

# LOW FREQUENCY NOISE OF ANISOTROPIC MAGNETORESISTORS IN DC AND AC-EXCITED METAL DETECTORS

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**Abstract.** Magnetoresistors can replace induction sensors in applications like non-destructive testing and metal detection, where high spatial resolution or low frequency response is required. Using an AC excitation field the magnetic response of eddy currents is detected. Although giant magnetoresistive (GMR) sensors have higher measuring range and sensitivity compared to anisotropic magnetoresistors (AMR), they show also higher hysteresis and noise especially at low frequencies. Therefore AMR sensors are chosen to be evaluated in low noise measurements with combined processing of DC and AC excitation field with respect to the arrangement of processing electronics. Circuit with a commercial AMR sensor HMC1001 and AD8429 preamplifier using flipping technique exhibited 1-Hz noise as low as  $125 \text{ pT}/\sqrt{\text{Hz}}$ . Without flipping, the 1-Hz noise increased to  $246 \text{ pT}/\sqrt{\text{Hz}}$ .

## 1. Introduction

Magnetoresistors (MR) fall between Hall sensors and induction sensors in terms of sensitivity and noise. Unlike induction sensors, MRs have the frequency response starting from DC and they are therefore favorite sensors for non-destructive testing devices which detect deeply buried cracks [1]. MRs have small dimensions and high spatial resolution which allows to build array arrangements which can be used for metal detection and object recognition [2]. They are also readily available in commercial packaging as electronic components.

The limiting factors for these applications are the noise of the sensor, gain temperature drift, hysteresis and also offset temperature drift when sensors are used at low frequencies or DC. These parameters limit the detection depth in metal detection and non-destructive testing. Noise can be generally filtered by averaging, however this affects the speed of operation and temperature drifts become more pronounced. There are generally three competing magnetoresistive technologies: giant magnetoresistive (GMR), tunneling magnetoresistive (TMR) and anisotropic magnetoresistance (AMR) sensors. In the case of GMR and TMR, the hysteresis and noise are generally higher [3] than for AMRs, which are subject of this study.

We focus on the sensor noise which disqualifies MRs in favor of induction coils, whereas other parameters speak for MRs – they have small size with high spatial resolution and they are mass produced devices available in packages for assembly in printed circuit boards, so that they can be easily used in arrays [4]. A widely used technique of improving of the AMR sensors parameters is the so called flipping – periodic remagnetization of the sensor by applying large bipolar magnetic field pulses. With the magnetization of opposite polarity the output characteristic is reversed – “flipped”. Flipping was shown to improve the offset and gain temperature stability and to reduce crossfield



sensitivity of the sensor [5]. Metal detector noise was investigated in three possible circuit arrangements with and without flipping - their effects on AC and also DC detector noise were studied.

## 2. Measurement setup

For experimental measurements, AMR sensor HMC1001 (Honeywell) was used. This sensor has still the best available noise specifications from the off-the-shelf magnetoresistors. It is a barber-pole sensor with MR elements with 850 ohms resistance arranged in a full bridge, featuring on-chip flipping and compensation coils for feedback operation. The sensitivity is 140 V/T for the selected supply voltage of 5.5 V. As the sensitivity is low, the contribution of the noise of the processing electronics is not negligible. Electronics noise could be removed by the crosscorrelation technique [6], it is however not practical (speed of measurement).

The typical choice for the signal processing of an AMR bridge is a low noise instrumentation amplifier (Figure 1a). We chose AD8429 with a 1 nV/ $\sqrt{\text{Hz}}$  input voltage noise (gain = 100x) and 1.5 pA/ $\sqrt{\text{Hz}}$  current noise. Due to the high common mode of the bridge, the instrumentation amplifier cannot be set to the full voltage span therefore another amplifier with the gain 10x was connected as the last stage. A similar arrangement was evaluated in [7] where the high bridge supply of 24 V was applied in order to achieve higher sensitivity and lower noise; however 24V is impractical due to sensor heating.

AMR sensor exhibits two significant types of noise: the 1/f type magnetic noise and the white thermal noise. The white magnetic noise is still some orders of magnitude below the thermal resistive noise of the bridge elements; therefore it is not further taken into account. Whereas the 1/f noise affects low-frequency measurements and depends on the manufacturing process, the white noise influencing AC measurements can be predicted by the bridge resistance and parameters of the instrumentation amplifier.

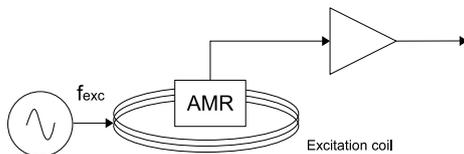


Figure 1a - Direct measurement

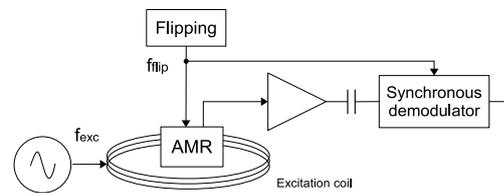


Figure 1b - Measurement setup with flipping

The commonly used method for improving the parameters of an AMR sensor is the so-called “flipping”: the sensitive magnetic layer of the AMR is remagnetized in the opposite direction, thus reducing the hysteresis and eliminating the temperature offset drift of the sensor and AC electronics.

For processing the output signal in the flipped mode where the output becomes modulated, a synchronous demodulator is used – Figure 1b. The demodulator in our case includes a switched integrator which eliminates noisy spikes in signal when the sensor is being remagnetized [3] – Figure 2a.

The noise was measured with the Agilent FFT Analyzer 35670A in all cases, without any further amplification, using DC-coupling, 100 averages and a Hanning window. The sensor together with amplifier stage was placed in a 6-layer magnetic shielding can with 100.000x attenuation of the ambient magnetic field noise.

## 3. Experimental results

### 3.1. Noise of the electronics

The noise of the electronics was evaluated by connecting a dummy bridge made of resistors of the same value as the MR elements in HMC1001 (850  $\Omega$ ). Figure 2b shows the noise spectrum obtained at the output of the amplifier (input of the synchronous demodulator in Figure 2a). The 1/f noise with the equivalent of  $B_E = 95 \text{ pT}/\sqrt{\text{Hz}}$  at 1 Hz (recalculated using sensitivity  $S = 140 \text{ V/T}$ ) is dominantly due

to the instrumentation amplifier noise. The white noise with the equivalent of 30 pT/√Hz results both from the bridge thermal noise and the voltage and current noise of the instrumentation amplifier.

The expected white noise of the electronics  $B_{EW}$  can be calculated as

$$B_{EW}^2 = (SV_R)^2 + (SV_N)^2 + (SRI_N)^2 \quad (1)$$

$$B_{EW} = S \cdot \sqrt{(V_R)^2 + (V_N)^2 + (RI_N)^2} \quad (2)$$

where  $V_R$  is the resistor voltage noise,  $V_N$  is the amplifier voltage noise and  $I_N$  is the amplifier current noise.

$$B_{EW} = \frac{140V}{T} \cdot \sqrt{\left(\frac{4.12nV}{\sqrt{Hz}}\right)^2 + \left(\frac{1nV}{\sqrt{Hz}}\right)^2 + \left(\frac{1.5pA \cdot 850\Omega}{\sqrt{Hz}}\right)^2} = 31.4 \frac{pT}{\sqrt{Hz}}, \quad (3)$$

which matches the measured amplifier noise in Figure 2 (b).

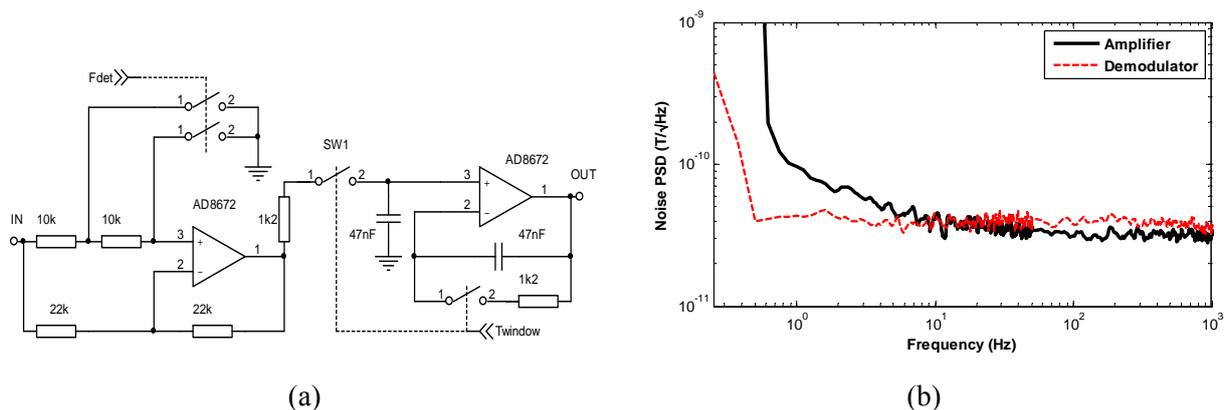


Figure 2. Synchronous demodulator schematics (a) and comparison of noise of the electronics at amplifier output and demodulator output (b)

The noise of synchronous demodulator was measured at the demodulator output with a 10-kHz reference and the same dummy resistor bridge. The spectrum shows an increased white noise level of 40 pT/√Hz. This was identified as the effect of the switched integrator used in the windowing circuit with the time window set to 70%. With the time window of 100%, the white noise level was 32 pT/√Hz. In the demodulator spectrum there is no 1/f noise of the instrumentation amplifier, due to the fact, that the frequency range was shifted by the 10-kHz demodulation frequency.

Knowing the electronic noise, the noise measurements were done using three different circuit arrangements.

### 3.2. Direct measurement

This arrangement with simple electronics is depicted in Figure 1a. The output of the AMR bridge is directly amplified. It has the full frequency span limited only by the corner frequency of the amplifier stage. The eventual feedback compensation, which eliminates gain drift and improves linearity, can be realized with a single-opamp PI controller. In this case, the 1/f sensor noise was dominating, the total noise value  $B_{N1} = 246$  pT/√Hz at 1 Hz (Figure 3b).

From the measured values, we can estimate the 1-Hz noise of the sensor itself ( $B_{S1}$ ) as

$$B_{S1} = \sqrt{B_{N1}^2 - B_{E1}^2} = \sqrt{246^2 - 95^2} \frac{pT}{\sqrt{Hz}} = 226 \frac{pT}{\sqrt{Hz}} \quad (4)$$

This result is in agreement with values published in [5]. The 1-kHz white noise, which would dominate in the AC application, is approx. the same as the electronic noise - 32 pT/√Hz. If we use this mode, a single remagnetizing pulse should be performed at least while switching on the device to assure the magnetic state of the sensor.

### 3.3. Modulation – flipping

The block diagram is shown in Figure 1b, the flipping current and output waveform are shown in Figure 3a. By using flipping at 10 kHz with peak-to-peak amplitude of 3.6 Amps, the output signal was modulated and shifted to the white-noise frequency range of the instrumentation amplifier. The resulting noise of 125 pT/√Hz at 1 Hz (Figure 3b) makes flipping the obvious choice for precise DC field measurements, avoiding the offsets and 1/f noise of the instrumentation amplifier. When compared to 1/f noise of the amplifier and non-flipped sensor (4), the noise clearly further decreased: flipping improved also the low-frequency noise of the magnetoresistor.

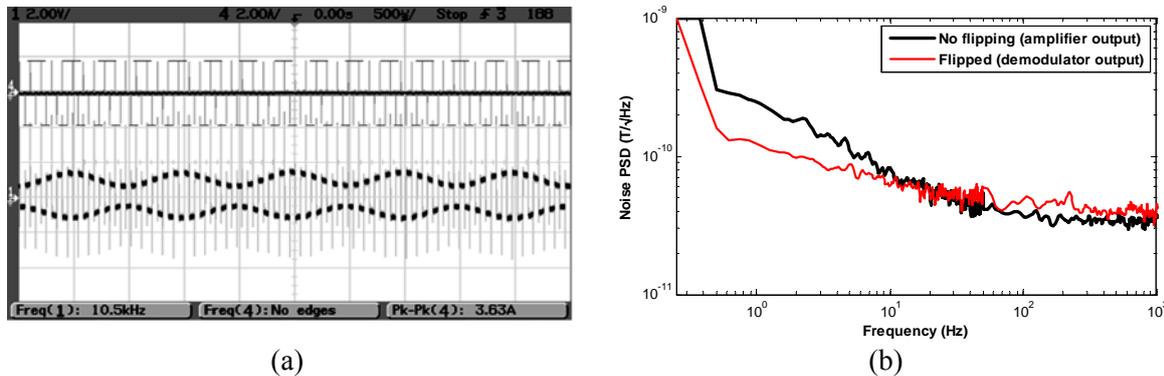


Figure 3 – Modulated output signal of flipped AMR (a) and comparison of overall noise with direct measurement (b)

However, flipping is power-demanding as the narrow current pulses have to have an amplitude of several amperes in order to properly magnetize the sensitive layer and reduce the 1/f noise [5]. The maximum allowed power dissipation allows maximum flipping frequencies in the order of tens of kHz, limiting the measuring frequency range. It is however possible to use a lower flipping frequency and higher excitation frequency.

### 3.4. D. Sensor as rectifier

A flipped sensor can be used as a rectifier [8], basic block diagram is presented in Figure 4a. If the flipping frequency is derived from the excitation frequency, the excitation signal is synchronously rectified and the output signal looks like in Figure 4b. The excitation frequency is evaluated with a simple low pass filter connected to the output of the amplifier stage, thus eliminating complex detection circuitry.

A simple feedback compensation is however possible only for a DC range, therefore the sensor should be positioned perpendicularly to the excitation field [1]. However a disadvantage is that the offset drift and the 1/f noise of the amplifier are not eliminated even at the excitation frequency  $f_{exc}$ .

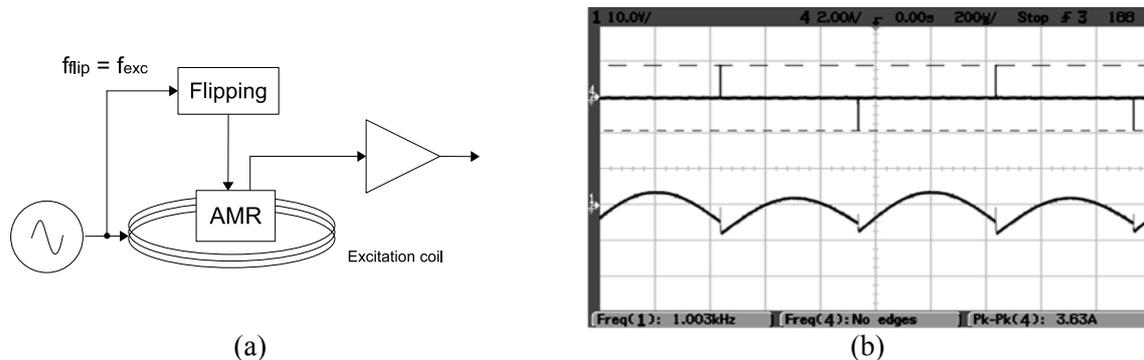


Figure 4- Special arrangement with  $f_{\text{flip}}=f_{\text{exc}}$  (a), and the flipping current (upper trace) and amplified sensor output (lower trace) (b)

#### 4. Conclusion

When the AMR-based metal detector works with an AC excitation field to sense the eddy current response of metal objects and only the AC frequency response is evaluated, then the noise level is determined by the sensor white noise level and it is approximately the same for either direct measurement or for flipping with demodulator– the 1-kHz noise was about  $30 \text{ pT}/\sqrt{\text{Hz}}$  in both circuit arrangements.

For DC measurements, the  $1/f$  noise of the amplifier and offset drifts of the sensor are best suppressed by flipping modulation technique. For the HMC1001 AMR sensor with  $5.5 \text{ V}_{\text{DC}}$  bridge supply and 10-kHz flipping frequency, we have found an improvement from  $246 \text{ pT}/\sqrt{\text{Hz}}$  1-Hz noise with direct measurement down to  $125 \text{ pT}/\sqrt{\text{Hz}}$  when using flipping with appropriate demodulation. This improvement was found to be larger than simple effect of shifting the modulated signal out of  $1/f$  amplifier noise: flipping was found to further improve the sensor low-frequency noise.

The commonly used flipping method is however power-demanding with complicated detection electronics; also the measuring frequency range is limited, which is a difficulty in NDE. The possibility of using  $f_{\text{flip}}=f_{\text{exc}}$  was thus investigated: while it allowed to reduce flipping power and to simplify signal processing circuitry, the  $1/f$  noise of the amplifier was however present in this case.

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