Implementation of an AMR Magnetic Sensor by Means of a Microcontroller to Achieve More Accurate Response

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Abstract: Small magnetic sensors are widely used integrated in vehicles, mobile phones, medical devices, etc for navigation, speed, position and angular sensing. Despite the practical advantages that anisotropic magneto resistive (AMR) sensors provide, they are highly temperature dependent. Another factor which extremely affects the measured magnetic field, is the inherent resistive structure of the family.

In this work a low-cost, effective micro controller digital solution is proposed to refine the accuracy and reliability of the (AMR) sensor. This approach will not only remove the dissimilarity of the Wheatstone bridge thin-film stripes and temperature drifts, but also corrects inaccuracies caused by the effect of nonlinearity and hysteresis.

Keywords: Anisotropic Magnetoresistive (AMR) sensors, Temperature drift, magnetic COTS-Components Off-The-Shelf.

1. Introduction

The Earth’s magnetic nature caused the magnetic sensors to be familiar from far centuries. Finding direction or navigation has been done over 2,000 years by using these kinds of materials. Nowadays, magnetic sensors are still a primary means of navigation but many more uses have evolved.

Due to the wide area of applications relevant to magnetic sensing, there is an indubitable need for improved sensitivity, smaller size, and compatibility with electronic systems.

Among the various technologies in sensing magnetic field, AMR sensors are the ones with a longer commercial history, speaking in domain of small sensors. They achieved a high maturity level at the end of the nineties, as was demonstrated in relevant environments like, for instance, the automotive and the mobile communications sectors. The effect, discovered in 1857 by William Thomson (Lord Kelvin), consists in the change of electrical resistance (in the order of 3 %) in a magnetic material as a response of a variation in the environmental magnetic field [1-4].

Commercial AMR sensors of the HMCxxxx series produced by Honeywell typically have dynamic ranges of hundreds of μT and resolutions in the order of 1 nT (detectivities in the order of nT/Hz1/2 for frequencies higher than 10 Hz [5]), with sensitivities in the order of 10 mV/(mT V bridge)[6]. They are able to measure fast variations in the magnetic field (bandwidth: 5 MHz) but are highly temperature dependent. Therefore, while they can operate over a huge temperature range (~-55ºC up to 155ºC), their temperature sensitivity coefficients can be as high as 1 ‰/ºC.

The commercially available AMR magnetic sensors of Honeywell like HMC1001, 1002, 1041, 1042 will all perform well. The mentioned sensors are one or two sensitive axis. Since we need to have the magnetic field in the 3 axis, HMC1043 was selected.

To implement the set/reset process and digitalize the output voltage representing the ambient magnetic field, we used the high performance and reliable C8051F123 microcontroller.

In the rest of the paper a summarized introduction to AMRs and especially HMC series is given. The next part will focus on the recourses of fault and how they appear. After that the compensation method will be presented and in the end concluding results are given.

2. Structure of AMR Sensors

The anisotropic magnetoresistive (AMR) sensor is one kind that matches well to the earth’s field sensing range. AMR sensors can sense dc static fields as well as the strength and direction of the field; which means it is not a scalar type of magnetometer but a vector one. This sensor is made of a nickel-iron (Permalloy) thin film deposited on a silicon wafer and is patterned as a resistive strip. The characteristics of the AMR thin film cause it to change resistance by 2-3% in the presence of a magnetic field. Typically, four of these resistors are connected in a Wheatstone bridge configuration, as shown in figure 1. A
common bridge resistance is 1k ohm, which is the right value of the resistance per bridge in HMC1043. Due to the large bandwidth of HMC family (5 MHz for HMC1043), the reaction of the magnetoresistive effect is very fast and not limited by coils or oscillating frequencies. The significant benefit of AMR sensors is they can be bulk manufactured on silicon wafers and mounted in commercial integrated circuit packages. This allows magnetic sensors to be auto-assembled with other circuit and system components.[7] Almost all commercially available AMR sensors use a "barber pole" structure, in which aluminium stripes sputtered on permalloy strips deflect the direction of the current by 45° and make the characteristics linear. Four such meander-shaped elements are connected into a Wheatstone bridge.

Figure 1. The Wheatstone bridge in AMR sensors

3. Factors of Inaccuracy

There are different items influencing on the accuracy of AMR field measurement. Here the most important ones are described and then the compensation method will be presented.

3.1 Effect of External Strong Magnetic Fields

AMR sensors are made to work in a specific range of magnetic field, which is ±6 Gauss for HMC1043. Strong external magnetic fields that exceed a 10 to 20 gauss "disturbing field" limit, can come from a variety of sources. The most common types of strong field sources come from permanent magnets such as speaker magnets, nearby high-current conductors such as welding cables and power feeder cables, and by magnetic coils in electronic equipment such as CRT monitors and power transformers. Magnets exhibit pole face strengths in hundreds to thousands of gauss. These high intensity magnetic field sources do not permanently damage the sensor elements, but the magnetic domains will be realigned to the exposed fields rather than the required easy axis directions. The result of this re-magnetization of the sensor elements will be erroneous measurements and indications of "stuck" sensor outputs. Since the set of small magnetic domains can easily change, a re-magnetization with a high current near them will restore the sensor.

3.2 Self-Noise of the Sensor Elements

AMR sensors are ferromagnetic devices with a crystalline structure. This same thin film structure that causes the sensor sensitive to external magnetic fields also has the drawback that changing magnetic field directions and thermal energy over time will increase the self-noise of the sensor elements. This noise, while very small, does impair the accurate measurement of sub-mill gauss field strengths or changes in field strength in micro gauss increments. The alignment of the magnetic domains in each permalloy element will drop the self-noise to its lowest possible level.

3.3 Temperature Drift

As the sensor element temperature changes, either due to self-heating or external environments, each element's resistance will change in proportion to the temperature. In the Wheatstone bridge configuration with the elements configured as a sensor, the bridge offset voltage and bridge sensitivity will drift with temperature. In compassing applications, the sensitivity drift of multiple sensor bridges are ignored due to the proportional method of deriving heading, but the bridge offset voltages must be updated and corrected for best accuracy as the temperature changes. One way to eliminate the bridge offset voltage is to find the offset value every time the measurement is done and subtract it from the output voltage.

4. Set/Reset Technique

According to the structure of the sensor which already mentioned, there are several thin film materials similar to magnetic recording tapes that causes strong magnetic fields can disturb the magnetic domains of the film portions from a smooth factory orientation to arbitrary directions. Accuracy and resolution of these sensors will deteriorate until the film magnetic domains are "reset" to make a uniform direction again.

Figure 2. Magnetic orientation

For the AMR magnetometer to operate with the same sensitivity which is substantial in offering accurate,
repeatable and reliable readings, each of the four thin-film stripes in the Wheatstone bridge must maintain the similar magnetic alignment and magneto-resistive properties. Over time the alignment may deteriorate or be disturbed, therefore changing their sensitivity to the applied magnetic field. This time-varying misalignment not only represents inaccuracy, it also causes non-repeatability in measurement, i.e., a constant magnetic field could yield different readings over a period of time. Misalignment of the device occurs over time or due to a large disturbing magnetic field of approximately 20 gauss. This misalignment effect can be removed by a set/reset process.

The Honeywell MR-sensors have patented on-chip set/reset straps. The set/reset straps are used to reduce effects of temperature drift, non-linearity errors and loss of signal output due to the presence of high magnetic fields. If a magnetic field larger than 3 Gauss is applied to a sensitive axis in the sensors, the polarity of the permalloy film may be upset or flipped, and result in a change of the sensor characteristics. Sensor characteristics may be restored by applying a strong magnetic field along the sensitive axis, using the set/reset straps. When applying a +5V bridge voltage \( V_{\text{BRIDGE}} \) and using 3A S/R pulses the sensors have a typical sensitivity of 5 mV/Gauss.

When a SET current pulse is driven from the SR+ pin in the set/reset strap the output response is the curve with positive slope in figure 3 (HMC1001-2, 1999). When a RESET current pulse is driven from the SR-pin, the output response is the curve with negative slope. The two output responses are mirrored about the origin, except for a bridge offset and an external offset. The bridge offset is due to resistor mismatch in the Wheatstone bridges from manufacturing. The external offset may be due to nearby ferrous objects or magnetic fields interfering with the field to be measured.

The magnetic field is measured by first driving a SET pulse through a sensor and then read the sensor output \( V_{\text{set}} \) when it has settled. Then a RESET pulse is driven through a sensor and the sensor output \( V_{\text{reset}} \) is read. This technique is called "set/reset switching" and the applied magnetic field can be found using equation 1. Fig 4.

\[
V_{\text{applied}} = \frac{V_{\text{set}} - V_{\text{reset}}}{2}
\]  

Bridge offsets, temperature offsets and offsets from the interface electronics are disappeared by using the "set/reset switching" technique.

![Figure 3. output voltage after set and reset applied](image)

5. Experimental results

To implement the set/reset process, analog-to-digital conversion, and the required computation for the digital compensation, a microcontroller is employed. The time scheduling for set/rest pulses and ADC conversions must be carefully planned to achieve fast and reliable measurement of magnetic field, while guaranteeing not to lose any data. As shown in Figure 3, the values of \( V_{\text{SET}} \) and \( V_{\text{RESET}} \) used to compute the bridge offset and eliminate the temperature drift are assumed measured for the same magnetic field. Although it is impossible to measure the values of \( V_{\text{SET}} \) and \( V_{\text{RESET}} \) at the same time, the time gap between these two measurements needs to be small enough in order to remain the magnetic field fairly constant in this duration. On the other hand, if the gap becomes too small it leads to a high frequency and high speed sampling, but the fact is that for an accurate measurement large enough time gap must exist to allow the signal reaching its steady state. As a result, choosing the appropriate frequency to maintain a trade-off is a significant issue.

The microcontroller used, is a C8051F123 one which has an Analog to Digital convertor with 10 bit resolution. The ADC reference voltage of the microcontroller is set to 3.3V and hence the ADC resolution will be \( 3.3V / (2^{10} - 1) = 3.255 \) mV. It is essential to ensure that the analog signal to be converted has range large enough (surely less than 3.3V) to utilize as many of the 1024 quantization levels as possible in order to achieve higher accuracy of measurement. The maximum sensitivity of the HMC1043 sensor is 1 mV/V/Gauss and the range of the magnetic field being measured is approximately \( \pm 1.0 \) Gauss. Since the voltage supply for the Wheatstone bridge in the magnetometer is 5.0V, the maximum range of the bridge output is only 5mV. For the 3.255 mV ADC resolution to be meaningful, we have to amplify the magnetometer reading before it is converted into digital signal. This can be done by using an instrumentation amplifier. The amplification gain is set at approximately 225 so that the
magnetometer reading at the maximum field of 1 Gauss will be amplified to 1.125V. This is then shifted by a DC voltage of +1.2V to allow the full range of values to be from 75mV to 2.325V. The calculations are summarized in equation (4-1), where Vout is the bridge output voltage of the magnetometer during a set or a reset state. The prototype, as described in advance, is shown in Fig.5.

\[ V_{adc} = 225 \times V_{out} + 1.2 \]  

(2)

The timing sequence for set/reset pulses and multichannel ADC conversions is constrained by the following: ADC clock, ADC conversion rate, the number of ADC channels, instrumentation amplifier slew rate, set/reset circuit, and any other calculations performed by the microcontroller. Each of these items can cause a bottleneck in timing. To maximize the sampling rate of the magnetometer, all these factors must be carefully considered.

The instrumentation amplifier employed is the Analog Devices AD620. With a gain of 225, the instrumentation amplifier has a slew rate of 0.75 V/μs which will require that the ADC sampling should occur after the instrumentation amplifier reaches a steady state. Taking the reading too early will cause errors in reading. The field being measured is approximately 1 Gauss. Due to having the best time to satisfy both reaching the steady state and remaining the magnetic field almost constant in this duration, 500 Hz frequency equal to 2 micro second time period, Fig.6, was chosen.

![Image of prototype](image1.png)

**Figure 5.** The prototype of magnetometer

![Image of oscilloscope](image2.png)

**Figure 6.** Set & Reset pulses with 2 μs duration and a peak of ±3 volt

![Image of oscilloscope](image3.png)

**Figure 7.** Oscilloscope picture of set/reset pulse and the corresponding output voltage

The oscilloscope picture in Figure 7 shows the set and reset pulses and the sensor response before converting to digital signal. As mentioned earlier, using equation 1 will remove offsets caused by temperature changes, Wheatstone bridge and other elements in the circuit.
The data points in Figure 8 were collected in the laboratory using an experimental setup that includes Honeywell 3axis HMC1043 magnetometer, C8051F123 microcontroller, Analog Devices instrumentation amplifier AD620 and the Helmholtz cage for generating magnetic field. The microcontroller is used to create the PWM pulse feed to set/reset circuit, perform the ADC sampling and conversions per set/reset cycle, control the timing, and carry out computations. The data points on each of the Vx, Vy and Vz lines are the measurements of the applied magnetic field on each axis. To obtain a data point on the Vx line, the magnetic field is measured twice - one in the set state as $V_{SET}$ and the other in the reset state as $V_{Reset}$ then the bridge voltage offset is computed as $V_{os} = (V_{SET} + V_{Reset}) / 2$ and the voltage at this point on the Vx line is $Vx = Vset - V_{os}$. In other words, the data points of Figure 8 show the output voltages of the bridges with bridge voltage offset corrections. It can be seen that the Vx, Vy and Vz lines are virtually straight lines. Although the bridge voltage offset has been corrected, these lines do not exactly pass through the origin. The reason is the external magnetic field offset, which is caused by a nearby ferrous object or an unwanted interfering magnetic field.

6. Conclusion

This work presented a practical microcontroller digital method to remove the inaccuracies caused by the imperfectly matched thin-film stripes of the Wheatstone bridge in the AMR magnetometer and minimizes the influence of nonlinearities, hysteresis and temperature drifts.

References