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Equivalent Noise Analysis and Modeling for a Magnetic Tunnel Junction Magnetometer with In Situ Magnetic Feedback

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Abstract: Magnetic tunnel junction (MTJ) sensors have been one of the excellent candidates for magnetic field detection due to their high sensitivity and compact size. In this paper, we design a magnetometer with in situ magnetic feedback consisting of an MTJ sensor. To analyze and evaluate the detectivity of the MTJ magnetometer, a noise model of the MTJ sensor in the magnetometer without magnetic feedback is first developed. Then, the noise model of the MTJ magnetometer with in situ magnetic feedback is also established, including the noises of the MTJ sensor and the signal conditioning circuit, as well as the feedback circuit. The equivalent noise model of the MTJ magnetometer with in situ magnetic feedback is evaluated through nonlinear fitting for the noise voltage spectrum. Although the noise generated by the MTJ sensor is much greater than that of the signal conditioning circuit, the noise introduced by the feedback coils into the MTJ sensor is slightly more than twice that generated by the MTJ sensor itself. The measurement results show that the detectivity of the MTJ magnetometer with in situ magnetic feedback reaches 526 pT/Hz^{1/2} at 10 Hz. The equivalent noise analysis method presented in this paper is suitable for the detectivity analysis of magnetometers with magnetic feedback.



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Keywords: MTJ; magnetometer; noise model; magnetic feedback

1. Introduction

The magnetic tunnel junction (MTJ) sensor has been shown to have the ability to sense magnetic fields at levels as low as tens of pT and have been broadly applied in many important areas such as geomagnetic detection, magnetic anomaly detection, and navigation [1–9]. Usually, an MTJ sensor is combined with a voltage amplifier (VA), feedback circuit, and analog-to-digital converters (ADCs) to form a closed-loop magnetometer as a way to increase the measurement range of the MTJ sensor and improve the linearity of the system [10–14]. Andrea et al. constructed a closed-loop system employing an instrumentation amplifier (INA), integrator, and power amplifier (PA) to address the effects of the hysteresis, nonlinearity, and operating temperature of magnetoresistive sensors on measurement uncertainty.

For the detection of ultra-low magnetic fields, the noise of the closed-loop magnetometer is vital for the detectivity of the system. Currently, noise research has mainly focused on the noise analysis of the MTJ sensor itself [1,2,15–23]. Paulo et al. summarized the noise generation mechanism in the MTJ sensor and the application of the MTJ sensor in weak magnetic field detection [2]. Naganuma et al. fabricated MTJs with a composite free layer and measured the field and temperature dependences of the low-frequency noise to understand the origin of noise [19]. Zhang et al. proposed an equivalent noise model to deal with the deviation between the output noise of the MTJ sensor and its intrinsic noise by considering both the noise sources and the corresponding noise transfer functions [18]. However, less work is reported on the noise analysis of the signal conditioning circuit [24].

It is critical to determine all of the noise sources of the MTJ magnetometer to obtain a higher detectivity. Gao et al. studied the equivalent noise of an MTJ magnetometer, while it adopted an open-loop structure and could only be applied to a small range of magnetic fields. In addition, this work did not give the noise spectra under different bias magnetic fields, which was also important for the noise analysis [24]. Du et al. designed planar spiral coils to compensate for the bias magnetic fields at the MTJ sensing element in order to maintain the actual magnetic field detected by the MTJ sensing element constant. The system was essentially an open-loop structure, and the compensating magnetic field could not adaptively change according to the bias magnetic field. The effect of each noise source in the signal conditioning circuit on the detectivity of the system was not analyzed in their paper [25].

In this paper, an MTJ magnetometer with in situ magnetic feedback is designed and fabricated, and an equivalent noise model is established by considering all the noise sources including the MTJ sensor, the signal conditioning circuit, and the feedback circuit. Through modeling and analysis, the maximum noise source is determined, and the detectivity of this magnetometer is predicted. The research results indicate that the noise introduced by the feedback coils into the MTJ sensor in the low-frequency regime is higher than the noise of the MTJ sensor itself. Therefore, the design of the feedback circuit is key to further improving the detectivity of the magnetometer, which provides an important theoretical and experimental basis for the design and optimization of the closed-loop magnetometer in future work.

2. Design of MTJ Magnetometer with In Situ Magnetic Feedback

2.1. Magnetic Field Sensing Element

The magnetometer adopts an MTJ sensor as the magnetic field sensing element. The MTJ sensor has a Wheatstone bridge configuration with a resistance of 44.7 k Ω at room temperature (290 K). Each bridge arm consists of 160 MTJs connected in series. The structure of the MTJs is Ta/Ru/PtMn/CoFe/Ru/CoFeB/MgO/CoFeB/NiFe/Ta, and the area of a single MTJ is about 120 μm^2 . The MTJ sensor is available in the SOP8 package.

To characterize the sensitivity, the MTJ sensor is placed at the center of the Helmholtz coils, and a linear regulator (LR) is used to provide a bias voltage of 1 V to the MTJ sensor, as shown in Figure 1. The transfer curve of the MTJ sensor can be obtained by sweeping the magnetic field with a computer-controlled DC source to vary the current in the Helmholtz coils. The current-to-magnetic field conversion ratio of the Helmholtz coils is 2.05 Oe/100 mA at the MTJ sensor, as measured by a gaussmeter. A digital multimeter (DMM) is used to capture the differential output of the MTJ sensor, and it also communicates with a laptop computer in which the data can be analyzed.

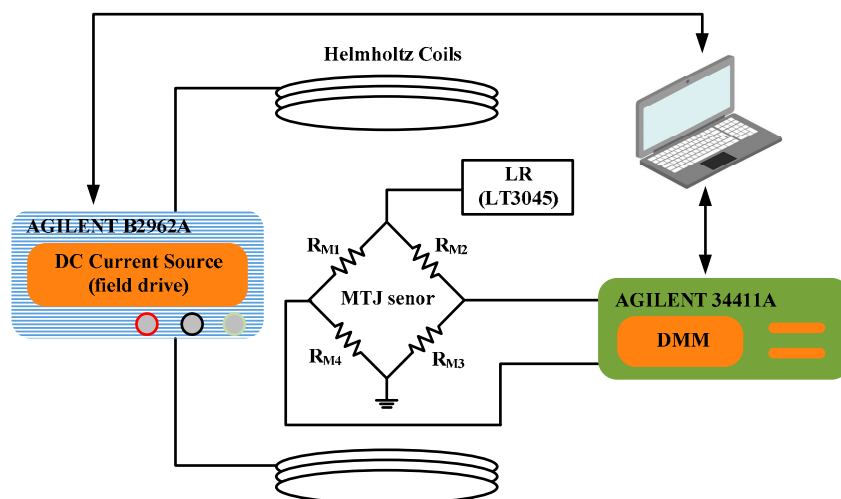


Figure 1. Transfer curve measurement system.

Figure 2 shows the output and sensitivity of the MTJ sensor as black and red curves, respectively. The MTJ sensor has a sensitivity s_1 of 115 mV/V/Oe in the linear operating field range of -0.5 Oe to $+0.5$ Oe.

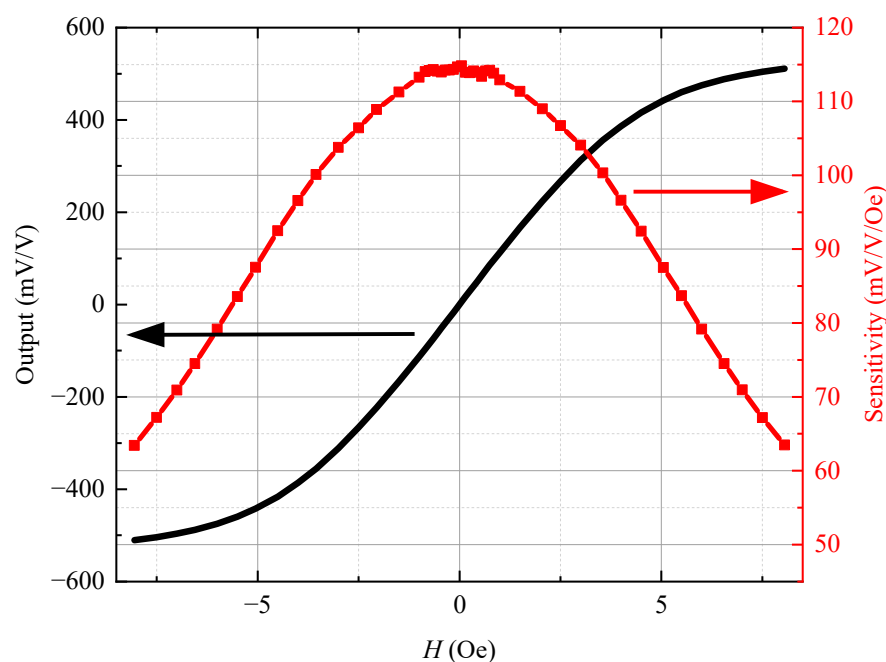


Figure 2. Output and sensitivity of the MTJ sensor.

2.2. Design of Signal Conditioning Circuit and Feedback Circuit

The signal conditioning circuit consists of a linear regulator (LR), two RC low-pass filters, an INA, and a voltage follower (VF). The RC low-pass filters are set at the differential output of the MTJ sensor to eliminate the effect of noise above 10 kHz in the magnetometer to avoid system oscillation. The INA is used to read and amplify the differential output voltage signal of the MTJ sensor. To increase the measurement range of the MTJ sensor and improve the linearity of the system, a feedback circuit is provided at the output end of the INA, including a PA and feedback coils. The VF is used as a voltage follower for isolation between the INA and the PA. The voltage gain of the PA is set to 1. The schematic diagram of the MTJ magnetometer with in situ magnetic feedback is shown in Figure 3. V_{out1} stands for the MTJ sensor output, and V_{out2} stands for the INA output.

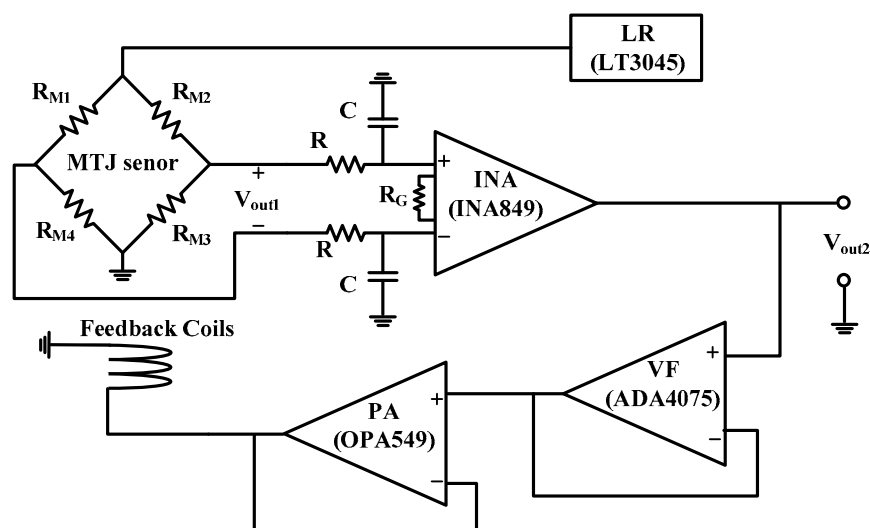


Figure 3. Schematic diagram of the MTJ magnetometer with in situ magnetic feedback.

Figure 4 shows the basic block diagram of the magnetic feedback principle. B_e and B_f denote the external and feedback magnetic fields, respectively.

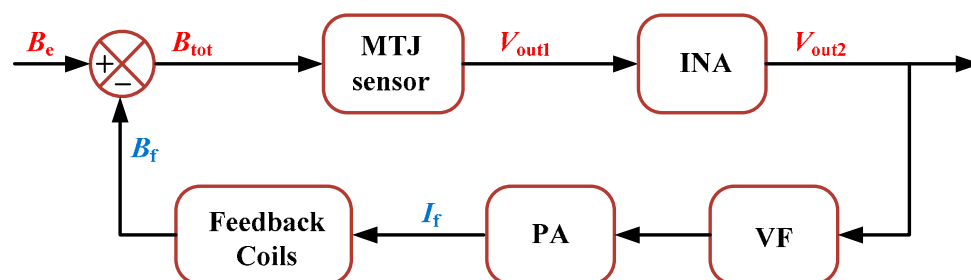


Figure 4. Basic block diagram of the magnetic feedback principle.

In this case, the total magnetic field B_{tot} measured by the MTJ sensor is $(B_e - B_f)$. The output V_{out2} of the INA will be $s_1 \times G \times (B_e - B_f)$, where G is the gain factor of the INA.

The feedback coils consist of two 5-turn planar spiral coils connected in reverse series to enhance the feedback magnetic field. The width and thickness of each turn in the feedback coils are 0.4 mm and 0.07 mm, respectively. The gap between two adjacent turns of the planar spiral coil is 0.17 mm. The central void in the planar spiral coil is 10 mm $\times$ 2 mm. Therefore, the overall size of the feedback coils is 15.36 mm $\times$ 14.89 mm. The feedback coils and the MTJ sensor are placed as shown in Figure 5. The sensitive axis of the MTJ sensor is perpendicular to the long side of the feedback coils. The current in the feedback coils has a magnetic field conversion ratio r_1 of 6.22 Oe/A at the MTJ sensor through finite element simulation and actual measurement. The feedback coils and the MTJ sensor are connected to the signal conditioning circuit through a detachable flexible printed circuit (FPC) board.

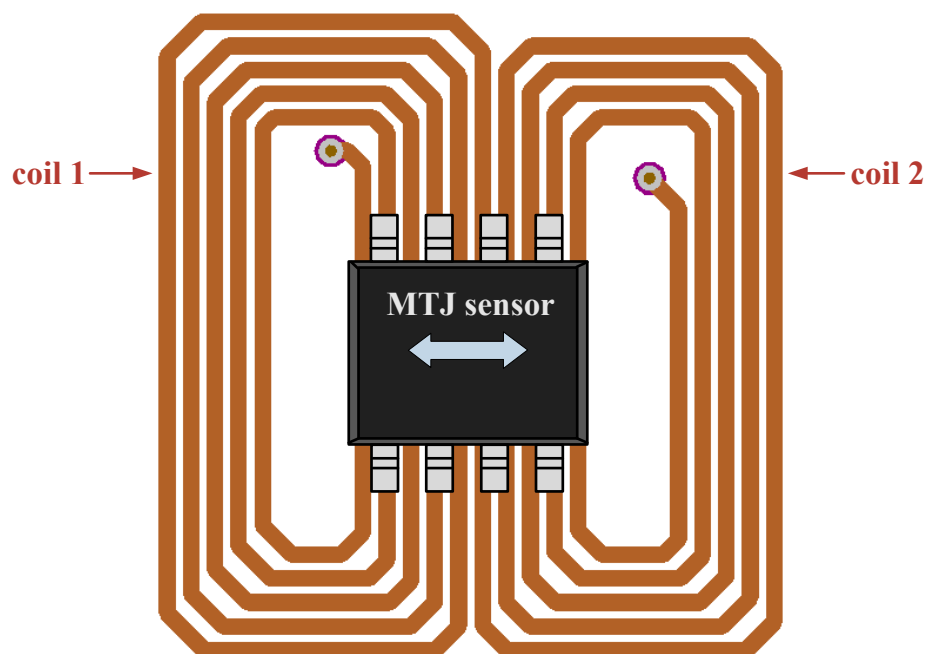


Figure 5. Schematic of the planar spiral feedback coils and MTJ sensor (arrow shows the sensing direction).

The outputs of the MTJ sensor and the INA in the magnetometer are both measured by varying the external magnetic field from -8 Oe to $+8$ Oe, as shown in Figure 6.

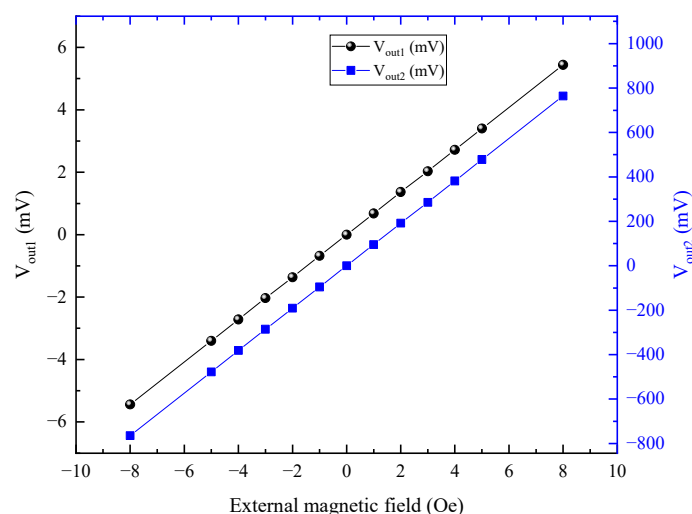


Figure 6. Outputs of the magnetometer.

As seen from the curves, both V_{out1} and V_{out2} exhibit an excellent linear relationship with the external magnetic field signal in the range of ± 8 Oe. Through calculation, the magnetometer with in situ magnetic feedback has a voltage conversion ratio of 0.68 mV/V/Oe at the MTJ sensor (the bias voltage of the MTJ sensor is 1 V). Compared with the curves in Figure 2, the linear operating field range of the MTJ sensor extends from ± 0.5 Oe to ± 8 Oe, about 15 times higher, demonstrating that the measurement range of the closed-loop magnetometer has been greatly increased. Furthermore, the feedback magnetic field can compensate for 99.409% of the external magnetic field at the MTJ sensor.

3. Noise Measurement Setup

As shown in Figure 7, the noise measurement system is built using a high-precision dynamic signal acquisition (DSA) card and a low-noise preamplifier (LNP) [26–28]. The magnetometer, Helmholtz coils, and LNP are placed in a magnetic shielding chamber for shielding environmental magnetic fields. After demagnetization, the remanence inside the magnetic shielding chamber is less than 1 nT. To reduce the noise introduced by a power supply, the LNP is powered by a lead-acid battery. The noises in V_{out1} and V_{out2} are collected for different external magnetic fields and compared.

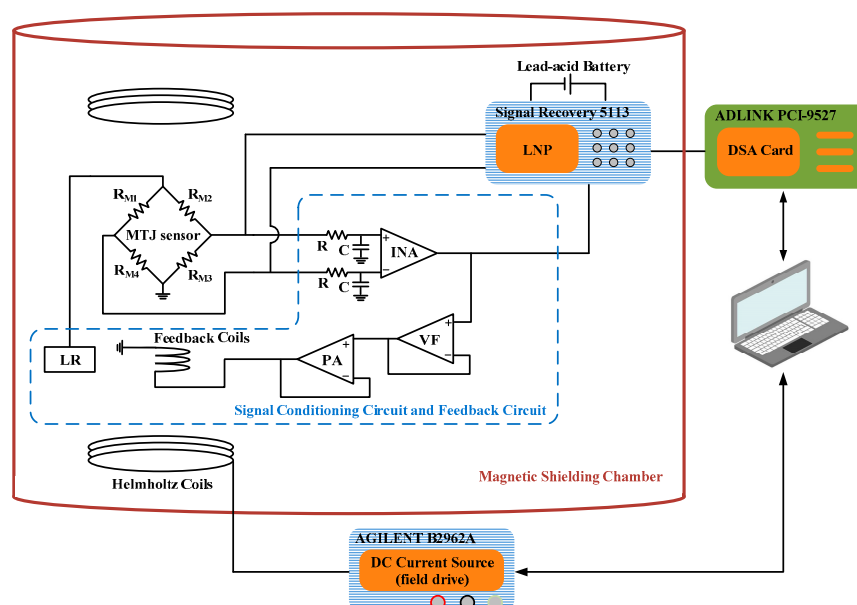


Figure 7. Illustration of the noise measurement setup.

The noise signals generated by the magnetometer are amplified by the LNP with a gain of 40 dB and further sampled by the high-precision DSA card with a sample rate of 400 kHz. The noise voltage spectral density (VSD) is calculated using the fast Fourier transform (FFT) method.

The noise measurement system is calibrated with a commercial metal film resistor whose resistance is 4.73 kΩ, and the precision of the system is about 2% [26].

4. Results and Discussion

4.1. MTJ Sensor Noise Model and Measurement

The noise power at the output of the MTJ sensor is equal to the noise in one bridge arm when the four arms of the Wheatstone bridge have equivalent noise sources [1,20]. The noise of the MTJ sensor consists of thermal-electronic noise, shot noise, thermal-magnetic noise, electronic 1/f noise, and magnetic 1/f noise [1,2,17,20,21,26].

Thermal-electronic noise, also known as Johnson-Nyquist noise, is caused by the random thermal motion of carriers near the Fermi surface affected by temperature [17]. The general expression for this noise power spectral density (PSD) is

$$S_{\text{therm-elec}}^{\text{MTJ}} = 4k_B T R_{\text{MTJ}} \quad (1)$$

where k_B is the Boltzmann constant, T is the absolute temperature, and R_{MTJ} is the resistance of a single bridge arm in the Wheatstone bridge. The thermal-electronic noise is only related to the resistance value and the ambient temperature. Shot noise arises in discontinuities in the conduction medium as a consequence of the discrete nature of the electrical charge and is described by the following expression [1,20].

$$S_{\text{shot}}^{\text{MTJ}} = \frac{2qI_{\text{MTJ}}R_{\text{MTJ}}^2}{N} \quad (2)$$

where q is the electron electrical charge, I_{MTJ} is the current flowing through each MTJ element, and N is the number of MTJ elements in a single bridge arm. Since the thermal-electronic noise and shot noise are intertwined in tunnel junctions, it is commonly expressed as a combination of the two noises [1,17,20]. A general expression for thermal-shot noise is given as

$$S_{\text{therm-shot}}^{\text{MTJ}} = \frac{2qI_{\text{MTJ}}R_{\text{MTJ}}^2}{N} \coth\left(\frac{qV_J}{2k_B T}\right) \quad (3)$$

where V_J is the voltage drop across each MTJ element. When the bias voltage is low, $qV_J \ll k_B T$, expression (3) is equivalent to thermal-electronic noise. On the other hand, at high bias voltage or low temperature, $qV_J \gg k_B T$, expression (3) approaches shot noise.

Thermal-magnetic noise is mainly caused by magnetization fluctuations due to the magnetic field and thermal excitation. Egelhoff et al. [20] proposed a method for calculating the field PSD of thermal-magnetic noise by employing the Gilbert damping parameter and Gyromagnetic ratio. The field PSD is given by

$$S_{\text{therm-mag}}^{\text{MTJ}} = \frac{4k_B T \mu_0 \alpha_G}{N \Omega \gamma M_s} \quad (4)$$

where μ_0 is the permeability of free space, α_G is the Gilbert damping parameter, Ω is the volume of the free magnetosphere, γ is the gyromagnetic ratio of electrons, and M_s is the saturation magnetization of the free layer.

The electronic 1/f noise occurs as soon as a current is applied to the MTJ sensor. Charge trapping in the barrier or near the layer interface is the source of the electronic 1/f noise [1,17,20]. It is typically written as

$$S_{\text{elect-1/f}}^{\text{MTJ}} = \frac{\alpha_{\text{elect}} I_{\text{MTJ}}^2 R_{\text{MTJ}}^2}{A f} \quad (5)$$

where α_{elect} is the electronic $1/f$ Hooge parameter, A is the total area of MTJ elements in a single bridge arm, and f is the frequency.

The magnetic $1/f$ noise originates from the magnetization hopping between the metastable ripple states [1,20,21]. The field PSD is given by

$$S_{\text{mag-}1/f}^{\text{MTJ}} = \frac{2B_{\text{sat}}\alpha_{\text{mag}}}{N\Omega f} \quad (6)$$

where B_{sat} is the saturation magnetic induction and α_{mag} is the magnetic $1/f$ Hooge parameter. Both thermal-magnetic noise and magnetic $1/f$ noise are magnetically derived noise. However, the significant difference between these two noises is that the latter is frequency-dependent. Thermal-magnetic noise and thermal-shot noise are frequency-independent and can be considered as white noise.

Since the thermal-shot noise, thermal-magnetic noise, electronic $1/f$ noise, and magnetic $1/f$ noise are incoherent, the total noise power is the superposition of all the uncorrelated noise sources mentioned above [1,2,20,21,26]. The noise power spectral density (unit of V^2/Hz) of the MTJ sensor is described as

$$\begin{aligned} S_V^{\text{MTJ}} &= S_{\text{therm-shot}}^{\text{MTJ}} + S_{\text{elect-}1/f}^{\text{MTJ}} + \left(\frac{dV}{dB}\right)^2 \times \left(S_{\text{therm-mag}}^{\text{MTJ}} + S_{\text{mag-}1/f}^{\text{MTJ}}\right) \\ &= \frac{2qI_{\text{MTJ}}R_{\text{MTJ}}^2}{N} \coth\left(\frac{qV_J}{2k_B T}\right) + \frac{\alpha_{\text{elect}}I_{\text{MTJ}}^2R_{\text{MTJ}}^2}{Af} + \left(\frac{dV}{dB}\right)^2 \times \left(\frac{4k_B T\mu_0\alpha_G}{N\Omega\gamma M_s} + \frac{2B_{\text{sat}}\alpha_{\text{mag}}}{N\Omega f}\right) \end{aligned} \quad (7)$$

where dV/dB is the sensitivity of the MTJ sensor.

During noise measurement, the output signal of the MTJ sensor is transmitted to the LNP. When the external magnetic field is zero, the measured noise voltage spectrum of the MTJ sensor without in situ magnetic feedback exhibits a distinct $1/f$ characteristic, as shown in Figure 8. This is because $1/f$ noise is dominant in the low-frequency regime [21]. Similar phenomena have been reported by other researchers on noise measurements of MTJ sensors [15,16,26,28].

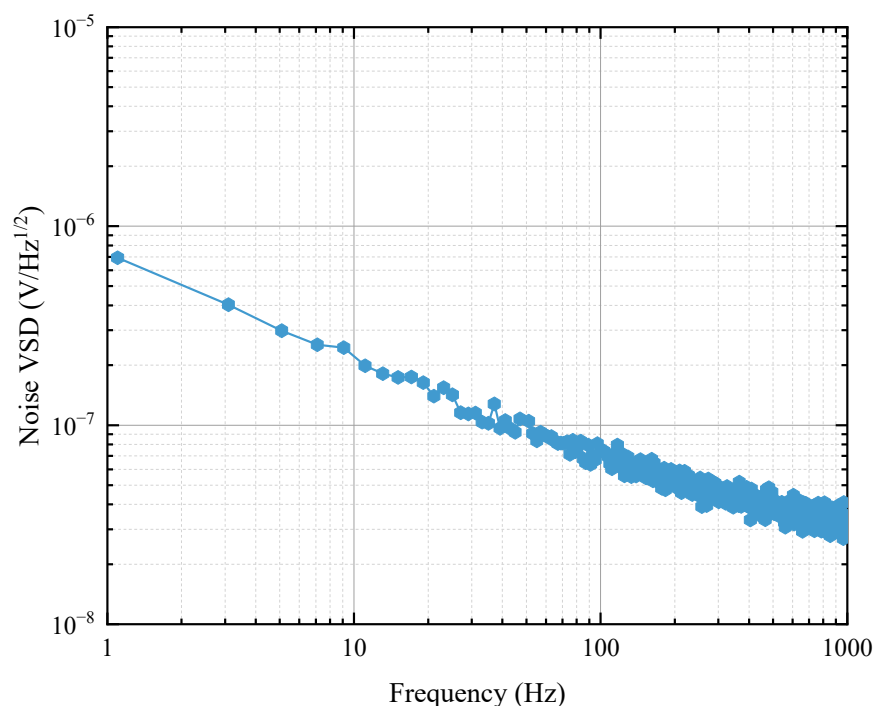


Figure 8. Measured noise voltage spectrum of MTJ sensor without in situ magnetic feedback at $H = 0$ Oe.

4.2. Magnetometer Noise Model and Measurement

Figure 9 gives an illustrative diagram of the equivalent noise model of the MTJ magnetometer with in situ magnetic feedback. The total noise mainly includes the noise e_{MTJ} from the MTJ sensor, the noise from the signal conditioning circuit, as well as the noise introduced by the feedback coils. The LR generates output voltage noise e_{NOLR} . The resistor in the signal conditioning circuit generates thermal noise e_R and e_{RG} . The INA generates input voltage noise e_{NI1} and current noise i_N . The VF generates input voltage noise e_{NI2} . The PA generates input voltage noise e_{NI3} . e_{FN} is the feedback noise transferred from all noise sources to the MTJ sensor through the feedback coils.

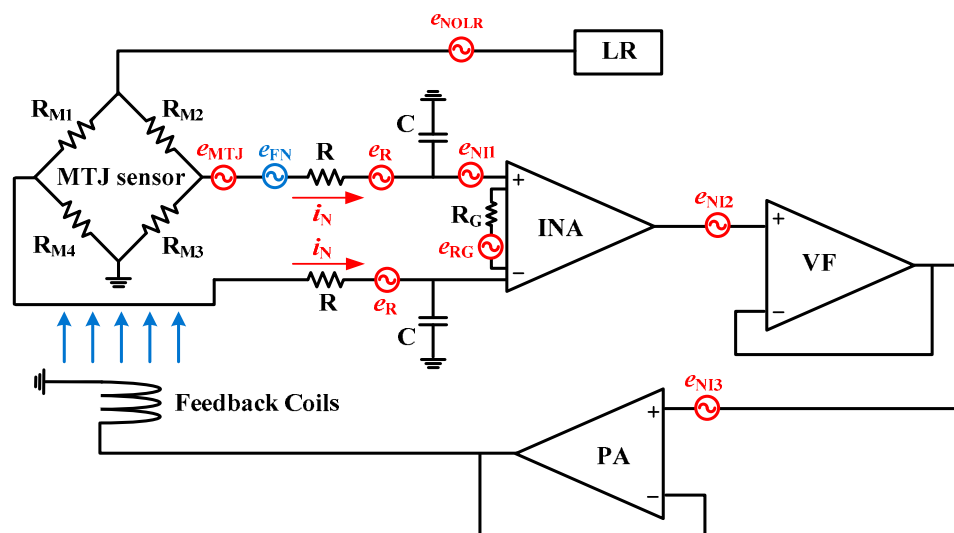


Figure 9. Noise sources in the magnetometer.

To express the referred to input (RTI) noise voltage spectral density of each noise source in Figure 9, the transfer function of the RC low-pass filter needs to be calculated first. The transfer function can be expressed as

$$H(s) = \frac{1}{1 + sRC} \quad (8)$$

where R and C are the resistance and capacitance used in the low-pass filter, respectively, R is 1 k Ω , C is 15 nF, and s is the complex frequency.

The gain factor (G) of the INA can be obtained directly from its datasheet as follows.

$$G = 1 + \frac{6 \text{ k}\Omega}{R_G} \quad (9)$$

where R_G is the resistance of the resistor used for gain selection. In this magnetometer, R_G is set to 43 Ω and G is 140.5.

According to Equations (2) and (3), the RTI noise VSD for all devices is summarized in Table 1.

Table 1. The RTI noise VSD for all noise sources.

Noise Source	Noise Type	RTI Noise VSD (V/Hz ^{1/2})
MTJ sensor	thermal-shot noise	e_{MTJ}
	thermal-magnetic noise	
	1/ f noise	

Table 1. *Cont.*

Noise Source	Noise Type	RTI Noise VSD (V/Hz ^{1/2})
LR (LT3045)	output voltage noise— e_{NOLR}	e_{NOLR}
Low-pass filter	thermal noise— e_{R}	$\sqrt{4k_{\text{B}}TR}$
INA (INA849)	input voltage noise— e_{NI1}	$\frac{e_{\text{NI1}}}{ H(s) }$
	current noise— i_{N}	$\frac{i_{\text{N}} \times Z_1}{ H(s) }, \frac{i_{\text{N}} \times Z_2}{ H(s) }$
	thermal noise— e_{RG}	$\frac{\sqrt{4kTR_G}}{ H(s) }$
VF (ADA4075-2)	input voltage noise— e_{NI2}	$\frac{e_{\text{NI2}}}{ H(s) \times G}$
PA (OPA549)	input voltage noise— e_{NI3}	$\frac{e_{\text{NI3}}}{ H(s) \times G}$
Feedback Noise	magnetic noise— e_{FN}	e_{FN}

where $Z_1 = R_{\text{M2}} \times R_{\text{M3}} / (R_{\text{M2}} + R_{\text{M3}}) + R$, $Z_2 = R_{\text{M1}} \times R_{\text{M4}} / (R_{\text{M1}} + R_{\text{M4}}) + R$.

The feedback noise e_{FN} is correlated with the noise generated by each device in the signal conditioning circuit and feedback circuit, so e_{FN} can be expressed by the following equation:

$$e_{\text{FN}} = c \times \frac{\sqrt{2 \times (e_{\text{R}} \times |H(s)| \times G)^2 + (e_{\text{RG}} \times G)^2 + (e_{\text{NI1}} \times G)^2 + (e_{\text{NI2}})^2 + (e_{\text{NI3}})^2}}{Z_3} \times r_1 \times s_1 \quad (10)$$

where c is the correlation coefficient between e_{FN} and the noises of devices, and Z_3 is the load impedance of PA, which is 0.6 Ω .

The noise characteristics of the integrated circuit (IC) devices in the signal conditioning circuit and the feedback circuit are listed in Table 2, which are cited from their datasheets. e_{NI} denotes input voltage noise, e_{NO} denotes output voltage noise, and i_{N} denotes current noise.

Table 2. Noise characteristics of the IC devices at 10 Hz.

Device	e_{NI} (nV/Hz ^{1/2})	e_{NO} (nV/Hz ^{1/2})	i_{N} (fA/Hz ^{1/2})
LT3045		70	
INA849	3		3
ADA4075-2	3.5		
OPA549	120		

Taking the frequency of 10 Hz as an example, $|H(S)|$ is approximately 1. Based on Figure 7 and Table 2, the referred to input noise VSD of each noise source can be calculated, as shown in Table 3.

Table 3. The calculated RTI noise VSD of each noise source.

Noise Source	Noise Type	Calculated RTI Noise VSD (nV/Hz ^{1/2})
MTJ sensor	thermal-shot noise	224
	thermal-magnetic noise	
	1/f noise	

Table 3. Cont.

Noise Source	Noise Type	Calculated RTI Noise VSD (nV/Hz ^{1/2})
LR(LT3045)	output voltage noise— e_{NOLR}	70
Low pass filter	thermal noise— e_{R}	4
INA (INA849)	input voltage noise— e_{NI1}	3
	current noise— i_{N}	0.08
	thermal noise— e_{RG}	0.8
VF (ADA4075-2)	input voltage noise— e_{NI2}	0.02

It can be seen that the e_{MTJ} is 224 nV/Hz^{1/2}, which is much greater than those of other devices in Table 3.

The noise in the differential output of the MTJ sensor in the magnetometer with in situ magnetic feedback is collected under different external magnetic fields, as shown in Figure 10.

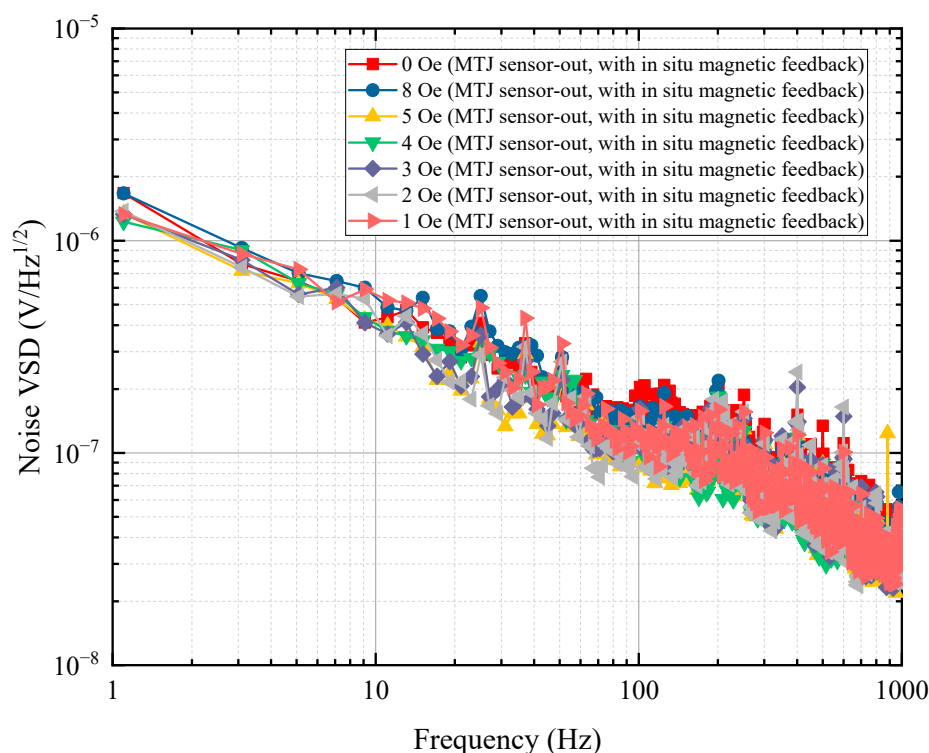


Figure 10. Noise spectrum comparison of the magnetometer with in situ magnetic feedback under different external magnetic fields.

As seen from the curves in Figure 10, the noise in the differential output of the MTJ sensor in the magnetometer with in situ magnetic feedback is almost the same for different external magnetic fields.

The noise voltage spectra of the magnetometer under zero magnetic field are given in Figure 11 and are fitted nonlinearly to obtain the low-frequency noise model. It shows that the noise of the MTJ sensor in the magnetometer with in situ magnetic feedback is obviously higher than the noise of the MTJ sensor in the magnetometer without in situ magnetic feedback.

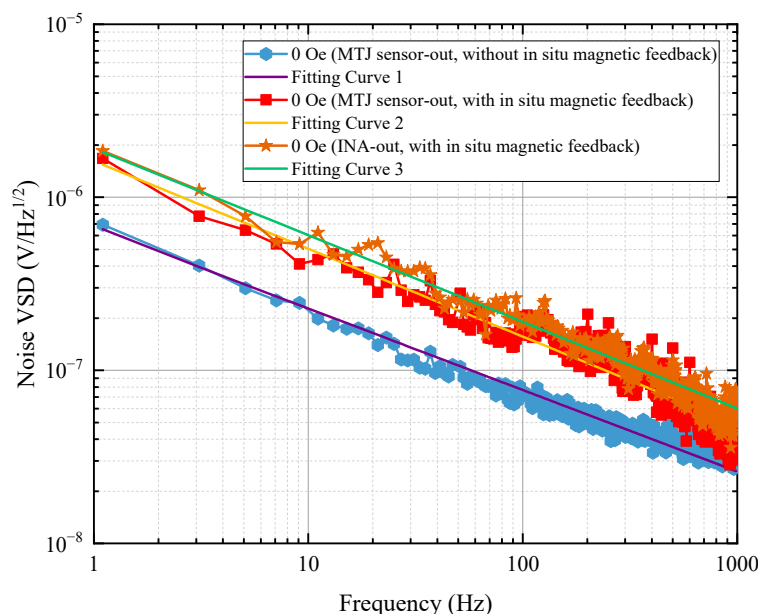


Figure 11. Noise spectra of the magnetometer with and without in situ magnetic feedback at $H = 0$ Oe.

The fitting relationships are $7.0794 \times 10^{-7}/f^{0.5008}$, $1.5948 \times 10^{-6}/f^{0.4983}$, and $1.9122 \times 10^{-6}/f^{0.5006}$ for curve 1, curve 2, and curve 3, respectively, so the feedback noise e_{FN} is given as follows:

$$e_{\text{FN}} = \sqrt{\left(\frac{1.5948 \times 10^{-6}}{f^{0.4983}}\right)^2 - \left(\frac{7.0794 \times 10^{-7}}{f^{0.5008}}\right)^2} \approx \frac{14.29 \times 10^{-7}}{f^{0.5}}$$

The e_{FN} is a little more than twice as large as the e_{MTJ} , which indicates that the noise introduced into the MTJ sensor through the feedback coils is the dominant noise source in the magnetometer with in situ magnetic feedback. Furthermore, the correlation coefficient c in Equation (10) can be calculated to be 0.418.

Dividing the measured noise voltage spectrum by the sensitivity of the MTJ sensor yields the detectivity, i.e., the lowest detectable magnetic field. The detectivity of the MTJ magnetometer with in situ magnetic feedback reaches 526 pT/Hz^{1/2} at a frequency of 10 Hz, as shown in Figure 12.

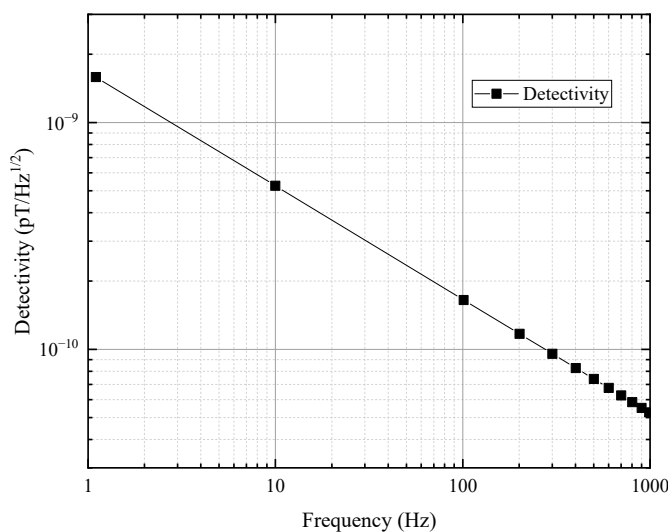


Figure 12. Detectivity vs. frequency for the magnetometer with in situ magnetic feedback at $H = 0$ Oe.

As can be seen from Figures 9–11, the noise of the MTJ magnetometer with in situ magnetic feedback is essentially stable, which is convenient for predicting the detectivity of the magnetometer under different external magnetic fields.

5. Conclusions

In this work, an equivalent noise analysis and modeling method for the MTJ magnetometer with in situ magnetic feedback is presented. Through nonlinear fitting of the noise voltage spectra for the differential output of the MTJ sensor and the output of the INA, it is shown that the noise of the MTJ magnetometer with in situ magnetic feedback exhibits a distinct $1/f$ characteristic. Among the devices of the magnetometer, the MTJ sensor is the largest noise source. More critically, the noise introduced through the planar spiral feedback coils is twice that of the MTJ sensor. Our results show that although the in situ magnetic feedback in the MTJ magnetometer could improve the characteristics of measurement range and linearity, but also introduce more noise and deteriorate the detectivity of the magnetometer, the design and optimization of the feedback circuit will therefore be key to improving the detectivity of magnetometers with in situ magnetic feedback in the future. For example, the gain of the instrumentation amplifier and the current-to-magnetic field conversion ratio of the feedback coils are critical factors that affect the feedback noise. More research efforts should focus on those two points.

Author Contributions: A.D. and R.B. contributed equally to this work. Conceptualization, A.D., R.B. and Y.S.; methodology, A.D., R.B. and Z.Q.; software, A.D., Y.S. and J.T.; validation, J.T., C.K. and X.X.; formal analysis, A.D. and R.B.; investigation, A.D., R.B. and Y.S.; resources, R.B. and Z.Q.; data curation, J.T., C.K. and X.X.; writing—original draft preparation, A.D. and R.B.; writing—review and editing, A.D., R.B. and Z.Q.; visualization, A.D. and R.B.; supervision, R.B. and Z.Q.; project administration, A.D. and R.B.; funding acquisition, R.B. and Z.Q. All authors have read and agreed to the published version of the manuscript.

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