# Suppression of Barkhausen Noise in Magnetoresistive Sensors Employing AC Bias

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***Abstract* — A magnetic field rotating in the plane of a thin-film magnetoresistive sensor provides continuous saturation of the ferromagnetic material if the magnitude of the field was sufficiently large. This mode of excitation allows operation free of errors related to remanence and in the same time it helps in suppressing the Barkhausen noise. The experiment demonstrates that the contribution of the magnetic noise in the sensor output is negligible when the period of the field rotation is less than 1 ms. This enables resolution of dc and low-frequency magnetic fields of the order of $10^{-10}$ T/√Hz. This result can be improved by decreasing the sensor induced anisotropy and a resolution of $10^{-11}$ – $10^{-12}$ T/√Hz might be attainable.**

## I. INTRODUCTION

Magnetoresistive (MR) sensors are promising devices for magnetometry applications. This is due to their miniature size, small power consumption and relatively high resolution. However, two basic phenomena in the material complicate the use of these sensors in sensitive and precise magnetometers. The first phenomenon is remanence in ferromagnetic materials. The remanence is not constant in time because of temperature changes, mechanical stresses, *etc*. The remanence is, therefore, a source of significant additional errors, especially at dc and low frequencies [1], [2]. Another principal problem is the Barkhausen noise caused by the multidomain behavior of the materials. It seems that there is only one radical way to avoid operation at remanence. This is attained by exciting ferromagnetic specimens by magnetic field that alternately saturates the specimen in one and in the opposite direction [1] – [3]. However, such ac bias causes multidomain activity and as a result Barkhausen noise is generated [2] – [6]. Hence, avoidance of remanence and the simultaneous suppression of Barkhausen noise seem contradictory. One possible way to overcome this difficulty is to employ a special mode of ac bias that provides continuous saturation of the ferromagnetic material. This continuous saturation should lead to a monodomain state of the material and as a result the Barkhausen noise should be reduced [2], [5] – [7]. Such mode of ac bias can be realized by exciting a ferromagnetic specimen by sufficiently large rotating magnetic field. Similar mode of excitation is mentioned in [2] for bulk ferromagnetic materials and is described in [7] for monocrystal YIG-films. Such mode is also described in [8] and [9] for thin-film MR sensors. Their objective however, was not at all related to the treatment of Barkhausen noise [8], [9]. In the present article we report results of experimental investigation of Barkhausen noise suppression in MR sensor excited by rotating magnetic field.

## II. THE ROTATING BIAS METHOD

Reference [9] considers a case of ac bias where elliptically rotating magnetic field continuously saturates a barber-pole MR sensor. The following equation, which is based on the Stoner-Wohlfarth model, approximates the normalized ac output of the sensor ($\delta V = \Delta V/\Delta V$p-p):

$$\delta V \approx 0.5 \sin\left(2 \operatorname{arctg} \frac{a\,(H_{by} + H_{ey})}{(a+1)(H_{bx} + H_{ex})}\right), \tag{1}$$

where $H_{bx}=aH_k\cos\omega t$ and $H_{by}=(a+1)H_k\sin\omega t$ are orthogonal components of the bias field. The $x$ and $y$ axes correspond to the sensor's hard and easy axes respectively. $H_k$ is the sensor's anisotropy field. $H_{ex}$ and $H_{ey}$ are orthogonal components of an external magnetic field. $a$ is a constant larger than $1+|H_e/H_k|$. This value of $a$ enables a continuous sensor saturation. It is interesting that (1) yields exact solutions when the external magnetic field is absent. This equation yields exact solutions even when the external field is present. This occurs when the sensor produces zero output [9]. In the first case the sensor output is a purely sinusoidal signal at twice the excitation frequency. In the second case the output signal becomes phase modulated. For external fields much weaker than the amplitudes of the bias fields the output signal can be expressed approximately as,

$$\delta V \approx 0.5\sin\{2[\omega t - H_{ex}\sin\omega t/aH_k + H_{ey}\cos\omega t/(a+1)H_k]\}. \tag{2}$$

The phase deviations of the signal caused by $H_{ex}$ and $H_{ey}$ components of the external field are given by:

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Manuscript received February 17, 1995.

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$$\begin{cases} |\omega\Delta t_x| \approx |(H_{ex} / a\, H_k)| \\ |\omega\Delta t_y| \approx |[H_{ey} / (a{+}1)\, H_k]|\,, \end{cases} \tag{3}$$

where $\Delta t_x$ and $\Delta t_y$ are the time shifts of the even and the odd zero-crossing points of the output signal respectively. Detection of the corresponding phase shifts (3) allows independent measurements of the external field components. It is interesting that (3) does not contain such parameters as resistance and current through the MR strip. Therefore, results of measurements are free of errors associated with the temperature drift of the sensor's resistance and current.

### *Resolution of the Method*

The sensor noise causes variations of the zero-crossing locations of the output signal. Fig. 1 shows that these variations can be calculated as follows:

$$\omega\Delta t_n = (\pi/4) V_n/V_m\,, \tag{4}$$

where $V_n$ is the noise voltage, and $V_m$ is the amplitude of the sensor output signal. One can obtain the minimal detectable field levels from (3) and (4)

$$\begin{cases} H_{ex\,min} \approx (\pi/4)\; a\, H_k V_n/V_m \\ H_{ey\,min} \approx (\pi/4)\; (a{+}1)\, H_k V_n/V_m\,. \end{cases} \tag{5}$$

This equation enables the evaluation of the thermal lower-bounds of resolution for commercially available MR sensors. The following parameters of MR sensor of type KMZ 10 A made by Philips are employed for this evaluation. $a = 1$, since this is the value for which the excitation fields are the smallest but still saturate the MR material continuously. Furthermore, $H_k \approx 0.8$ kA/m. The sensor's resistance thermal-noise voltage is $V_n \approx 4$ nV/√Hz. $V_m \approx 100$ mV. The resulted lower thermal-bounds of resolution are of about, 26 pT/√Hz for the $x$-direction and of about 50 pT/√Hz for the $y$-direction.

## III. EXPERIMENTAL RESULTS

Fig. 2 shows schematically the experimental setup. We have used a commercially available thin-film MR sensor of type KMZ 10 A. The anisotropy field of the sensor was measured to be $H_k \approx 780$ A/m. The supply voltage of the sensor was set about 8.5 V. Two orthogonal coils were used for ac biasing along the sensor axes. A crystal-controlled clock-generator and a frequency divider produce reference frequency for the two sinusoidal generators of the ac bias. An ultralow-noise monolithic operational preamplifier of voltage gain of 100 was used to amplify the sensor output. A comparator transforms the sensor output to a rectangular-waveform, whose duty cycle follows the zero-crossing locations (Fig. 1). A band-pass filter prevents the influence of dc offset, drift and $1/f$ noise of the sensor and the preamplifier and also cuts noise above 10 kHz. The comparator's output is then detected by a lock-in amplifier.

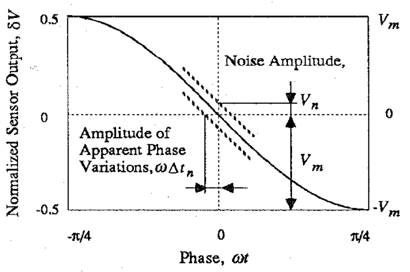


Fig. 1. The relationship between the sensor output and excitation and noise.

Fig. 3 (a) and Fig. 4 (a) demonstrate that the sensor may produce strong Barkhausen noise when an ac bias is applied only along the easy axis direction.

A rotating magnetic bias has been applied in the sensor's plane. We found, that when this bias (whose components $H_{bx}$ and $H_{by}$ definition accompanies (1)) is sufficiently large, namely $a > 2$, and when the frequency of rotation is $f \geq 1$ kHz, then the Barkhausen noise is effectively suppressed. The corresponding sensor output is shown in Fig. 3 (b). Fig. 4 (b) shows the spectrum of this output. Fig. 3 (c) shows a scaled up representation of the sensor response to an external magnetic field at the zero-crossing point. A field of magnitude of about 1 A/m causes 80 ns time shift of the zero-crossing points of the sensor output. This time-shift dependence on the field is practically linear for $|H_{ex}| \leq 1$ A/m. One can see from Fig. 3 (c) that the output noise voltage is about 0.5 mVp-p for bandwidth of about $10^4$ Hz. Therefore, the total noise voltage of the MR sensor and the preamplifier is less than 10 nVrms/√Hz. This result is close to the theoretical combination of the thermal noise of the MR sensor and the preamplifier noise. Hence, the contribution of the magnetic noise in the sensor output is negligible and Barkhausen noise is seems to be effectively suppressed. One can obtain from (5) $H_{ex\,min} \approx 0.15$ nT/√Hz; $H_{ey\,min} \approx 0.22$ nT/√Hz for this case. Therefore, resolution of dc and low-frequency magnetic field measurements of the order $10^{-10}$ T/√Hz is achievable.

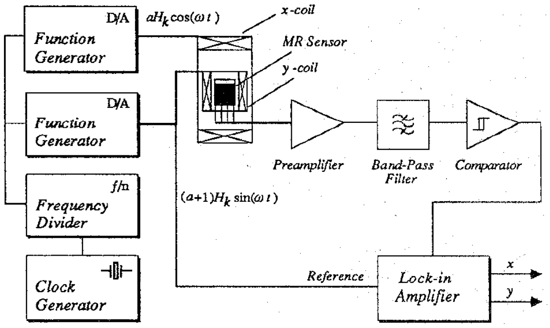
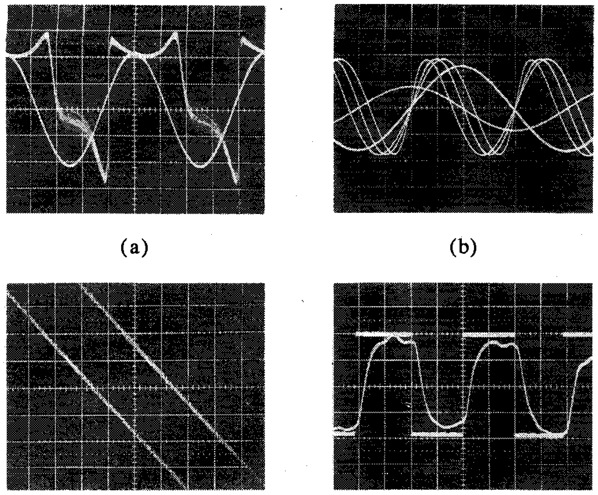


Fig. 2. Block diagram of the experimental setup.



(a) (b) (c) (d)

Fig. 3. Experimentally obtained outputs of the magnetoresistive sensor. (a) The sensor is excited only along its easy axis by a sinusoidal field $H_{bxm} \approx 1$ kA/m. X=0.2 ms/div; Y=100 mV/div. (b) – (d) The sensor is excited by elliptically rotating and saturating magnetic field. (b) The sensor outputs vs time. The traces of relatively low frequency correspond to the excitation fields $H_{bxm} = 2$ kA/m and $H_{bym} = 2.8$ kA/m. $H_{ey} = 0$. $H_{ex} = +630$ A/m (the right trace); $H_{ex} = 0$ (the center trace); $H_{ex} = -630$ A/m (the left trace). X=125 μs/div; Y=5 V/div. (c) Phase change of the sensor output in response to a square-wave external magnetic field $H_{ex} \approx 1$ A/m of frequency 100 Hz. The output is obtained through 0.2 – 10 kHz band-pass filter. Duration of the photo exposition is about 30 s. X=50 ns/div; Y=2 mV/div. (d) Detected response for a 0.25 Hz square wave external field of amplitude 10 nT. $H_{bxm} = 1.6$ kA/m; $H_{bym} = 2.4$ kA/m; $f \approx 10$ kHz. X=1 s/div; Y=5 nT/div.

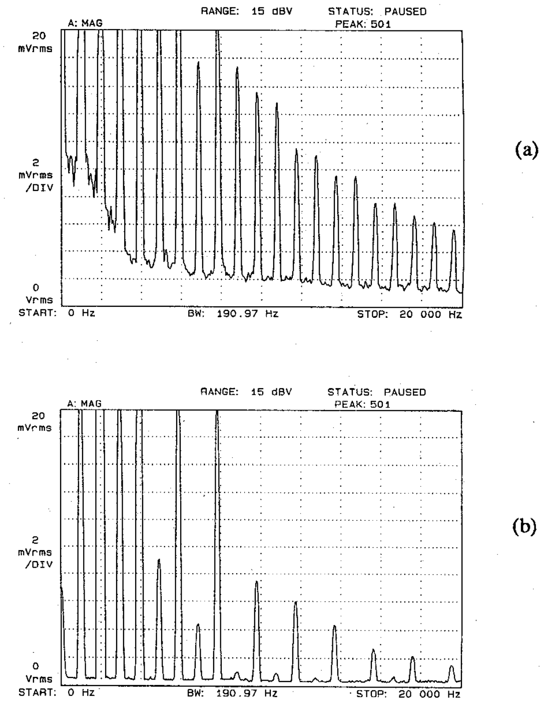


Fig. 4. Spectrograms of the sensor output. (a) The spectrogram corresponding to the case of Fig. 3 (a) where the sensor is excited only along its easy axis. (b) The spectrogram corresponding to the case of Fig. 3 (b) where the sensor is continuously saturated by the rotating bias.

Fig. 4 (d) shows the resulted output of the lock-in amplifier in response to an external square-wave field. Noise level of the order of 0.2 nTrms and offset stability of the order of 2 nTrms were achieved in laboratory conditions.

## IV. CONCLUSIONS

Barkhausen noise can be suppressed by continuously saturating the magnetic material of MR sensors. This objective has been obtained in the present work by rotating a sufficiently large bias field in the MR sensor's plane. The present measurements suggest that this technique is of potential value. It is demonstrated that the sensor's thermal noise and the noise of the associated electronics are the dominant factors that limit the resolution of measurements in the present case. Moreover, the sensor output is also remanence-errors free and offset-errors free. The output signal is obtained and detected at twice the frequency of bias rotation, which is relatively high. This eliminates $1/f$ noise of the electronics and reduces the thermal drift errors. Hence, a resolution of the order of $10^{-10}$ T/$\sqrt{\text{Hz}}$ is achievable. This resolution can be still improved by decreasing the sensor's induced anisotropy and a resolution of $10^{-11}$ – $10^{-12}$ T/$\sqrt{\text{Hz}}$ might be attainable. Such resolution appears possible even with no external flux concentrator.

Recent works of Soohoo [10] suggest that Barkhausen noise can be regarded as a quasi-deterministic process. This may give rise to the further improvement of methods for increasing the signal-to-noise performance of MR sensors.

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