Comparison of Five Readout Techniques for an Integrated Magnetometer

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Abstract

Five readout techniques for an integrated permalloy magnetic sensor are investigated. Measurements of scale factor, minimum detectable signal, and long term stability are compared. Significant improvements using more complex modulation techniques are not readily attained over the commonly used DC readout method.

Introduction

Integrated sensor technology offers the capability to include several electronic functions directly with the transducer. Functions such as temperature compensation, self-checking, self-calibration, auto-ranging, and I/O adaptability are examples of electronic circuits which could be part of a "smart sensor". The design of these functions is highly dependent on the knowledge of the transducer's response and the readout method for generating the transducer's electrical signal. This paper deals with a comparison of several readout techniques for an integrated magnetic transducer.

Magnetic Transducer Characterization

The integrated magnetometer involves sputter-depositing four resistors composed of a magneto-resistive material onto a Si substrate. Permalloy is used as the magneto-resistive material because of its relatively high magneto-resistive coefficient, its low magnetostriction coefficient, and its compatibility with IC fabrication processes. The four permalloy resistors form a bridge and are designed so that the unbalanced voltage is a function of the external magnetic field.

Resistor Design

The thickness of the permalloy layer is 300 angstroms and the sheet resistance is $10 \Omega/\square$. Each resistor in the bridge is approximately $100K \Omega$. The permalloy resistors have a relatively large, but well matched temperature coefficient of $2400 \text{ PPM}/^\circ\text{C}$ ($@25^\circ\text{C}$) $\pm 30 \text{ PPM}/^\circ\text{C}$. Figure 1 shows the TCR linearity is within $\pm 1\%$ from -40°C to 100°C for seven transducer chips.

Two designs of permalloy sensor chips were evaluated. The difference between the two is that one includes a cobalt thin film overcoat providing a permanent magnetic bias to the permalloy resistors and the other chip design is without the cobalt magnet.

Figure 2 shows a typical magneto-resistance curve for our permalloy resistors. The purpose of the cobalt magnet layer is to shift the operating point of the transducer

FIGURE 1, Nonlinearity of temperature coefficient for Permalloy resistors

FIGURE 2, Magneto-resistance curve for Permalloy
The dash line represent the bias point due to the Co magnet.

to the most sensitive and linear position for DC external field measurements. The sensor chips have dimensions of 100×200 mils and are mounted in a special package having no magnetic material.

Angular Response

The response of the sensor as a function of angle is shown in Figure 3. The zero angle position was chosen as being along the resistor length. The maximum sensitivity occurs at 90° and 270° for both the chips with and without cobalt magnets. This result concurs with that expected for the transducer's permalloy bridge layout.

Noise

The noise in the bridge was measured using batteries and an ultra-low noise circuit to record the bridge output. This data, plotted in Figure 4, shows $1/f$ noise dominates to 100 Hz and a white noise of $10 \text{ nV}/\sqrt{\text{Hz}}$ dominates above 100 Hz.

FIGURE 3, Angular response of Permalloy magnetic sensor

FIGURE 4, Noise spectrum for resistor bridge of magnetic sensor

Readout Techniques

Five readout techniques were studied for the two sensor chip designs. Each method is described below and labeled by two parameters - the bridge voltage and magnetic biasing waveforms.

1. DC-DC: This method shown in Figure 5, is a completely DC readout of the sensor and is the technique most often used for many integrated sensors. A 12.8V battery is used to bias the bridge and an ultra-low-noise op amp (OP-37) is used as a pre-amp. A second order low pass filter is used on the output.

**FIGURE 5, DC-DC read out technique
DC bridge bias and DC magnetic bias, open loop**

2. AC-DC: Figure 6 shows this method's block diagram where an AC voltage is used to bias the resistor bridge. This allows one to use a phase sensitive detection scheme (i.e. a lock-in amplifier). The minimum detectable signal is enhanced because through the AC carrier the 1/f noise inherent in the bridge can be side stepped. However, the stability of the phase shifter is critical to this method's accuracy and drift.
3. DC-AC: In this method, shown in Figure 7, an AC magnetic signal is applied to the chip through an external electro-magnetic coil. The external field then affects the magnitude, phase, and frequency (due to harmonic generation) of the sensors response as illustrated in Figure 8.
4. AC-AC: This method (Figure 9) is similar to an AM radio signal. Two modulations are applied to the sensor at different frequencies. A major concern for this method is the separation of the modulation frequencies and the bandwidth of the transducer to accommodate both modulations.

**FIGURE 6, AC-DC read out technique
AC bridge bias and DC magnetic bias, open loop**

**FIGURE 7, DC-AC read out technique
DC bridge bias and AC magnetic bias, open loop**

**FIGURE 8, Waveform due to magnetic modulation
about three point on the magneto-resistance curve**

**FIGURE 9, AC-AC read out technique
AC bridge bias and AC magnetic bias, open loop**

5. DC-AC, closed loop: The previous four methods have shown open loop sensor readout schemes. This method, illustrated in Figure 10, modifies the DC-AC method for a closed loop operation. The peak of the magnetic response curve (Figure 8) was selected as the closed loop operating point. This peak is a unique point in the sensor's response where only harmonics of the modulation field are evident and the fundamental is suppressed. A DC bias is added to the modulation coil to offset the external field and this voltage is used as the sensor readout.

FIGURE 10, DC-AC closed loop read out technique
DC bridge bias and AC magnetic bias, closed loop

Measurement Results

The above methods were compared for scale factor, minimum detectable signal, and long term stability. In each method the bandwidth of the readout was adjusted for a DC to 10 Hz response to external magnetic fields. During the testing the chips were mounted inside a zero gauss chamber which included a coil for applying uniform magnetic fields to the sensor.

Sensor chips incorporating cobalt magnets were primarily used for methods 1 and 2 and transducers without the cobalt were primarily used for methods 3, 4, and 5.

Scale Factor

The scale factors measured for the open loop methods are listed in Table 1. Also listed are the modulation conditions for the measurement. The scale factor sensitivity is expressed as the voltage output per Gauss of externally applied magnetic field (DC to 10 Hz). The sensitivity of the AC methods depends on the modulation frequency and amplitude. Figure 11 plots the scale factor for the AC-DC method as a function of the modulation frequency.

This roll-off in frequency response shown in Figure 11 results from a relatively large capacitance along and between each resistor in the bridge. This limitation in frequency response then made it impossible to operate the AC-AC readout technique with any reasonable sensitivity. In order to operate

SENSING METHOD	SENSITIVITY	BRIDGE VOLTAGE	MAGNETIC MODULATION
DC-DC	5.8mV/G	12.8V DC	
AC-DC	4.3mV/G	12Vp-p 1KHZ	
DC-AC	10.6mV/G	12.8V DC	5 Gp-p 1KHZ
AC-AC		12Vp-p 10KHZ	1 Gp-p 1KHZ

TABLE 1, Summary of scale factor for sensitivity measurement

FIGURE 11, Scale factor as a function of frequency for AC-DC read out technique

the AC-AC method the two modulation frequencies must be separated so that each can be demodulated without distorting the other modulation. Table 1 lists the extremes for the two modulations which still resulted in poor performance.

The modulation magnitude also affects the scale factor. Amplitude changes in the bias voltage modulation have a linear relationship with the scale factor. However it was discovered that amplitude changes in the magnetic modulation had a non-linear effect. Figure 12 shows the scale factor as a function of magnetic modulation amplitude for the DC-AC readout technique. Below 2Gpp and above 5Gpp unresolved non-linear phenomena are occurring.

Minimum Detectable Signal

The minimum detectable signal (M.D.S.) was measured by first optimizing the technique's signal to noise ratio (SNR) by amplifying

FIGURE 12, Scale factor as a function of magnetic modulation amplitude for DC-AC readout technique

the output. Then the smallest applied magnetic field that produced a SNR slightly greater than 1 was recorded. This data for the M.D.S. is listed in Table 2. For the reasons above the AC-AC method was not used. The best result was for the DC-DC method with an amplifier gain of 80 dB.

The hysteresis in the M.D.S. varied between the DC-DC and DC-AC, closed loop methods for large changes in the external field (± 3.4 G) the DC-DC M.D.S. had 200 mG hysteresis and the DC-AC, closed loop had 70 mG. For small field changes (± 0.1 G) the hysteresis was 10 mG and 2 mG respectively.

SENSING METHOD	M.D.S.	BRIDGE VOLTAGE	MAGNETIC MODULATION
DC-DC	0.5mG	12.8V DC	
AC-DC	1.2mG	12Vp-p 1KHZ	
DC-AC	6.0mG	12.8V DC	5 Gp-p 1KHZ
DC-AC (CLOSED LOOP)	3.0mG	12.8V DC	5 Gp-p 1KHZ

TABLE 2,Summary of minimum detectable signal measurement

Long Term Stability

Twelve hour stability runs for the DC-DC and DC-AC, closed loop techniques are shown in Figure 13. Shown in these plots are the

sensor output for a constant external field and room temperature as a function of time. These runs were made during the night to reduce the effects from environment noise (i.e. people and building). Table 3 summarizes this data.

SENSING METHOD	DRIFT(12h)	BRIDGE VOLTAGE	MAGNETIC MODULATION	TEMP.
DC-DC	12~20mG	12.8V DC		1.5°C CHANGE
DC-AC (CLOSED LOOP)	4~8mG	12.8V DC	5 Gp-p 1KHZ	1°C CHANGE

TABLE 3,Summary of long term stability measurement

Summary

Five readout techniques for an integrated magnetic sensor have been investigated. The DC-DC and DC-AC, closed loop methods produced the best results. The DC-DC case had the best minimum detectable signal and the closed loop method greatly improved the sensor's long term stability. It is hoped this characterization will lead to methods for self-checking and improved calibration for these magnetic sensors. An important point to also note from this data is that more complicated electronic readout schemes, such as the modulation techniques, do not guarantee orders of magnitude improvement in performance over a carefully designed DC readout method.

FIGURE 13,Stability runs showing sensor output and room temperature for magnetic sensor
(a) DC-DC for transducer with Co magnet
(b) DC-AC,closed loop for transducer without Co magnet