Theoretic and Experimental Investigation of Flux-Gate Magnetometer Noise

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Abstract

The problems of calculation and measurement of magnetic noise (MN) are considered, the results of research in this branch are described. It is shown that the amplitude distribution of MN is the more deviating from the normal distribution the wider is the frequency band and the lower is the signal frequency. The rise of MN density in the direction of very low frequencies can be approximated by $1/f^{\alpha}$ function where $\alpha \cong 3/4$ but exact value of α is not important for calculation of MN in low frequencies up to 1 year period. It is shown experimentally that the $1/V^{1/2}$ dependence of MN from core volume is true for constructions without additional error sources independently from the core dimensions ratio. Exponential dependence of MN with excitation frequency growth is theoretically explained. The materials with low saturating induction and Curie point close to working temperature showed low MN near the absolute minimum at that time.

Keywords: flux-gate, sensor, magnetometer, noise

1. Introduction

The flux-gate magnetometers (FGM) are the most widespread instruments for weak magnetic field measurements. The magnetic noise (MN) - fluctuations, arising by periodic magnetization of flux-gate sensor (FGS) core - are in principle unremovable and determine sensitivity threshold of modern FGM. Another sources of short-term errors, including electric fluctuations in electronic part, may have influence on output noise of high sensitivity FGM mostly in non-professional constructions and are not taken into account more.

The MN problems were considered mostly in parallel both for FGS and magnetic modulators (MM) because of their similar principle of operation and because MM are investigated in details for former applications, i.e. nanovoltmeters [1]. It was both experimentally and theoretically proved by the author that MN for both FGS and MM with the same ring core dimensions are practically the same with multiplier 1.41 [2]. That is why a set of results, related to common MN problems for MM and FGS, are taken below into account without reservation.

The present work summarizes the results of many years of investigations in this branch in LCISR. The author's papers were published in former Soviet Union in numerous editions which are little known by western specialists. At the same time the number of works published in the West is estimated to be about some hundreds, and so the bibliography even concerning only basic mentioned problems would take too much place. That is why the references are given here only to works having character of priority.

2. Amplitude distribution and spectral density of noise

It is accepted that MN of the specific device is characterized enough completely with its spectral density and amplitude distribution. A lot of papers is devoted to the study of spectral density, but the data about amplitude distribution are absent in known papers, though in a number of cases this parameter may be important. Apparently this is because of the fact that MN is related to noise process, what guarantees from the point of view of the investigators the stationarity, ergodicity and normal distribution of MN amplitude probabilities. Our study of MN amplitude distribution showed, however, that it differs from the normal law [3].

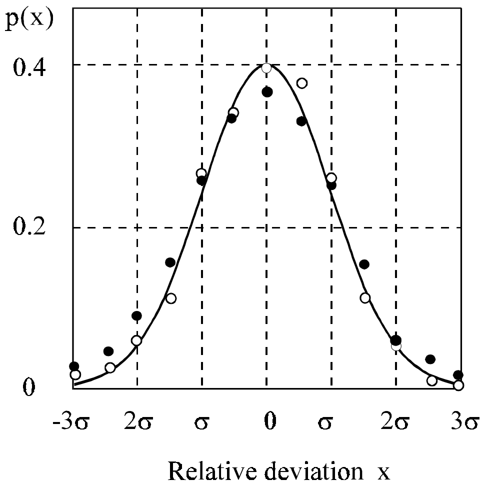

Fig.1. Magnetic noise amplitude probability distribution

The corresponding experimental study was done and the resulting probability distribution for three frequency subranges 0.5 ... 100 mHz, 30 ... 300 mHz and 1 ... 10 Hz, was estimated. The big total time of measurements (up to 17 hours, more than 60000 samples at each serial) was used for increasing the accuracy.

Fig.1 illustrates the obtained results. Here solid curve corresponds to theoretical normal low, dark circles - to the 0.5...100 mHz subrange, open circles - to 1...10 Hz subrange. The data measured for 30...300 mHz subrange gave middle results between said two low and high frequency subranges and were not given at Fig.1. High frequency range results negligibly deviate from the theoretical curve, but for low frequencies experimental points form more «flat» curve than theoretical one.

One can say that these discrepancies are also negligible but it is not so in reality: apparently small shifts in the band of big relative deviations σ give considerable changes in p(x) probability for big σ. For example, for 3 σ and greater deviations the p(x) estimation gives about (2.5 $\pm$0.7)%, what is approximately 8 times more than for normal low distribution and the necessary standard value of 0.3% is obtained here only for ~4 σ.

In other words, it means that the coefficient K in the expression $B_p = K \cdot B_{sq}$ for calculation a peak deviation B_p of low frequency MN with known root-mean-square B_{sq} should be increased in comparison with standard value of 2.5, roughly up to 3...3.5.

The physical and mathematical models which were used originally for the analysis of the MN frequency spectrum, predict its uniform shape. The rise of MN spectrum in the low frequencies range we discovered apparently for the first time [4] and further it was the subject of detailed research. It was found that MN density b(f) and root-mean-square value B_{sq} may be estimated by the following semi-empirical equations:

$$b(f) = b_0 [\, 1 + (f_0 / f)^{\alpha} \,]; \qquad (1)$$

$$B_{sq} = \{ \int_{f\,min}^{f\,max} b\,(f)\,df \,\}^{1/2} =$$

$$= \{\, b_0 [\, f_{max} - f_{min} + f_0^{\alpha} (\, f_{max}^{\beta} - f_{min}^{\beta} \,) / \beta \,] \,\}^{1/2}, \qquad (2)$$

where $\beta = 1 - \alpha$, f_{max} and f_{min} - correspondingly maximum and minimum frequencies of full frequency band of FGM.

The shape of MN frequency spectrum is determined by the corner frequency f_0 and coefficient α. In early FGM developments the corner frequency f_0 was about some hundreds Hz, while for DC amplifiers with MM at the input - only some Hz. The investigators admitted that this difference in the shapes of the frequency spectra reflects the basic difference in physical processes, occurring in MM and FGS.

From our point of view an extra noise of FGS is connected only with its specific design. Further, especially because ring-core and race-track FGS were developed, the value of f_0 in the majority of the cases was reduced up to ~1 Hz both for FGM and MM.

By its character MN is similar to flicker noise, for which α=1 is usually taken. However our detailed research of MN frequency spectrum for different materials and designs in frequency band up to 1 mHz showed that the value of α for FGS has to be accepted in limits of 0.75...0.8.

Let us emphasize again that in known works the α value was more often accepted to be equal to 1 and even more than 1. This apparently small difference gives principally other results as to the MN power calculation. Really, for α=1 equation (2) is transferred to

$$B_{sq} = b_0 [f_{max} - f_{min} + f_0 \ln (f_{max} / f_{min})] \qquad (2a)$$

what means that the more observation time increases the more noise deviations are approaching to infinity.

But it is not observed in practice - even during one year of observation (what corresponds to $f_{min} \cong 3 \cdot 10^{-8}$ Hz) the zero level of FGM changes in rather narrow limits. This is because of logarithmic increasing of B_{sq} value while b(f) is growing hyperbolically when $f_{min} \to 0$. Even the increasing of b(f) by many orders leads only to moderate growth of B_{sq}.

In order to explain this let us proceed as follows. B_{sq} value is determined on the interval from f_{min} to f_{max}. Its growth when f_{min} is decreased (or, what is the same, observation period T_{max} is increased) is convenient to estimate in relative units. Let us take as comparison base the noise signal with constant density $b(f)=b(f_0)$=const and corresponding B_{sq} value designate as $B_{sq}(T_0)= B_{sq}(1\,s)$ when $f_0 = 1$ Hz.

The $B_{sq}(T_{max})$ / $B_{sq}(T_{max})$ ratio is presented on Fig.2, upper plot for α=1, lower one for α=0.8.

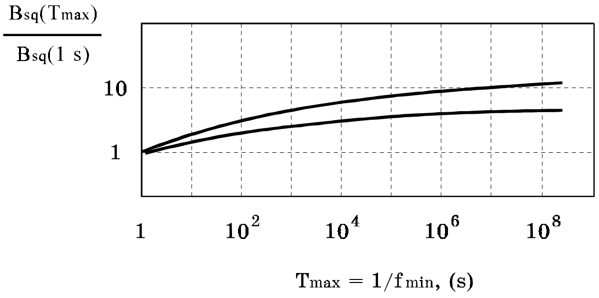

Fig.2. Magnetic noise peak growth with $f_{min} \to 0$

It is interesting to stress that for the observation time equal to 1 day (~86400 s) MN density for α=1 also augments in 86400 times, but B_{sq} is only 8 times higher (Fig.2, upper curve) relatively to uniformly distributed $b(f)=b(f_0)$ density. Correspondingly for 1 year period for which $b(f_{min})/\ b(f_0) \approx 3.1\cdot 10^7\ B_{sq}$ augments only in 11 times.

It is seen that for periods from 1 day to 1 year the ratio between B_{sq} values for α=0.8 and α=1 is ~2.2...2.5, what is essential but not coincides with «infinite» growth of b(f).

It follows also from equation (2a) and Fig.2 that even for 1 year period the calculated value of peak-to-peak MN deflection for typical FGM with $b_0^{1/2} \cong 10$ pT/Hz$^{1/2}$ is in good enough agreement with experimental data obtained in practice - 1...2 nT. Thus, extremely low-frequency MN process obeys to the laws as usual infra-low-frequency ones and expressions (1,2) may be used in the frequency band approaching zero too.

Going back to the expression (2), it is evident to conclude that the only alternative to lower the FGM MN is to decrease b_0 value. the possibilities of this are analyzed in details below.

3. Excitation current shape, amplitude and frequency influence

The simplified theory of FGS predicts the dependence of MN level on excitation frequency f_e by the law of $1/f_e^{1/2}$ and the achievement of minimal level of MN with excitation current amplitude I_{em} which corresponds to maximal sensitivity. This theory doesn't take into account the influence of excitation current shape and was not proved to be true in practice: the decreasing of MN with increasing of frequency has an asymptotic character, MN minimum is achieved at very large meanings of I_{em}, and the shape of the excitation current $i_e(t)$ has essential importance.

This discrepancy with the theory was thoroughly investigated. As we obtained, it is because of sharp difference of remagnetization process of high-permeability sheet-shaped ferromagnetic alloys used as FGS core from the commonly adopted model. Main cause of this, as we think, is that the eddy currents in these works are taken into account simply by introducing the correction of B(H) dependence. Considering strong skin-effect it is far from sufficient.

According to our model, for typical material and thickness of FGS core tape the magnetic reverse occurs in the narrow surface layer which is extended from the surface into the center of tape. Above the edge of magnetic alloy reversed layer the material is saturated in the direction of magnetizing field, under it - in the opposite direction which remained from previous magnetizing period. The thickness of magnetically reversed layer which determines the common equivalent magnetic permeability of a sheet with other equal conditions depends on speed of the magnetic induction change, i.e. on instant value of the voltage applied to the excitation winding. After bulky mathematical transformations the final formula for relative magnetic permeability of material during the remagnetization time, averaged through the sheet thickness looks as follows:

$$\mu \cong 2.5 / (\mu_0 \cdot \sigma \cdot f_e \cdot d^2) \qquad (3)$$

where $\mu_0 = 4\pi\cdot 10^{-7}$ H/m; σ - specific conductance of the material, $1/(\Omega\cdot m)$; d - thickness of tape, m.

This expression can be used only for the time intervals corresponding to the magnetization period. For rectangular shape of the excitation voltage the magnetization speed and remagnetized layer thickness as well as μ value are independent from time. Also from the expression (3) follows that μ is in inverse proportion to the excitation frequency f_e and does not depend on the material permeability μ_m . The accepted model of remagnetizing process explains it as a consequence of proportional decrease of remagnetized layer thickness with the growth of μ . So, the maximum μ value for given f_e can be obtained when the magnetization voltage is as slowly changed as possible, i.e. by rectangular excitation voltage. For comparison, the sinusoidal current excitation mode leads to the case when magnetization occurs within a smaller part of excitation period what is equivalent to the sharp growth of f_e .

Still one disadvantage of changes of excitation voltage instantaneous value within the remagnetization period is that it causes the corresponding variations of $\mu(t)$ what results in both output voltage spectrum and sensitivity level changes.

So, the best FGS excitation mode is when the excitation voltage shape is as close to the rectangular one as possible and the excitation current is as high as possible. These both features may be best of all realized in so called ferroresonance excitation mode (FEM), when the excitation winding W_e of flux-gate core and its shunting capacitance C_k form a non-linear oscillator with low active losses [5]. Fig.3 presents the realization of FEM and Fig.4 - diagrams of current and voltages in the circuit.

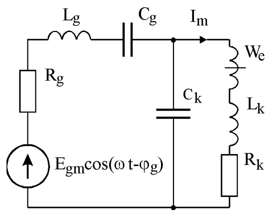

Fig.3.
FEM schematic diagram

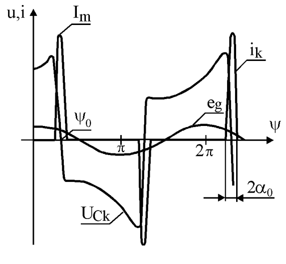

Fig.4. Voltage and
current curves of FEM

The main idea of FEM consists in the use of storing capacitance C_k charge which is formed in the end of almost rectangular interval of the excitation voltage for the generation of discharge pulse of great amplitude at the interval, when the core material is saturated. Because of relatively short time of the saturation interval the energy input is sharply decreased, especially when discharge circuit has high Q- factor.

It should be noted that the coupling of the capacitance in parallel with the FS excitation windings was used by some investigators with simple and physically clear aim to compensate the reactive power component in the excitation generator circuit. But only deep and thorough analysis of FEM based on non-linear circuits theory (and not on their linear approach) allowed to reveal in full volume both potential FEM advantages and inherent difficulties, including error analysis .

Using FEM, it is possible to have in the excitation winding current pulses I_m (see Fig.4) achieving amperes, when mean consumed current is only tens of milliamperes and active losses in the winding are less than 0,05 watt. High amplitude of excitation field (2000 A/m and more) allows to reduce MN and zero drift up to minimum possible level.

The important FEM advantage is that the excitation current pulse width $2\alpha_0$ (see Fig.4) which mainly determines the FGS sensitivity, is dependent only on the C_k value and w_e parameters when the core is saturated. It means that the FGS sensitivity remains stable when variations of excitation voltage and ambient temperature (and connected to it core saturation induction) occur.

In order to compare the known excitation modes their main parameters are assembled in the Table 1.

Table 1. Comparison of excitation modes.

Excitation mode / Parameter	Current sinu-soidal	Voltage sinu-soidal	Voltage rectan-gular	FEM
Sensitivity threshold *	+	+ +	+	+ +
Even harmonic error *	+	+ +	+	+ +
Generator voltage changes error *	+	0	0	+ +
Zero offset by overload*	0	+	+	+ +
Sensitivity stability **	0	+	+	+ +
Rapidity **	+	+ +	+ +	+ +
Self-heating of sensor *	0	+	+	+ +
Realization simplicity**	+ +	+ +	+ +	+
Analysis and calculation simplicity**	+ +	0	+	0

In Table 1 for convenience:

for * : + + low; + medium; 0 high.
for ** : 0 low; + medium; + + high.

The calculation of FEM excitation circuit is fairly complicated and it may be realized only for relatively narrow set of parameters. But for the practical use important is only to have clear understanding of qualitative relation of FEM parameters and of the process in the circuit.

In fact the FEM realization needs higher qualification of circuit designer as other modes, what is, may be, its greatest disadvantage. But the gains are still greater and can not be achieved by any other known means.

Using FEM or other excitation modes, close to square-wave voltage, is recommended also for the excitation voltage even harmonic error reducing. If to analyze the physical process of the one-element FGS with bar core operation, it can be seen that in the sinusoidal current excitation mode when the amplitude of saturation field H_{em} is enough high, the output signals for constant measured field strength H_0 and for the field of second and forth harmonics of excitation current H_2, H_4 with the same amplitude will be equal [6].

Fig. 5 illustrates that the induction curves produced by the constant measured magnetic field H_0 (Fig.5, b) and by the fields H_2 (Fig.5, c) and H_4 (Fig.5, d) are very close. Correspondingly practically equal will be also the false output signal having the second harmonic frequency.

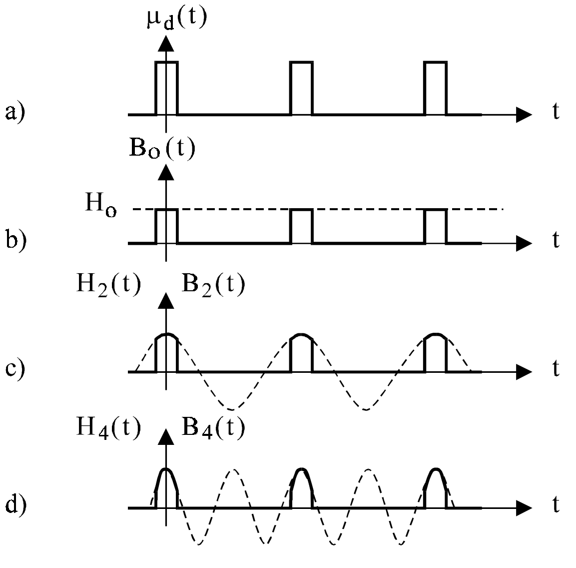

Fig.5. Even harmonics influence at sine wave excitation

In two-elements FGS the influence of even harmonics is reduced proportionally to the symmetry of elements or the sides of the closed core, but no more than in ~30...100 times. The fluctuation of FGS false signal are reduced additionally proportionally to instability coefficient of false even excitation harmonics, but the smaller is the content of even harmonics the worse is their stability. For very low frequencies the directly measured total level of fluctuations is about 0.0001%. Accepting for an estimation the amplitude of the excitation field H_{em} = 1000 À/m, we receive for the given excitation current the fluctuations of the FGS output signal about 10...30 pT that is rather unacceptable.

The use of FEM allows to decrease considerably the even harmonics influence. This is because the current pulse I_m (see Fig.4) in the core saturation state is determined only by circuit impedance and is not directly connected with the excitation voltage. The more is the Q-factor of the C_k discharge circuit including excitation winding W_e the better is the relative even harmonics damping. It is because when Q is enough high the core magnetization process is driven mostly by the energy stored in C_k and the amplitude of the external current is very low because this current is used only for the small additional charge of C_k. To this, the discharge pulse takes only a small part of the excitation voltage period.

The exact theoretical analysis of possible errors was made [7,8] and corresponding formulae were obtained, too cumbersome to show them here. The estimation using these formulae was made. It was shown that false second harmonic influence when FEM is used can be 1.5...2 orders of magnitude lower than in given current excitation mode. Also for higher orders of even harmonics the FEM theory predicts still higher damping.

4. Core volume and shape influence

The simplified theoretical analysis of MN dependence on core sizes was made originally for MM. From simple physical reasons it followed that with increasing of the area of the core section useful signal and number of noise jumps grow proportionally to the area and the rms noise voltage - proportionally to square root of jumps number. The similar relations are observed for the increase of the core diameter. From this follows that in units of measured intensity of the field $MN \equiv 1/\mathrm{sqrt}(V_c)$, where V_c is the core volume. This conclusion of the theory has not received confirmation in published experimental research of FGM MN. The small duration of jumps, the absence of their overlapping etc.- obviously did not correspond to an observed physical picture. Moreover, very low frequency part of the amplitude and phase spectrum of MN has not satisfactory theoretical explanation. The majority of the researchers have the opinion that the FGS core dimensions are not or very few influencing the MN level, though they did not state it definitely.

When ring-cores were introduced again, the attention was paid that MN along ring core are almost fully correlated. Thus it was supposed that because of correlation and subtraction of noises of ring halves in a measuring winding the resulting MN of ring-core FGS will be less than that of MM. Unfortunately, it is not so: it was shown [4] that MN level in units of voltage, from one side, is inversely proportional to square root of core cross-section area S and, from the other side, proportional to square root S because of the MN jumps number increase, so has no dependence on S. The sensitivity of FGS does not practically depend on S, then MN in units of B_x is also stable. The ring-core construction is optimal from another point of view - the uniform magnetic remagnetization promotes the elimination of by-effects, connected with residual magnetization of the core parts.

During our experimental research the main attention was given to elimination of the additional noise sources, connected with the quality of the manufacturing of MM and FGS cores with big volume of ferromagnetic - the winding defects, mechanical stresses and so on. To achieve the statistically authentic results the cores with the large band of volumes and made in each series from the same batch of material with the common heat treatment and identical shape and amplitude of excitation field were investigated [9].

Our experience shows that $1/V_c$ dependence of MN is always observed if augmentation of V is not accompanied by mentioned secondary effects both for MM and FGS for any ratio of the core geometric sizes. For the given material and the excitation mode the MN can be obtained using modified formulae (1,2):

$$b(f) = C_{\hat{A}}^2 \left[1 + (f_0 / f)^{\alpha} \right] / V_c \, ; \tag{1a}$$

$$B_{p-p} = (5...7) \cdot C_{\hat{A}} \left\{ \left[f_{max} - f_{min} + f_0^{\alpha} (f_{max}^{\beta} - f_{min}^{\beta}) / \beta \right] / V_c \right\}^{1/2} \tag{2b}$$

where $\beta = 1 - \alpha$, $C_{\hat{A}}$ - MN density for given material and excitation parameters. Taking into attention that the possibilities of $C_{\hat{A}}$ reduction because of the increasing of frequency and amplitude of the excitation field for sheet ferromagnetic are limited, for estimation calculations it is possible to accept minimal technically meaningful values of $(C_{\hat{A}})_{min}$. Approximate values of $(C_{\hat{A}})_{min}$ for some of mumetal types (first 4 items) and one type of ferrite are given in Table 2.

Table 2

Material	79 HM	80 HXC	80 ÍÌA	83 HÔ	M 2000
$C_{\hat{A}\,MIN} \cdot 10^{15}, T \cdot m^{3/2} \cdot Hz^{-1/2}$	7.4	3.6	1.5	0.8	19

The calculations using the expression (2b) and with the account of Table 2 showed the good coincidence with certification results for FGS with core length from 20 to 100 mm and different cross-section area.

5. Optimal parameters of FGS core material

As it was shown, the development of new soft magnetic materials remains till now one of the most perspective ways for FGM MN reduction. In the numerous papers the low level of MN was explained by zero value of magnetostriction of low-noise materials, as well as by the large differential magnetic permeability. However, further was found that the minimal MN is achieved not at zero value of magnetostriction and the achievement of the maximal differential magnetic permeability by no means did not result in minimization of MN (MN minimum correlated not with the differential but with the initial magnetic permeability which is not connected directly with the characteristics of sensitivity of MM and FGS). Nowadays the advertising characteristics of the new low-noise materials reflect mostly their high cleanliness and uniformity than their scientifically reasonable macroscopic magnetic characteristics. This question concerns mostly to metal physics, than to the magnetic measurements technology. We shall consider some other aspects of the problem.

As was specified above (p.3) with other equal conditions MN minimum is realized at deep saturation of core material and possibly smaller influence of the induction currents. For this the maximal reduction of the saturation induction of the material B_S and achievement of the B - H curve shape with a sharp transition to saturation is expedient.

In order to realize these requirements we offered to use both in MM and FGS the core which has been heated up to temperature close to a Curie point θ of the material [10]. In such a way it is possible to ensure not only arbitrarily small value of B_S, but also the increasing of magnetic permeability (Hopkinson effect).

It is curious to note, that although the study of MN dependence from temperature was already described in literature, the attention was paid only to low temperatures up to absolute zero - apparently the researchers tried to find effects, similar to the phenomenon of superconductivity. It was established that in opportunity to electric noises the MN do not decrease at the reduction of temperature, this fact has received a theoretical explanation and the interest to the problem was lost. The similarity of processes of the saturation induction decrease at approach to the Curie point and of conductors resistance decrease at approach to absolute zero remained unnoticed.

The experimental tests showed that the decrease of MN when the core is heated to θ in comparison with usual temperature reaches 4...6 times and more in units of the measuring field induction. Certainly, it is not necessary to heat up the core to high temperature - the creation of materials with low θ does not make principal difficulties; amorphous materials of such type have appeared recently.

The results of experimental test for two materials (72HMDX - for MM [11], amorphous alloy - for FGS) are given in Table 3. In both cases the MN minimum was achieved at temperature of the core material $T \approx (0.92 \ldots 0.99)\,\theta$, what corresponds to saturation induction of material equal to 0.1...0.4 of its value at lower temperature.

These data have an illustrative character, therefore characteristics of devices are not presented. It is interesting to note that the material with low Curie point 72HMDX was initially developed for magnetic screens, which have to be demagnetized by heating after assembling and not as low-noise one.

Table 3.

temperature,°C material	10	20	40	50	80	115
	$C_{\hat{A}} \cdot 10^{15}$, $T \cdot m^{3/2} \cdot Hz^{-1/2}$					
72HMDX	-	5.2	-	3.8	1.7	0.9
amorphous alloy	1.9	1.4	0.6	0.3	-	-

A little bit later the similar results were obtained in works of Japanese researchers, where ferrite with low Curie point were used.

It is important from practical point of view that the discussed method of MN decrease can be used independently and as an addition to other known technical solutions. It is essential also that the achieved in our experiments MN is the absolute minimum at present time ~ 0.3 pT·$Hz^{-1/2}$.

The efficiency of the method can be estimated by comparison of MN decrease by increasing of the core volume: the decreasing in 6 times would require the increase of the volume in 36 times, by this we have the appropriate increase of the power losses, temperature errors and so on.

6. Miscellaneous

In known papers periodically a number of problems is discussed connected with possible increase or potential decrease of MN. So, it was noticed that MN of ring-core FGS is decreasing when the output winding size increase. This fact did not receive any explanation in the papers whereas it follows directly from the comparative analysis of MM and FGS MN. For example, for an output winding in the shape of narrow sections the contribution of magnetization fluctuations close to these sections will be increased in comparison with the fluctuations in other parts of the core. Thus such a core works as the core with reduced volume. The output winding of the larger size averages the useful signal and the fluctuations in all the core volume. Of course, the increase of size and initial output inductance of the FGS leads to decreasing of sensitivity but it has no important influence on the noise characteristics and MN of such FGS will be lowered.

Unfortunately such a way for MN decreasing is rather limited (about 10...20 %) and can be realized only in FGS designs with non-optimal proportions and small cross-section of the core, i.e. for FGS with high initial MN.

A possible increase of MN was discussed in connection with magnetostriction fluctuations in the core. The formulae for calculation of the sizes of FGM ring core were offered which allow to avoid the occurrence of magnetostriction resonance. But the subsequent practice of FGM development has shown, that this noise source apparently is exaggerated - the cases when the core size correction allowed to lower MN are not described in the papers.

One time FGS with transversal excitation were considered as perspective. The simplicity of the core and the excitation circuit design (permalloy wire with the excitation current) looked rather attractively, but MN has appeared much more here, than in typical FGS with longitudinal excitation.

The influence of FGS capacity loading ensuring an opportunity of sharp increase of sensitivity, has not attracted the attention of the researchers. It was supposed that the change of sensitivity is proportional both for useful output signal of FGS and for MN, i.e. the level of MN in terms of the measured signal should be the same. However even rather small capacity loading can lead to the condition close to self-generation at one of higher even harmonics. Such a condition is not influencing essentially the initial level of the 2-nd harmonic of the output signal, but the arising common zero instability can be displayed as the increasing of MN.

The dependence of MN on a FGS output signal type was not investigated. Some remarks were made practically concerning the FGS with a differential pulse output, for which worse level of MN in comparison with FGS with an output on the second harmonic is accepted.

It was shown in our research [1] that MN of FGS with output on various even harmonics (2-nd, 4-th and 6-th) is similar by instant values at very low frequencies, but differs at frequencies above 1 Hz. The MN spectrum is strongly polarized: - the MN voltage effective value at the phase angle which is appropriate to the useful signal is much more than for $\pm \pi/2$ angle deviation. This difference decreases at higher frequencies though some polarization factor remains in all investigated area up to tens Hz.

From the first sight this fact represent only theoretical interest, but the weakening of correlation decrease between FGS output signals at different even harmonics specifies that the MN voltage is not identical to measured output noise signal, transformed with appropriate sensitivity for different even harmonic. This implies, in particular, that the noise fluctuations of the magnetic flow, which is determining the output signal in the core, can have the character of phase fluctuations, for which the changes of all even harmonics are connected one to another.

In this case it is possible principally to decrease the MN using the correlation between the output signals at different even harmonics and using «the sum of even harmonics» as output parameter of FGS. May be the low level of MN for the described FGM with digital processing of the output signal without any filtration is connected just with this circumstance.

It is necessary to note also, that the extraction of the signal type «the sum of even harmonics» without the filtration is possible to realize using the phase detector, with the voltage-to-current converter [12], which ensures the necessary broad linearity range for efficient damping of non-balanced voltage at FGS output being the main parasitic factor for digital FGM.

Conclusion

The new data on MN for the different types of FGS and electronic parts of FGM periodically appearing in papers often cause doubts. By the estimation of results it is useful to pay attention to some other imperfections of FGS and electronic circuit design. To such attributes it is possible to relate:

- short-term FGM zero offset after the first switching on and also after the following short-time switching;
- too high (more than 3Hz) corner frequency of the MN spectrum;
- small jumps of zero line during long-term operation;
- zero drift caused by the excitation channel outpur circuit.

At the same time some principal and technical problems of MN research remain unsolved. It is possible to allocate the following questions of the MN theory, the progress in research of which can promote to the essential improvement of the metrological characteristics of FGM and devices on MM basis:

- the analytical and experimental research of MN for materials with small induction of saturation and low Curie point. By this it is possible to create the parameters of the excitation circuit for which the heating and maintenance of required working temperature of the material will be carried out automatically by reduction of magnetic losses at approaching to Curie point;
- the study and manufacturing of materials with a sharp transition to the saturation state, and also the development of excitation parameters and design of FGS, ensuring achievement of the maximal amplitude of the remagnetization field in combination with small power losses;
- the study and development of materials with low specific conductance in combination with excitation frequency increase [13];
- the study of MN with other types of FGS output signals besides filtered 2-nd harmonic and the ways of the useful signal extraction on the background of non-balanced voltage [14];
- the study of MN statistic characteristics and appropriate relations for long-term periods from one hour to one year and more;
- the study of MN and development of FGS with the cores of small size but with the significant volume of ferromagnetic.

These works on MN study are subject of research carried out in LCISR.

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