Low-frequency noise measurements on commercial magnetoresistive magnetic field sensors

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Low-frequency noise was measured in the frequency range from 0.1 Hz to 10 kHz on a variety of commercially available magnetic sensors. The types of sensors investigated include anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), and tunnel magnetoresistance (TMR) effect devices. The $1/f$ noise components of electronic and magnetic origin are identified by measuring sensor noise and sensitivity at various applied magnetic fields. Commercial magnetometers typically consist of four elements in a Wheatstone bridge configuration and are biased with either a constant voltage or current. Voltage fluctuations at the sensor output are amplified by a pair of battery powered low-noise preamplifiers and input to a spectrum analyzer. A two-channel cross-correlation technique is used when the performance of a single preamplifier is not sufficient. For the AMR and GMR sensors investigated, both electronic and magnetic components contribute to the overall sensor noise. Maximum noise occurs at the bias field which gives maximum sensitivity. The noise of TMR based sensors is primarily due to resistance fluctuations in the tunnel barrier, having little to no field dependence. The best low-field detectivity of the sensors that have been measured is on the order of 100 $pT/Hz^{0.5}$ at 1 Hz. [DOI: 10.1063/1.1861375]

INTRODUCTION

Low-field magnetoresistive (MR) magnetometers are currently used in applications such as speed and position sensing in automotive products, magnetic encoder detection, current sensing in circuit board traces, and detection of the Earth's field. Several parameters such as bias voltage, required bias field, and sensitivity will determine how useful a specific sensor is for a given application. However, the ultimate performance-limiting factor in terms of minimum detectable field is a sensor's intrinsic noise. Thus, sensor noise is a crucial parameter in low-field applications. If it is possible to understand and reduce $1/f$ noise in MR sensors, it would allow MR sensors to compete with fluxgate sensors and possibly optically pumped and superconducting quantum interference device sensors in applications such as geomagnetic imaging, magnetocardiograms, and weapons detection. $1/f$ sensor noise can be electronic, such as from a fluctuating bond in the tunnel barrier, or magnetic, such as from a fluctuation in the magnetization next to a defect. These two noise processes can be identified by comparing the noise level and sensitivity at various applied magnetic bias fields.

In this article, noise measurements in the frequency range from 0.1 Hz to 10 kHz are presented for several commercially available low-field magnetometers. Three sensor types are investigated including those based on anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), and tunneling magnetoresistance (TMR) devices. Table I lists the specific sensor models.

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MEASUREMENT

Measurement of low-frequency noise has several inherent difficulties. First, all electronic components have intrinsic $1/f$ noise,[1] which is often quite large at frequencies near or below 1 Hz. At higher frequencies, Johnson or shot noise become dominant. Minimizing noise of the detection electronics is critical in obtaining accurate measurements of sensor noise. In a measurement system the noise level of the first amplification stage and noise in applied fields are of particular importance. Environmental magnetic noise must also be minimized to obtain accurate measurements of sensor noise.

A block diagram of the measurement system is shown in Fig. 1. Two preamplifiers based on a commercially available instrumentation amplifier are used in either a single-channel or two-channel cross-correlation mode. Preamp gains of 100 or 500 are selectable. The two-channel cross-correlation technique is commonly employed to effectively reduce the noise floor of the measurement system.[2] Noise from the sen-

TABLE I. List of commercial sensors that have been measured.

Manufacturer	Model	Sensor type	Resistance	Flux concentrators
NVE	AA002	GMR (bridge)	5.3 kΩ	Yes
	AAL002	GMR (bridge)	5.9 kΩ	Yes
	AAH002	GMR (bridge)	2.1 kΩ	Yes
	SDT (prototype)	MTJ (bridge)	30.3 kΩ	Yes
Honeywell	HMC1001	AMR (bridge)	0.86 kΩ	No
	HMC1021	AMR (bridge)	1.0 kΩ	No

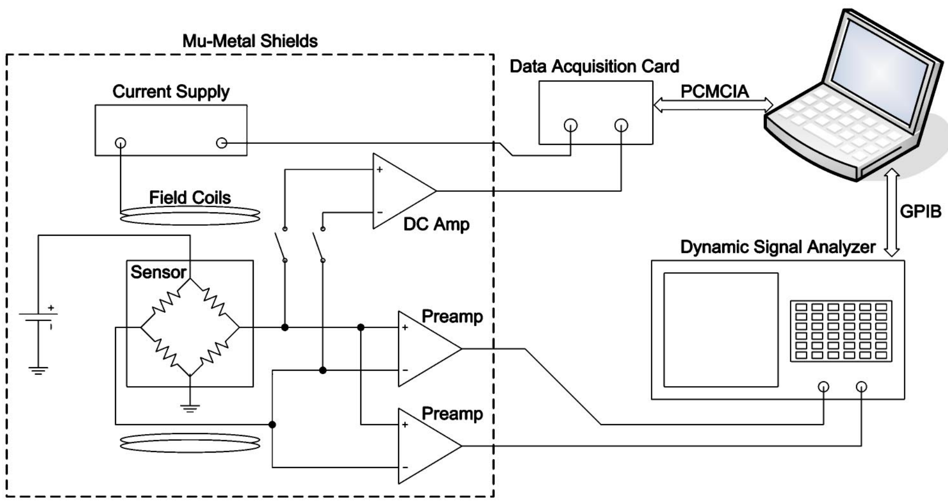

FIG. 1. Block diagram of noise measurement setup.

sor will be correlated on the two channels, while that from the two amplifiers and any spurious pickup on the cables will not be correlated. In order to minimize power supply noise the preamps are powered by lead-acid batteries. Figure 2 shows the measured voltage noise spectral density of the preamps with the inputs grounded both with and without using the cross-correlation technique. The equivalent input noise voltage is nearly an order of magnitude lower when using the cross-correlation technique. The noise spectrum is measured as the non-dc part of the sensor output using a fast Fourier transform signal analyzer. The dc output of the sensor is amplified by a general purpose instrumentation amplifier and monitored by a 16-bit data acquisition card connected to a laptop computer. This amplifier is connected to the sensor by digitally controlled reed relays and is automatically disconnected during collection of noise spectra.

The sensor voltage bias is also supplied by a battery to minimize unwanted noise. The bridge configuration of the sensor is inherently immune to bias noise since any voltage fluctuations will appear on both output signal lines and will be subtracted. However, the bridge configuration is subject to unwanted pickup of external magnetic field fluctuations that can be due to a noisy bias field or environmental noise (i.e., 60 Hz and its harmonics). To provide a quiet dc bias field, custom current sources controlled by the data acquisition card are used to drive small three-axis Helmholtz coils. These voltage controlled current sources include several low-pass *RC* filters to minimize noise due to the control voltage and reduce their current noise. The resistors in the *RC* filters can be switched between high and low values to speed up capacitor charging and decrease the settling time when the bias field is incremented. In order to minimize pickup of environmental noise, all components of the measurement system (except the data acquisition card, spectrum analyzer, and laptop computer) are enclosed in a three layer mu-metal shielding structure.

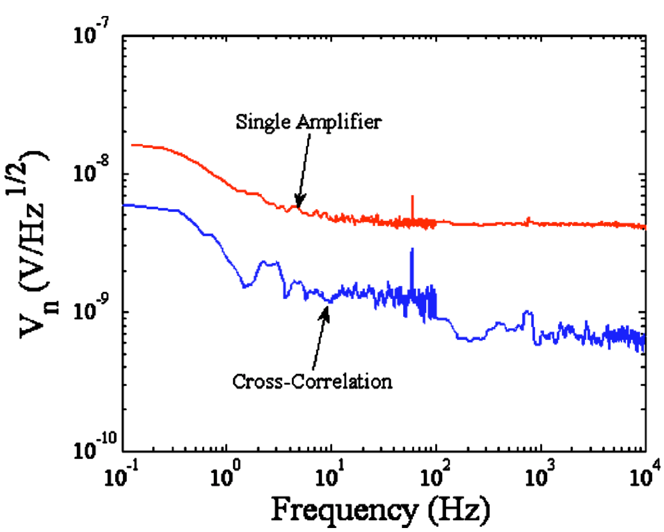

FIG. 2. Comparison of the voltage noise spectra when amplifier inputs are grounded with a single amplifier and with two channel cross-correlation technique.

RESULTS

Measured noise data presented here are for sensors at room temperature with a constant voltage bias of approximately 1.2 V supplied by a Ni–Cd battery. Battery voltage is monitored during the course of a measurement sequence and typically remains within 0.1% of the initial voltage. The output of each sensor is normalized by the bias voltage. The general test sequence includes a dc field sweep to measure the sensor transfer curve [dc voltage output (V_{out}) versus dc applied magnetic field (H_{ap})]. Noise spectra are taken at predefined points during the field sweep. The sensor transfer curve is numerically differentiated to determine its sensitivity at each bias field point. The cross-correlation method is employed for the lowest resistance sensors which have Johnson noise levels near or below that of a single amplifier.

The sensor noise can be magnetic or nonmagnetic in nature. At bias fields that result in high sensitivity the noise component due to fluctuations of the magnetic structure will increase. Noise due to nonmagnetic resistance fluctuations will be independent of applied magnetic fields. For example, Fig. 3 shows the measured voltage output and voltage noise

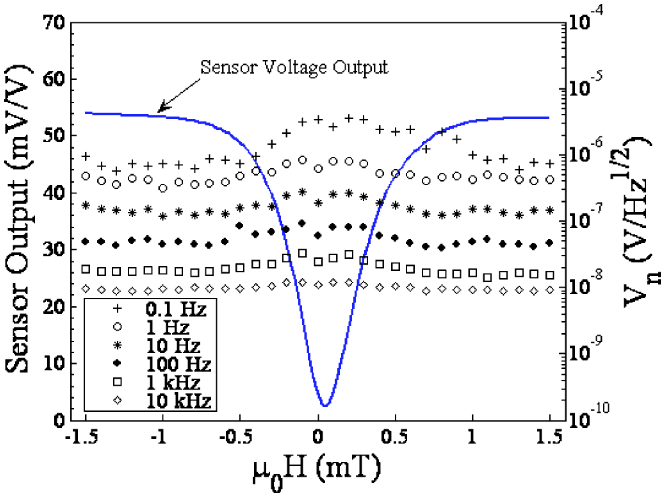

FIG. 3. Measured dc output (solid line) and voltage noise vs bias field of an NVE AAH002 sensor.

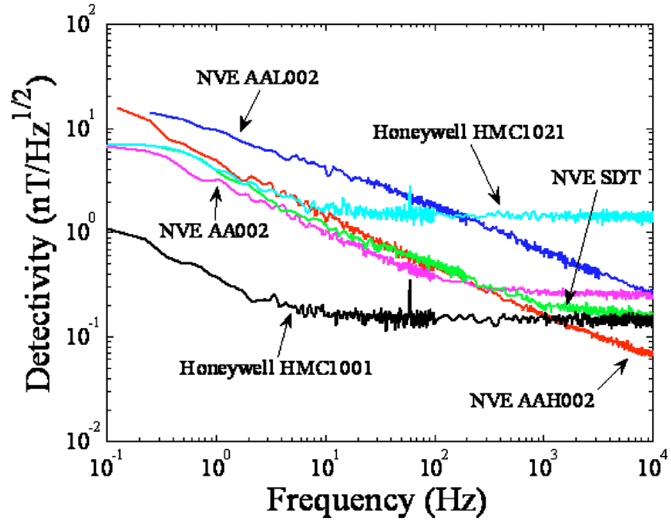

FIG. 5. Detectivity of various commercial magnetometers at dc magnetic bias field that results in highest sensitivity.

at various frequencies versus applied magnetic field of a (NVE) AAH002 GMR sensor. The voltage noise increases when the sensitivity (the slope of the transfer curve) is high, indicating that a magnetic noise component is present. These same data can be expressed in terms of an equivalent field noise, or detectivity, by dividing the noise voltage spectral density by the sensor sensitivity at each bias field. The detectivity, which gives an approximate minimum detectable magnetic field, is shown in Fig. 4 for the same AAH002 sensor. The best (lowest) detectivity occurs at the points of highest sensitivity. Not all of the measured sensors showed a dominant magnetic noise component. The measured noise of the NVE magnetic tunnel junction sensors was essentially independent of applied magnetic field. This nonmagnetic noise has been previously reported and is thought to be due to charge traps in the tunneling barrier or to fluctuations of the spin-independent tunneling resistance.[3–5]

The low field performance of all the measured sensors is compared in Fig. 5. The equivalent field noise or detectivity is shown at the dc bias field which results in maximum sensitivity for each sensor. Of the measured sensors the AMR-type Honeywell HMC1001 has the lowest detectivity at frequencies below 100 Hz. Although GMR and TMR sensors typically have higher sensitivities, their intrinsic noise is higher, resulting in a higher low-field detectivity limit. The higher noise of these sensors is likely due to their more complicated multilayer structure.

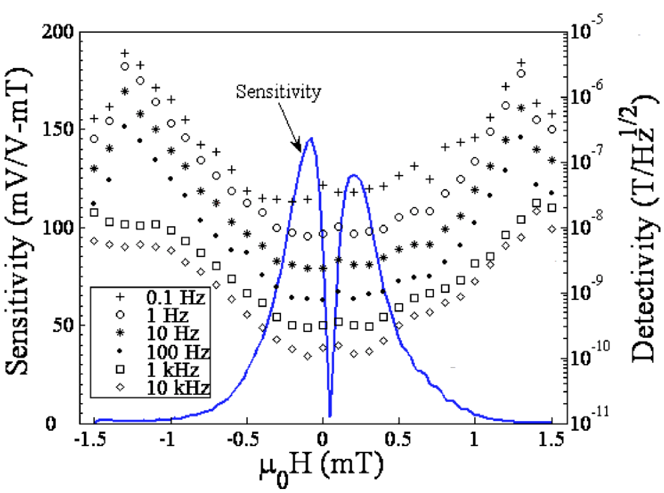

FIG. 4. Sensitivity (solid line) and detectivity of NVE AAH002 vs applied magnetic field.

CONCLUSION

Low-field noise measurements on commercial AMR, GMR, and TMR magnetic field sensors have been performed. At frequencies near 1 Hz and at bias fields that produce maximum sensitivity, the AMR- and GMR-type sensors typically have a noise component dominated by magnetic fluctuations. The measured noise of the TMR sensors is dominated by a nonmagnetic component and is essentially independent of bias field. Although the TMR sensors typically have higher intrinsic noise, they also have higher sensitivity, which allows them to detect fields on the same order of magnitude as the AMR and GMR sensors. The lowest field detectable with all of the measured sensors is on the order of 10^{-10} T/Hz$^{1/2}$. In order for magnetoresistive sensors to be utilized in applications such as magnetocardiograms, an improvement by a factor of about 100 is necessary. The measured noise will be included in a National Institute of Standards and Technology maintained database that is under development to catalog low-field sensor performance.

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