2}$ [7].

Further μ_c reduction is caused because IM manufacturers select the coil length l_n always smaller than the core length l. This is because μ_c is not uniform along the core and its maximal value μ_{cc}, which is located in the center, for a commonly used prismatic rods is given by the expression [5]:

$$\mu_{cc} = \frac{\mu}{1 + 0.974 \frac{S}{l^2} \left[\ln\left(l \cdot \sqrt{\frac{\pi}{S}} \right) - 1 \right] \cdot (\mu - 1)}. \tag{7}$$

The coil length l_n occupies not all the core length l because the relative voltage picked up by the coil is decreasing with $l_n / l \to 1$ [6]. In general case the following relation is recommended:

$$l_n \approx (0.5 - 0.7)l \,. \tag{8}$$

From this point of view to name "optimal" the coil construction, which covers all the core length, proposed in [11] is rather doubtful.

Correspondingly, average value μ_{cca} of the μ_c, which has to be taken into account for the coil with fixed l_n gives [5]:

$$\mu_{cca} = \mu_{cc} \cdot \left[1 - 0.255 \cdot \left(\frac{l_n}{l} \right)^2 \right]. \tag{9}$$

After the influence of main coil and core parameters on the IM sensitivity are considered, let us discuss the peculiarities of IM optimal design.

4. IM Design Methodology

For relatively narrow-band IM $(f_{\max} / f_{\min} < 1000)$ it is not very difficult to determine the sensor parameters and the simple approach given in [10, 11] will not give big error: really achievable noise level is close to the theoretical one for given weight and dimensions of a sensor.

For wide-band IM $(f_{\max} / f_{\min} > 1000)$ direct optimal matching of sensor and preamplifier is impossible because of different dependence of sensor output impedance and optimal impedance of signal source for the preamplifier on frequency. Calculation of IM noise with given threshold sensitivity for wide frequency band and weight/dimensions restrictions requires taking into account simultaneously a great number of its 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 (e.g., wire diameter). That is why in spite of as one would think rather simple task, the optimal set of values determination by versions look-over or equations system solution is impossible.

To make the task easier, 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 possible values given by the desired construction;
2) The recommended in papers relations between some intermediate parameters are accepted and another ones which are necessary for calculations are postulated, 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 considerable errors.

Mostly the optimal combination of sensor and preamplifier one finds as a calculation of optimal sensor parameters for an ideal preamplifier, and then the matching with the real preamplifier is executed by the sensor turns number correction. This procedure gives not absolute optimum combination but the complex of two relative optima, what leads to incorrect result, especially important in high frequency band.

A new approach for the optimized wide-band IM design was proposed [13, 14] and corresponding calculation method and computer program were developed. The main peculiarity of this method consists in the introduction of so called "generalized parameters" of the sensor, which values may be considered as constant for the given core material.

A set of 4 main generalized parameters K_i and 3 additional ones are given in the Table 1.

Table 1. IM generalized parameters.

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

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

The use of generalized parameters allows conceiving all the sensor parameters in very simple and physically clear form, for example:

$$G = K_S f \cdot l^2 \cdot n ; \quad (10)$$

$$L = K_L \cdot l \cdot n^2 ; \quad (11)$$

$$Q = 1/[K_R/(f \cdot l^2) + 1/Q_h + f/f_F] ; \quad (12)$$

$$f_{res} = K_f/(l^{1/2} \cdot n) ; \quad (13)$$

$$R = 2\pi K_R \cdot K_L \cdot w^2/l , \quad (14)$$

where Q is the main component of q-factor, depends on core and winding losses.

As a comment, it is necessary to say the following. The choice of a determined combination of generalized parameters means implicitly the choice of IM materials and construction with determined geometrical sizes relation. That is why the given calculation methodology is especially simple and efficient for the determination of optimal length and turns number of geometrically similar IM for standard operation conditions (wide frequency band, including infralow part, limited weight etc.).

As to a preamplifier, the frequency spectrum of its noise is characterized by an extended set of 8 noise parameters: minimal noise voltage density W_{u0}; corner frequency and angle of elevation at low frequencies f_{u1}, αu; corner frequency of additional elevation at extremely low frequencies f_{u2}; minimal noise current density W_{i0}; corner frequency and elevation angle of the current noise at high frequencies f_{i1}, αi; corner frequency at low frequencies f_{i2}. Then voltage and current noise densities frequency responses of the amplifier may be calculated with the equations:

$$W_{uamp} = W_{u0}[1 + (f / f_{u1})^{\alpha u} + (f / f_{u2})^2]; \tag{15}$$

$$W_{iamp} = W_{u0}[1 + (f / f_{i1})^{\alpha i} + (f_{i2} / f)^2]. \tag{16}$$

The equations for the calculation of frequency spectrum of the complete IM noise are composed according to equivalent IM diagram on Fig. 3, 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 eddy currents losses one - R_F) with density $W_r = 4kT(R + R_h + R_F)$, I_{ro} - noise current of the losses (R_0) in the output winding capacitance C with density W_{Ir0}, R_i - input resistance of preamplifier (all resistors are supposed to be noiseless), U_n and I_n - input noise voltage and current of the preamplifier with densities W_{uamp} and W_{iamp} respectively, which are characterized by mentioned 8 parameters.

According to Fig. 3, the resulting voltage noise density W reduced to the amplifier input is:

$$W = W_r \cdot k_U^2 + W_{Uamp} + \left(W_{Iamp} + W_{Ir0}\right) \cdot Z^2 \cdot k_U^2, \tag{17}$$

$k_U = \dfrac{Z_C}{Z_C + Z_L}$ is the circuit transfer function, where $Z = \dfrac{Z_C \cdot Z_L}{Z_C + Z_L}$ is the coil impedance, $Z_C = \dfrac{R_0 / j\omega C}{R_0 + 1/ j\omega C}$, $Z_L = R + R_h + R_F + j\omega L$.

The total power noise density in the values of the measured magnetic field W_B, using the definition for the coil sensitivity $G = U_0 / H_e$ from (1), is

$$W_B = \frac{W}{G^2 \cdot k_U^2} = \frac{1}{G^2} \cdot \left[W_r + \frac{W_{Uamp}}{k_U^2} + \left(W_{Iamp} + W_{Ir0}\right) \cdot Z^2 \right]. \tag{18}$$

On the base of the resulting expression (18) the calculation program was created with a developed service part, what allows us to present the set of IM NL in the form of plots or tables, where some given parameters can be changed, starting from those of sensor and ideal lossless 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 stored. A special version of the program is developed which allows automatic look-over of possible IM realizations within given limitations and alleviates the choice of the version, providing the minimum NL 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 corresponding changes in noise spectrum is made automatically. The example is given on Fig. 4 which illustrates the calculation example when sensor winding turns number is varied. It is clearly seen that the low frequency parts of noise plots are bent and noise minima are shifted to lower frequencies with the number of turns increasing (plots 1, 2, 3; w3>w2>w1). When an optimum is passed, IM noise becomes higher for all frequencies (plot 4, w4>w3).

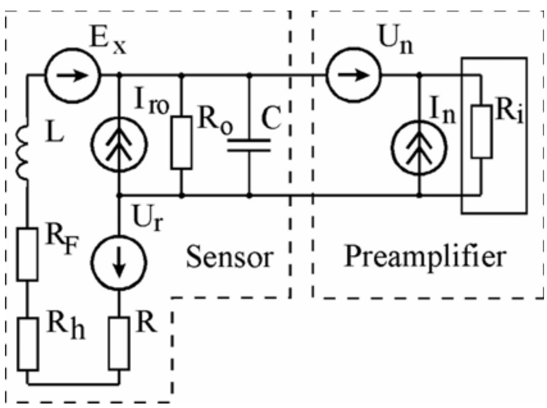

Fig. 3. Equivalent noise circuit of IM.

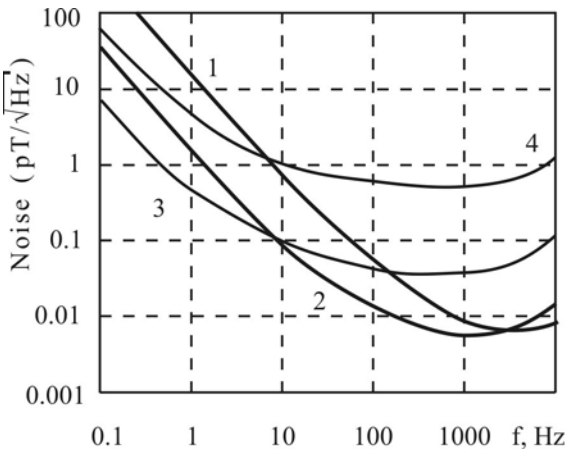

Fig. 4. Influence of turns number change on IM noise level.

To estimate how close the obtained magnetic noise density is to the lowest possible NL for the given length l, a following semi-empirical formula [15] may be used which gives theoretically lowest possible NL:

$$W_{Bl} \approx h_0 (1 + A / l^5 \cdot f^2 + B / l^5 \cdot f^4)^{1/2}, \quad (19)$$

where $h \approx 10^{-14}$T / Hz$^{1/2}$; $A \approx 30\ m^5 \cdot$Hz^2; $B \approx 10^{-4}\ m^5 \cdot$Hz^4.

Some comments to this expression are necessary. First, here it is postulated that the NL threshold is depending on l only, what is valid for geometrically similar IMs. Next, it has sense for the frequency band $f < f_{res}$ only and is valid for the optimized IM with the core made of best materials with high μ. And last, the second term – $B / l^5 f^4$ – reflects the additional preamplifier noise increment in the infra-low frequency band for a direct amplification chip. If a chopper is used as a preamplifier, this term has to be neglected.

The restricted article volume does not allow us to go further into low noise IM design details which may be found in given references [5, 6, 7, 12, 15], but it is necessary to mention that, because of clear commercial validity of the optimal IM design to compete at world market, the most important details of low noise IM manufacturing remain as know-hows of the producers, never published in open literature.

To compare the quality of the existing at the market IMs produced by different companies, an attempt to introduce an impartial assessment is made.

5. IM Quality Assessment

The principal goal to give the criteria to compare IM quality was to introduce a parameter which could help first of all to the numerous professional and amateur designers to estimate the efficiency of the novelties they introduce against the existing IM.

We realize that this task is not a simple one, as well as every IM has its individual parameters, operation frequency range etc. Nevertheless, taking into account the fundamental dependencies of the most important IM parameter – noise level – on sensor geometry and weight, we made an attempt to express it in terms of the postulates given in the present paper. Main of them are:

- NL threshold decreases with l as $l^{5/2}$;
- NL threshold decreases with weight M as $M^{1/2}$.

For existing IM the W_B values of threshold NL for a fixed frequency are documented in technical specifications. Then a quality factor QF may be deduced as:

$$QF = \frac{K_c}{W_B l^{5/2} M^{1/2}}, \quad (20)$$

where K_c is the scale factor.

This expression has following physical sense. Having the length of the IM, we may use (19) to estimate the lowest possible W_{Bl} level for the given sensor with length l. Then, using (6) and accepting that for geometrically similar sensors all terms there besides M may be taken constant and equal to K_1, we may rewrite expression (6) for the same frequency as

$$W_B = K_1 \cdot M^{-1/2} \quad (21)$$

and find lowest possible W_B value for this weight. So, we'll get NL estimations for ideal sensor with given l and M.

Then for every IM we take real value of W_B given in their specifications, which is always higher as ideal one, and multiply all values according to the equation (20). Now it is evident that the closer real W_B is to the ideal W_{Bi} for given l and M, the higher is QF and the better is the IM.

The efficiency of such an approach was confirmed by the comparison of best known low-frequency IMs (Table 2) which operate in the frequency band from ~10^{-4} till ~10^3 Hz: LEMI-120, LEMI-121 (by LC ISR), ANT/4 (by Zonge Engineering), MFS-06, MFS-07 (by Metronix), BF-4, BF-7 (by EMI), MTC-50 (by Phoenix).

Table 2. Best commercially available low frequency IMs.

IM	Frequency range, Hz	Sensitivity at flat part of FR	Dimensions, m	Weight, kg	Sensitivity threshold W_B, $nT/\sqrt{Hz}$, at 1 kHz
MTC-50	$2\cdot10^{-4}\div4\cdot10^{2}$	1 V/nT	l=1.41; d=0.06	10.5	$3\cdot10^{-4}$
BF-4	$1\cdot10^{-4}\div1\cdot10^{3}$	0.3 V/nT	l=1.42; d=0.06	7.9	$8\cdot10^{-5}$
BF-7	$1\cdot10^{-4}\div1\cdot10^{3}$	0.3 V/nT	l=1.04; d=0.06	7	$1.5\cdot10^{-4}$
ANT/4	$5\cdot10^{-4}\div1000$	100 mV/nT	l=1.38; d=0.048	6.2	$1\cdot10^{-4}$
LEMI-120	$1\cdot10^{-4}\div1\cdot10^{3}$	200 mV/nT	l=1.38; d=0.085	5.8	$1\cdot10^{-4}$
MFS-06	$2.5\cdot10^{-4}\div500$	0.2 V/nT	l=1.25; d=0.075	8.5	$1\cdot10^{-4}$
MFS-07	$1\cdot10^{-3}\div500$	0.64 V/nT	l=0.8; d=0.075	5.5	$3\cdot10^{-4}$
LEMI-121	$1\cdot10^{-4}\div500$	200 mV/nT	l=0.56; d=0.085	4	$5\cdot10^{-4}$

It is interesting to compare first their noise plots – see Fig. 5. All of these plots are below the plot representing the natural noise spectrum and are rather close one to another, what shows practical similarity of all best known low-frequency IMs by this parameter, but does not give possibility to say what design is better - *l* and *M* of these IM are different.

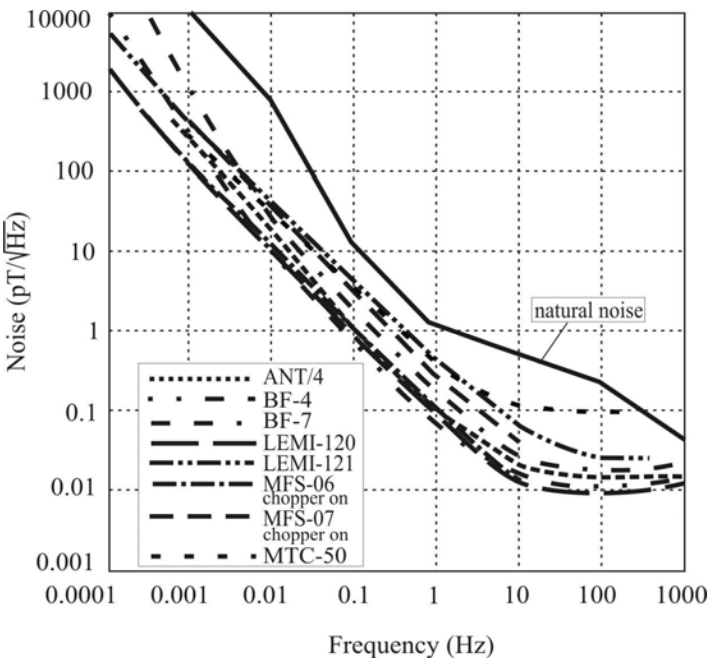

Fig. 5. Noise plots for low frequency IMs.

But if to calculate *QF* and plot them (Fig. 6), we immediately see the difference: majority of them are rather similar, and only two are out of the cluster (column A). The attempt to compare high frequency

IMs (Table 3) also gives good clustering of their parameters (column B on Fig. 6), whereas their noise plots do not allow the comparison at all (Fig. 7). But if to take specialized IMs, for example for space research, we have very big scattering, what may be also explained: one of the main conditions – geometric similarity – is not observed here and the comparison of their quality needs further research.

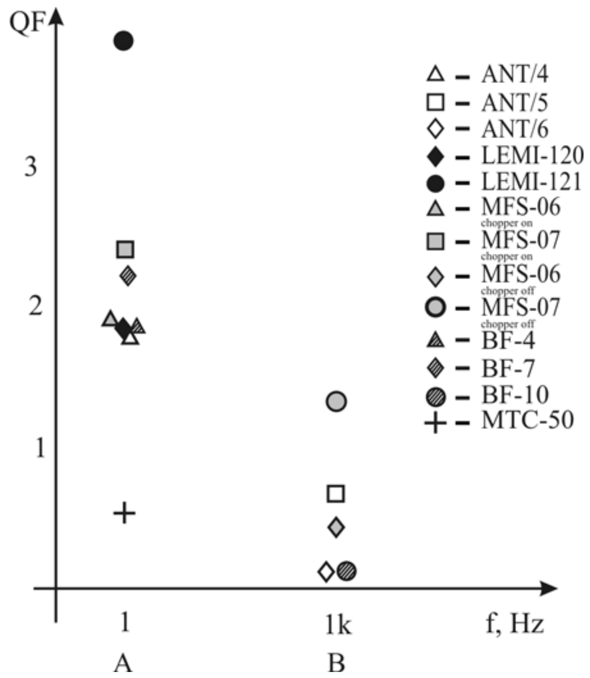

Fig. 6. QF estimation for low frequency and high frequency IMs.

Table 3. Best commercially available high frequency IMs.

IM	Frequency range, Hz	Sensitivity at flat part of FR, mV/nT	Dimensions, m	Weight, kg	Sensitivity threshold B_{th}, $\mathrm{nT}/\sqrt{\mathrm{Hz}}$, at 1 kHz
BF-6	$1\text{-}1\cdot10^5$	300	l=0.73; d=0.05	1.7	$1.5\cdot10^{-6}$
BF-10	$0.1\div1\cdot10^4$	300	l=1.42; d=0.06	7	$1.5\cdot10^{-6}$
ANT/6	$0.1\div1\cdot10^4$	200	l=0.91; d=0.048	3.2	$1\cdot10^{-6}$
ANT/5	$0.25\div1\cdot10^4$	100	l=0.61; d=0.036	1.5	$2\cdot10^{-5}$
LEMI-118	$0.1\div1\cdot10^5$	20	l=0.85; d=0.046	1.7	$3\cdot10^{-5}$
LEMI-106I	$0.5\div1\cdot10^5$	20	l=0.4; d=0.035	0.33	$2\cdot10^{-5}$
MFS-06	$10\div1\cdot10^4$	200	l=1.25; d=0.075	8.5	$5\cdot10^{-7}$
MFS-07	$10\div5\cdot10^4$	640	l=0.8; d=0.075	5.5	$5\cdot10^{-7}$
SHFT-02	$1\cdot10^3\div3\cdot10^5$	50	0.17x0.19x0.17	5.5	$5\cdot10^{-5}$

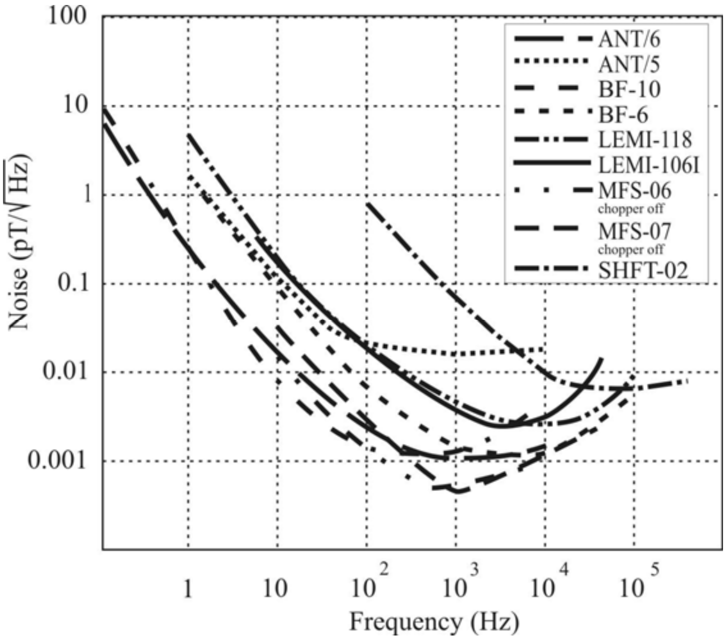

Fig. 7. Noise plots for high frequency IMs.

6. Conclusions

The aim of this short review of IM design technology was to show that first, to get IM with low noise needs a complicated calculation procedure. Second, it is stated that modern level of different approaches to the IM development is rather similar. This conclusion is confirmed by the comparison of the IM excellence using the proposed quality factor. Though, probably, validity of this comparison is not enough thoroughly substantiated, the users opinion as to different IM types quality, especially for the most widespread – low-frequency IM – is mostly coinciding with given QF estimation. The authors goal was also to stimulate the research in this branch, as far as until now there is not a generalized approach to the IM quality comparison, the need in which is obvious both for commercial reason and for to have though any criterion to pave the way for further attempts of new IM design efficiency estimation.

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References

[1]. V. K. Arkadyev, Electromagnetic processes in metals, Part 1, *ONTI*, 1935 (in Russian).
[2]. R. M. Bozorth and D. M. Chapin, Demagnetization factors of rods, *J. Appl. Phys.,* Vol. 13, 1942, pp. 320-326.
[3]. M. A. Rozenblat, Demagnetization factors of high permeability rods, *J. Techn. Phys.,* Vol. 24, Issue 4, 1954 (in Russian).
[4]. K. Varmuth, Uber den ballistischen Entmagnetisierungsfactor zylindrischer, Stabe *Arch. f. Elektrotechnik,* Vol. 41, 1954, pp. 242-257.
[5]. L. Ya. Miziuk, Primary transducers for low-frequency magnetic fields measurement, *Naukova Dumka,* Kyiv, 1964 (in Russian).

[6]. G. Dehmel, Magnetic field sensors - induction coil (search coil) sensors, Chapter 6 in: Sensors – a comprehensive survey, *VCH Publishers,* 1989, pp. 205-254.
[7]. F. F. Vakulski, L. Ya. Miziuk, R. V. Prots, Yu. Yu. Sikachevski, Instrumentation for aerogeophysical prospecting with magnetic and electromagnetic informational channels, *Naukova Dumka,* Kyiv, 1985 (in Russian).
[8]. P. Ripka, Induction Sensors, Chapter 2 in: Magnetic sensors and Magnetometers, *Artech House*, 2001, pp. 47-74.
[9]. S. Tumanski, Induction coil sensors – a review, *Meas. Sci. Techn*., 2007, Vol. 18, pp. 31-46.
[10]. C. Coillot, J. Montoussamy, P. Leroy, G. Chanteur, A. Roux, Improvements on the design of search coil magnetometer for space experiments, *Sensors Letters*, 2007, Vol. 5, pp. 167-170.
[11]. E. Paperno and A. Grosz, A miniature and ultralow power search coil optimized for a 20 mHz to 2 kHz frequency range, *J. Appl. Phys*., 2009, Vol. 105, 07E708.
[12]. V. Korepanov and R. Berkman, New approach to the exact design of low noise search-coil magnetometers, in *Proceedings of XIV IMEKO Word Congress: New measurements - challenges and visions*, Tampere, Finland, 1997, Vol. IVA, Topic 4, pp. 103-108.
[13]. L. Kadinskaya, To the calculation of the different permeability of cores for magnetomodulation sensors. Technical information bulletin on geophysical instrumentation, Leningrad, 1958 (in Russian).
[14]. R. Ya. Berkman, Wideband induction magnetometers with minimal weight, in *Proceedings of the V National Symposium of Magnetic Measurements,* Kielce-Borkow, Poland, 22-24 October, 1997, pp. 45 – 52 (in Russian).
[15]. V. Korepanov and R. Berkman, Comparison of magnetometers efficiency for ELF band, in *Proceedings of the 2nd International Conference of Measurement (Measurement'99),* Smolenice, Slovak Republic, 26-29 April, 1999, pp. 195-198.

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