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THE EMPLOYMENT OF AMORPHOUS $Fe_{77.5}Si_{7.5}B_{15}$ WIRES IN FLUXGATES

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The performance of two different kinds of fluxgate sensors that employ magnetic cores made of amorphous $Fe_{77.5}Si_{7.5}B_{15}$ wires is presented in this work. In the first kind, the high axial anisotropy of the aforementioned wires is utilized for signal extraction. In the latter kind, the Matteucci effect observed in $Fe_{77.5}Si_{7.5}B_{15}$ wires is employed, without the use of a secondary coil. It is well known that the sensitivity of second-order-harmonic fluxgate sensors is inversely proportional to the magnetic core cross-section. For this reason, amorphous wires, especially glass-covered ones, are being rarely used as magnetic cores in conventional fluxgate sensors. For compensating this disadvantage a novel signal extraction technique is employed, instead of the second-order-harmonic one, that makes sensor response independent from core cross-section, hysteresis loop shape and excitation frequency. For the noise performance of the fluxgate sensors to be optimized, the repeatability of axial B_z-H_z and circumferential B_φ-H_z hysteresis loops provided by 125 μm, conventional and 40 μm, glass-covered wires are quantitatively and qualitatively verified. Great attention is paid to the repeatability of B_φ-H_z loops provided by wire-samples, excited with magnetic field waveforms of different frequency and amplitude and subjected to different torsion levels, or subjected to prior torsion-annealing. The Matteucci effect is well respected, because its employment offers the possibility for constructing miniature sensors. The influence of temperature increase in hysteresis loop repeatability is also investigated.

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1. Introduction

Currently, only three technologies enable the construction of small-dimension, low-cost magnetometers for static field sensing, with total precision in the nT range. They employ a) the Fluxgate principle, b) the AMR effect, and c) the GMR effect. Magnetometers based on the two latter technologies suffer from poor cross-field immunity and high repeatability and hysteresis errors. Magnetometers based on the fluxgate principle do not suffer from repeatability and hysteresis errors, but require the precise construction of two coils and the employment of one (or two) well prepared magnetic cores. For a fluxgate sensor to be immune against perpendicular fields (cross-field sensitivity), bar-like cores with high axial anisotropy are required. Unfortunately, the closure magnetic domains that are present in such cores and their high coercivity, are considered responsible for high magnetic noise levels. Furthermore, the flux-reversal process of thick, multi-domain cores used in fluxgates is by definition irreversible, as it is based on domain wall motion rather that on magnetization rotation. A way to reduce the magnetic noise produced by the reversal process is to employ cores, whose flux-reversal is based on the motion of multiple domain walls. This process allows for averaging the magnetic noise generated by the motion of every single wall. This may be the reason for the excellent noise performance achieved with cores made of multiple layers of amorphous strip [1]. Another way to reduce the magnetic noise might be the employment of cores having fine magnetic structure, like amorphous wires. In such wires, in the case that an excitation field is applied uniformly the flux-reversal process may be considered a combination of wall-motion and magnetization rotation. The finer the magnetic structure of a core is, the more predictable its hysteresis loop appears. In this work, the possibility of employing $Fe_{77.5}Si_{7.5}B_{15}$ amorphous wires in fluxgate sensors is exploited. An attempt to employ glass-covered wires for magnetic field sensing is presented in [2-3].

2. Theory

For the classical second-order-harmonic fluxgate the signal-to-noise ratio, as derived in [3], is given in equation (1). Pulse excitation is assumed, with pulse amplitude and rise time denoted respectively with H_o and T_R and waveform period denoted with $T_o=1/f_o$. With σ_H^2 and σ_N^2 are denoted respectively, the signal-power, and the noise-power captured by the secondary coil (or equivalently the noise-power that superimposes to the Matteucci voltage output). In the case that an amorphous wire is employed as magnetic core, whose cross-section is denoted with A, the approximation shown in equation (1) can be done.

$$\mathrm{SNR} = -10 \cdot \log\left(\sigma_{H_c}^2 / \sigma_H^2 + \mathrm{NNR}_{H_o} / \mathrm{SSR} \cdot \sigma_{H_o}^2 / \sigma_H^2 + \mathrm{NNR}_{T_R} / \mathrm{SSR} \cdot \sigma_{T_R}^2 / \sigma_H^2 + 1/\mathrm{SSR} \cdot \sigma_N^2 / \sigma_H^2 \right) \tag{1}$$

$$\mathrm{SNR} \approx -10 \cdot \log\left(1/\mathrm{SSR} \cdot \sigma_N^2 / \sigma_H^2 \right) \quad \text{where} \quad \mathrm{SSR} = \left(50/H_o \cdot C/T_o \cdot T_R/T_o \right)^2 \quad \text{and} \quad C \propto A$$

A similar expression as the one of equation (1) is valid in the case of triangular or sinusoidal excitation waveform. For the current-sampling fluxgate, that is mathematically revised in [2] the signal-to-noise ratio, as derived in [2], is shown in equation (2). In this equation with σ_{sw} and σ_d are denoted the standard deviation values of the switching field intensity, H_{sw} and the flux-reversal duration, T_d. The parameter σ_E^2 represents the power of noise, which is superimposed to the excitation waveform. Parameters $C_{cs}=I_e/H_e$ and $k>2$ are positive constants. The first of them gives the current-to-field-intensity ratio of the primary coil.

$$\mathrm{SNR} = -10 \cdot \log\left(\left(\sigma_{H_c}^2 + 0.5 \cdot \sigma_N^2 \cdot \left(H_o \cdot T_d^2 / T_R \cdot k \cdot C \cdot B_{sat} \right)^2 \right) / \sigma_H^2 \right) \tag{2}$$

$$\mathrm{SNR} = -10 \cdot \log\left(\left(\sigma_{sw}^2 + \cdot \left(H_o / T_R \right)^2 \cdot \sigma_d^2 + 0.75 \cdot \sigma_E^2 / C_{cs}^2 + 0.5 \cdot \sigma_N^2 \cdot \left(H_o \cdot T_d^2 / T_R \cdot k \cdot C \cdot B_{sat} \right)^2 \right) / \sigma_H^2 \right)$$

For amorphous wires with cross-section with magnitude in the order of 10^{-9} m^2 the current sampling technique provides with higher SNR.

3. Experiment

A series of fluxgate sensors of two different kinds have been constructed in order to verify the nature of noise generated by $Fe_{77.5}Si_{7.5}B_{15}$ wires. The fluxgates of the first kind employ two coils, one excitation and one receiving coil, and the fluxgates of the second kind employ one coil and the Matteucci effect. The sensors have been excited with triangular waveform and thus it is $T_R=0.5/f_o$. The amorphous wires used as magnetic cores are subjected to various torsion levels. The voltage in the output of the sensor-heads has been densely sampled and the core hysteresis loops has been constructed by numerical integration. The repeatability of the coercive force intensity, H_c, is investigated. Some useful results are presented in Fig. 1.

The noise-power density is increasing for increasing f_o. This fact indicates that σ_N^2 and σ_d^2 are the dominating noise sources, because according to equation (2) and to [4], the noise-power spectra density can be written as shown in equation (3), where with M is denoted the sample length and with $f_s=1/T_s$ is denoted the sampling rate.

The results presented in Fig. 1 allow for the estimation of the σ_d parameter, in the least-squares sense. For the circumferential magnetization component has been found that $\boldsymbol{\sigma_d \approx}$ **30 nsec** and $\mathbf{T_d \approx}$ **20 μsec** or for the relative error it is $\boldsymbol{\sigma_d/T_d \approx}$ **0.15%**. The relative error is considered to hold approximately also for the longitudinal component for which it is $\mathbf{T_d \approx}$ **4 μsec**. Given that H_{sw} lies between 100 A/m and 300 A/m, depending on the ratio $r = H_o/T_o$, the waveform amplitude must be $H_o > H_{sw}$, or $H_o > 300$ A/m. The rms-amplitude spectra density of the equivalent sensor noise granted to the variation of T_d has been found to be $\mathbf{0.12 \cdot T_d}$ **nT/(μsec·√Hz)** at f = 1 Hz and for $f_o = 1$ kHz and $H_o = 300$ A/m.

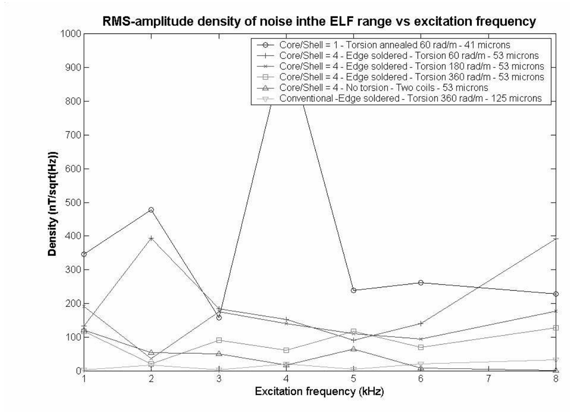

Fig. 1. Spectra density of the rms-value of H_c in the ELF range (f=1).

$$\sigma^2 / f = \left[\sigma_{sw}^2 + (2 \cdot f_o \cdot H_o)^2 \cdot \sigma_d^2 + 0.75 \cdot \sigma_E^2 / C_{cs}^2 + 0.5 \cdot \sigma_N^2 \cdot \left(2 \cdot H_o \cdot T_d^2 \cdot f_o / k \cdot C \cdot B_{sat} \right)^2 \right] \cdot M \cdot T_s \qquad (3)$$

$$M \cdot T_s \propto 1/f_o$$

The contribution of both σ_N and σ_d is reduced for decreasing ratio r. For the fluxgates that employ the Matteucci effect, a threshold value, $r_{min} = 100$ kA/sec·m, has been found for the ratio r, below which the noise power increases rapidly. This threshold value is found independent on torsion level and on wire diameter. This is caused due to the hysteresis loop splitting effect, presented in Fig. 2. This effect occurs for values of r for which it is $r < r_{min}$. For two-coil fluxgates there are neither loop splitting, nor threshold value for r found. Temperature increase boosts magnetic noise-power and forces the threshold r_{min} to increase.

Further noise measurements at fluxgates employing the Matteucci effect manifested that a) 125 μm, conventional wires show an abrupt noise increase at lengths smaller than 20 mm, b) glass-covered wires with cover-thickness to core-diameter ratio smaller than 0.5 at length of 20 mm show also abrupt noise increase. Increasing the axial anisotropy in fluxgates with two coils allows for noise reduction.

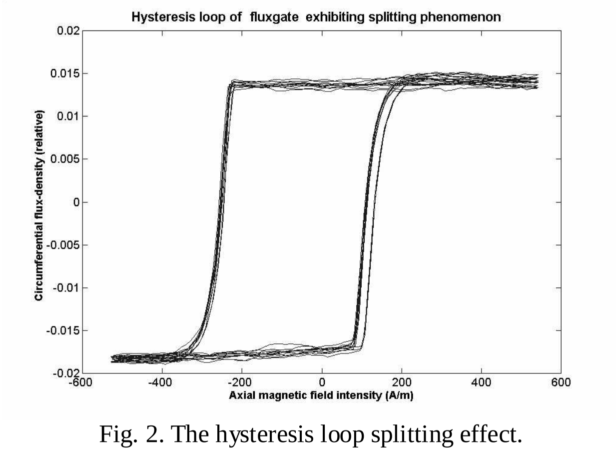

Fig. 2. The hysteresis loop splitting effect.

4. Conlusion

Three parameters do mainly affect the signal-to-noise ratio, and thus the performance, of fluxgates that employ amorphous wires as magnetic cores. They are a) the switching field intensity H_{sw}, b) the ratio r, and c) the saturation flux density B_{sat} (circumferential or longitudinal). The decrease of H_{sw} allows for decreasing H_o that subsequently reduces the σ_E^2 noise-power. This happens because the relative error of a common analog current waveform generator hardly exceeds the value of 0.01%. A generator with relative error 0.03% that supplies a waveform having amplitude 300 A/m would evoke at the output of a fluxgate sensor an additional uncertainty with standard deviation 0.1 A/m. This corresponds to a noise rms-amplitude density of **2.8 nT/√Hz** at f = 1 Hz and for f_o = 1 kHz. The decrease of r and the increase of B_{sat} reduce the influence of the noise sources σ_d and σ_N.

The magnetic noise generated by an amorphous wire may be considered to consist of two components, the variation of H_{sw} denoted with σ_{sw}, and the variation of T_d denoted with σ_d. The magnetic noise contributes also in the power σ_N^2 [P3], but as long as the current-sampling technique is being used, the two first components dominate. Out of the two first components, the flux-reversal variation seems to be dominant, in the case of fluxgates that employ the Matteucci effect. This happens because of the high values of T_d that have been found independent on the ratio r, on the applied torsion, and on wire diameter.

The magnetic noise in Fluxgates employing the circumferential flux-reversal (Matteucci effect) seems to reduce for increasing circumferential anisotropy. Thick glass-covers, small core diameters, and low torsion levels cause circumferential anisotropy reduction. Respectively fluxgates that employ the axial magnetization component seem to generate lower noise for increasing axial anisotropy. Thick glass-covers and high stress levels cause axial anisotropy increase. This is explained mainly by the increase of B_{sat}, in the case of fluxgates employing the Matteucci effect. In the case of two-coil fluxgates, this is to be explained mainly by the reduction of T_d. Switching field noise should also reduce for increasing anisotropy at two-coil fluxgates, but there is inadequate data to support this assumption. Unfortunately, anisotropy increase forces H_{sw} to increase.

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