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УДК 621.317.445

LOW FIELD MAGNETIC SENSING WITH ANISOTROPIC MAGNETORESISTIVE SENSORS

ИЗМЕРЕНИЕ СЛАБОГО МАГНИТНОГО ПОЛЯ С ПОМОЩЬЮ АМР ДАТЧИКОВ

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Изучена работа магниторезистивных датчиков HMC1001 и HMC1002 производства фирмы Honeywell при низких температурах. Показано, что датчики могут быть успешно использованы для измерения слабых магнитных полей в криогенной аппаратуре.

Operation of Honeywell's AMR sensors HMC1001 and HMC1002 has been investigated at low temperature. It has been shown that the magnetoresistive sensor can be used to monitor low magnetic environment in cryogenics.

Ключевые слова:
Магнитное поле, магниторезистивный датчик, феррозонд, криоэлектроника

Key words:
Low magnetic field, magnetoresistive sensor, fluxgate, cryoelectronics.

Introduction

Large quantities of magnetic field investigations are routinely gathered over space exploration. The results of those measurements can provide important information about Earth, planets and other cosmic objects because their bodies and surfaces contain proportions of materials with different magnetic susceptibility.

Besides conventional requirements the satellite magnetic measurement equipment need to be robust for high mechanical vibrations, radiation persistency and operate at a very wide temperature range. Various magnetic sensors are available for space use. In the report we discuss suitability of AMR application in satellites.

Magnetic sensors for space

There are many techniques for magnetic sensing, including Hall effect sensor, magnetoresistors, magneto-optical sensor, Lorentz force based on MEMS sensor, fluxgate magnetometer, search coil magnetic field sensor, SQUID magnetometer etc. The most relevant sensors are shown in a comparison Table 1.

As we see from the Table 1 magneto-resistor has a competitive precision and radiation hardness, but it concedes in power consumption. Fortunately, the magneto-resistors have a relative high bandwidth in the range of MHz and low noise. It allows using the magneto-resistors with a pulse read-out with a low duty cycle to reduce device power.

Table 1. Magnetic sensors

Sensor	Sensitivity per 1 Hz bandwidth	Power consumption, continues operation	Own field at distance of 1 cm	Radiation immunity	Drawback
Fluxgate	<0,1…0,3 nT	Middle, <0,3 mW	~10 nT	High	• Power consumption • Size • Drift
Magneto Resistor	<0,1…0,3 nT	High, <30 mW	<<1 nT	High	Power consumption
SQUID	<0,000005 nT	Small, ~1 nW	<<1 nT	Low	Relative measurement
Searchcoil	Frequency dependent	Small, ~1 uW	<<1 nT	High	• AC measurement, • Frequency dependent sensitivity

Anisotropic Magnetoresistive Effect

Magnetoresistance is defined as the property of a material to change the resistivity when an external magnetic field is applied. This effect exists in all types of metal, being normal or ferromagnetic. There are two types of effects which exist in bulk, simple structures, ordinary magnetoresistance (OMR) and anisotropic magnetoresistance (AMR). The other effects, giant magnetoresistance (GMR), colossal magnetoresistance (CMR), and tunnelling magnetoresistance (CMR), all require complex material structures (eg. layed structures) or phase transitions to exist.

In ferromagnetic the magnetoresistance effect can be broken down into three different types: $R(M(T))$ is the resistance changes due to indirect manipulation of magnetization through thermal changes, $R(M)$ is the resistance change due to direct manipulation of magnetization, and $R(\theta_{M,I})$ is the resistance change due to the angle between the magnetization and current [1]. The one we are interested in for our application is $R(\theta_{M,I})$. The resistivity of the material showing such behavior can be modeled by $\rho(\theta_{M,I}) = \rho_0 + \rho_\Delta \cos^2(\theta_{M,I})$, where $\rho(\theta_{M,I})$ is the zero-field resistivity and ρ_Δ is the material constant. The resistance change is maximum when the current and magnetization are orthogonal to each other (Fig. 1, left). Since the ferromagnetic material will saturate after some certain applied magnetic field, the resistance change to applied field looks as shown in Fig. 1 (right).

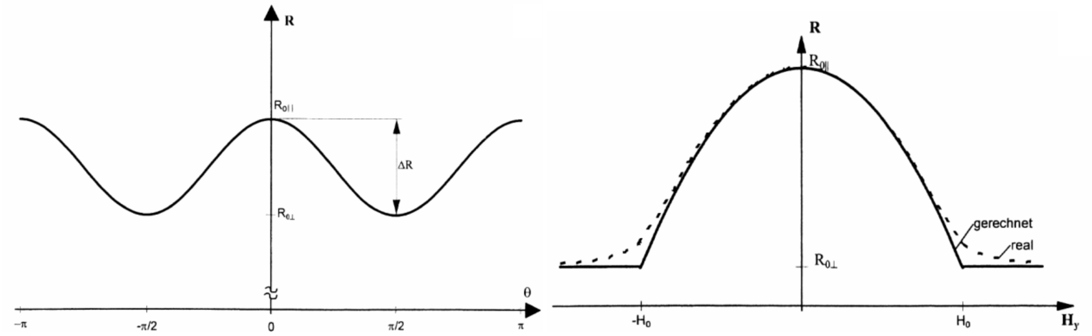

Fig. 1. Left: Resistance of ferromagnetic thin film in x direction as a function of the angle Θ between the current I and the magnetization M; right: Resistance of a thin ferromagnetic film as a function of the transversal field H_y [2]

As one can see, near the origin the resistance change is very small, being zero for $H = 0$. For low field sensing this would not make a useful sensor device. In order to overcome this lack of sensitivity and also non-linear output a 45° bias is applied to shift the sensor output into the linear region (Fig. 2, left).This is called the barber pole structure (Fig. 2, right).

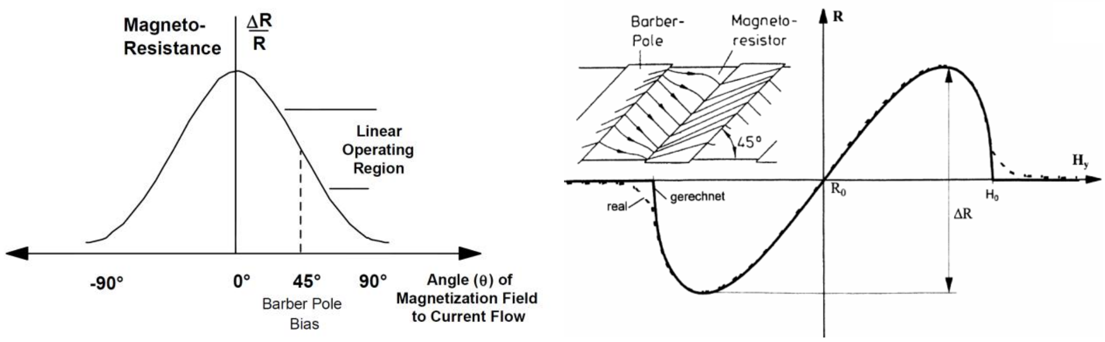

Fig. 2. Barber pole structure sensor. Left: Magnetoresistive Variation with Angle Theta [3]; right: Current flow in a barber pole structure, and resistance R of a thin ferromagnetic film with a barber pole structure as a function of the transversal field H_y [2]

Honeywell HMC 1002 AMR Sensor

The AMR sensor which was chosen for our tests was the Honeywell HMC1001 sensor (or HMC1002, which contain two identical sensors oriented perpendicular to each other) [4]. It provides a lot of additional functionality aside from the ferromagnetic thin film resistive element. Each of the HMC1001 sensors is composed of four identical thin film elements made out of a Nickel-Iron alloy (Permalloy). Two of the films are shielded, another two are sensitive to outside field. These Permalloy elements are aligned in the barber pole structure with shorting bars separating the thin films. The shorting bars cause the current in the «pole» to flow at 45° in the Permalloy elements. The four resistive elements are arranged in a Wheatstone bridge configuration (Fig. 3) to provide very accurate measurements over a large range of temperatures.

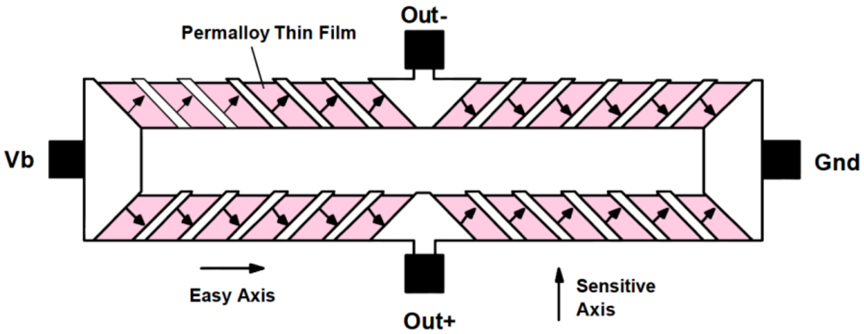

Fig. 3. AMR Wheatstone bridge element. Vb – bias voltage [4]

The easy axis of the sensors is the preferred direction of magnetization with zero magnetic field. Applying an external field along the sensitive axis of each element the angle between the current flow and the magnetization changes which leads to changes in the output voltage of the bridge.

The HMC1001 sensor allows for two modes of operation referred to as set and reset mode. Each mode differs from each other by having their easy axis of magnetization at 180° to each other. This causes the response of the sensor to be opposite in each mode. The output of the AMR magnetometer is shown in Fig. 4.

As seen in Fig. 4, there is some dc offset to each of the set and reset curves. Ideally if all 4 Permalloy elements were the same, the output voltage would be zero at zero field. However due to imperfections in the manufacturing process all 4 elements cannot be the same resulting in a bridge imbalance at zero field. This dc offset can be compensated with consistent measurement in set and reset modes [5].

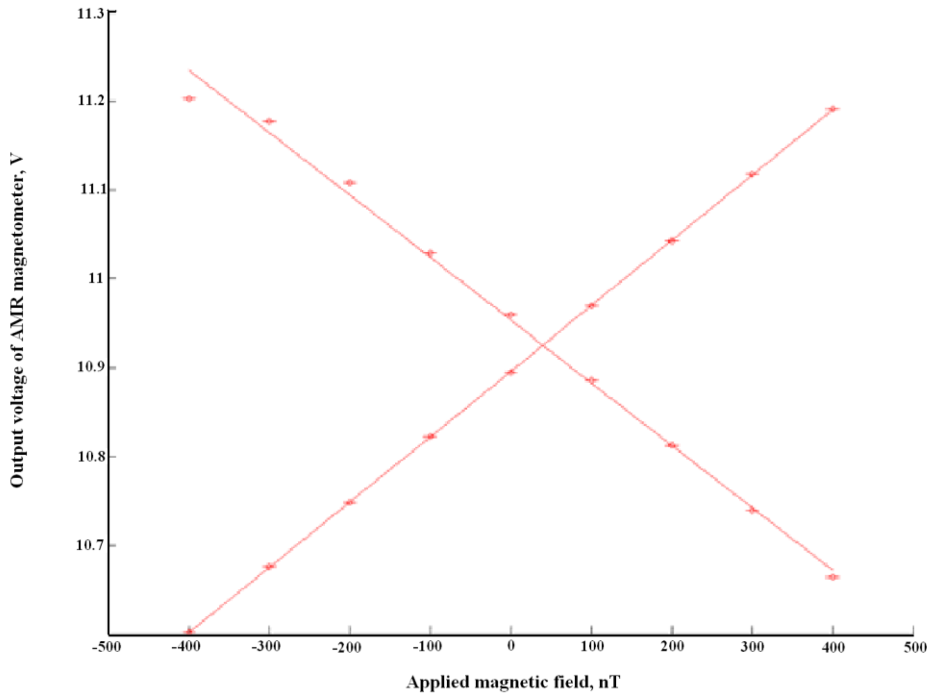

Fig. 4. Sensor output vs magnetic field for both set and reset modes

In addition, the set/reset capability of the sensor allows for compensation of cross-axis effects [6] (perpendicular component of the field that is trying to be sensed in the plane of the thin film). Looking at the difference of the set and reset voltage the cross axis effects become negligible.

Test circuit design

The designed circuit allows measuring up to 8 sensors simultaneously. The electronics used to control the sensor board utilizes an FPGA for its digital circuitry. It has various DACs and ADCs to control signals as well as read them [5].

The PCB has four Honeywell HMC 1002 sensors and one Honeywell HMC 1001, nine sensors in total. Eight of the nine are wired up and share a common offset and set/reset line. Each sensor is measured serially using a multiplexer for the input bridge voltage and the output voltage lines. The PCBs are shown in Fig. 5.

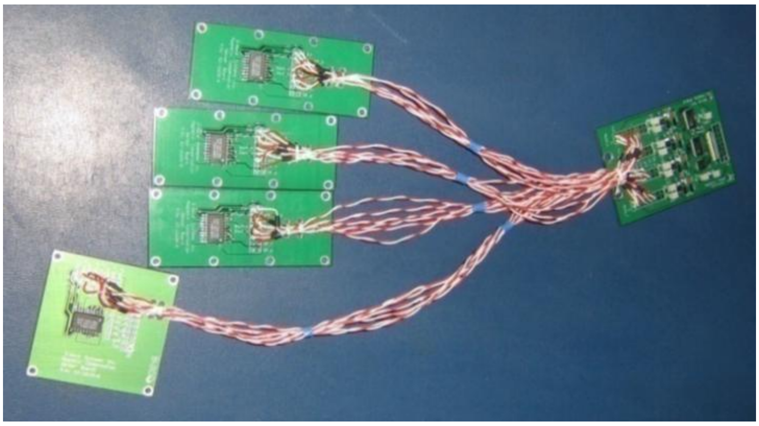

Fig. 5. Test PCBs

Results

Various experiments were run at different operating environments to test the functionality of the AMR sensors. The three main operating environments were at temperatures of 300, 77 and 4 K. Running the test for both set and reset modes to produce the AMR sensor's voltage vs the magnetic field curves, the outputs were seen as it is shown in Fig. 4. There are two curves for each sensor. These curves represent the measurements after the set pulse and the measurements after the reset pulse. The difference between the set curve and the reset one is the negative response to field change as compared to the set curve.

After tests the PCB sensors were placed into a dilution refrigerator. During the cool down of the dilution fridge from room temperature (300 K) to approximately 9 K the magnetic field was recorded using the AMR sensors and a fluxgate sensor. The fluxgate sensor was mounted in the z direction about 2 inches from AMR sensors. The AMR sensors were setup to take measurements every 20 min. and the fluxgate was setup to take measurements every 1 min. The results are shown of Fig. 6.

All eight sensors were operational throughout the entire cooldown. A large change of field was seen at about 40 K due to the stainless steel parts inside the fridge which have not been annealed.

As investigation showed the room temperature amplifier noise dominates in the measurements. The results of the noise measurement at 10 K are shown on the Fig. 6. For read-out transform coefficient (150 nV ≈ 1 nT) the white noise output level of 505 nV/Hz1/2 corresponds to 3,37 nT/Hz1/2 (Fig. 7). Further noise reduction is possible with a cooled preamplifier [7, 8].

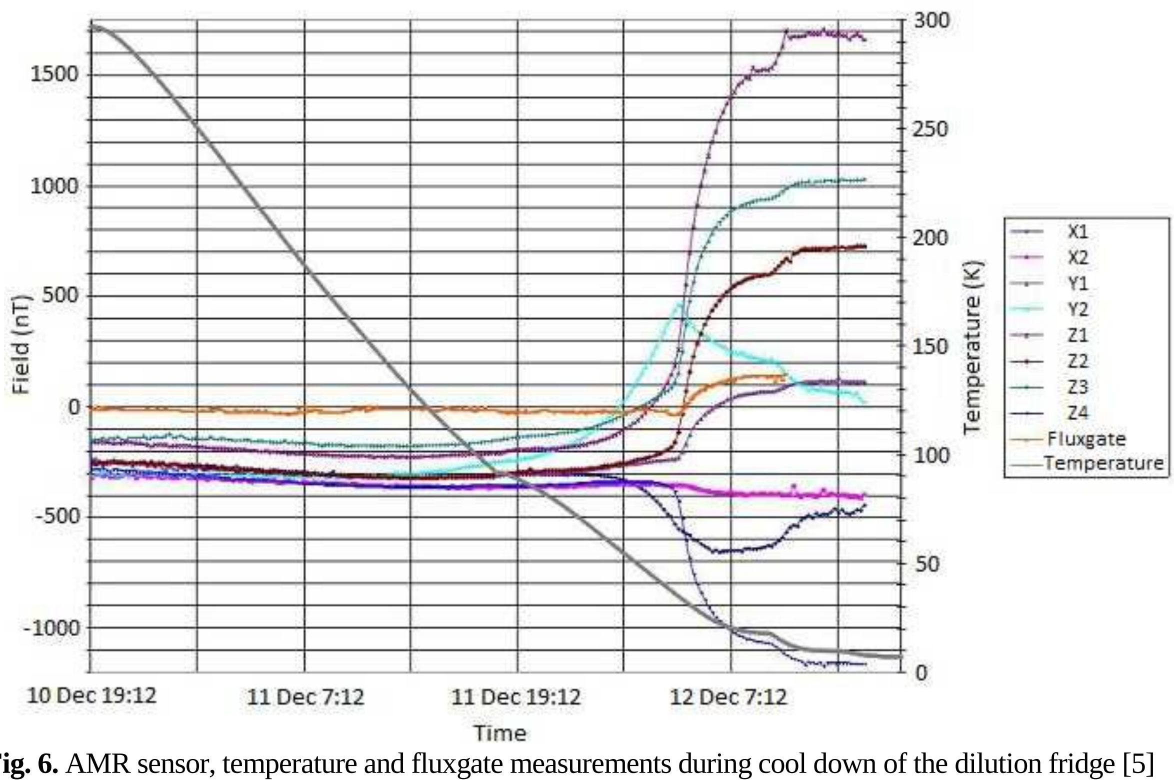

Fig. 6. AMR sensor, temperature and fluxgate measurements during cool down of the dilution fridge [5]

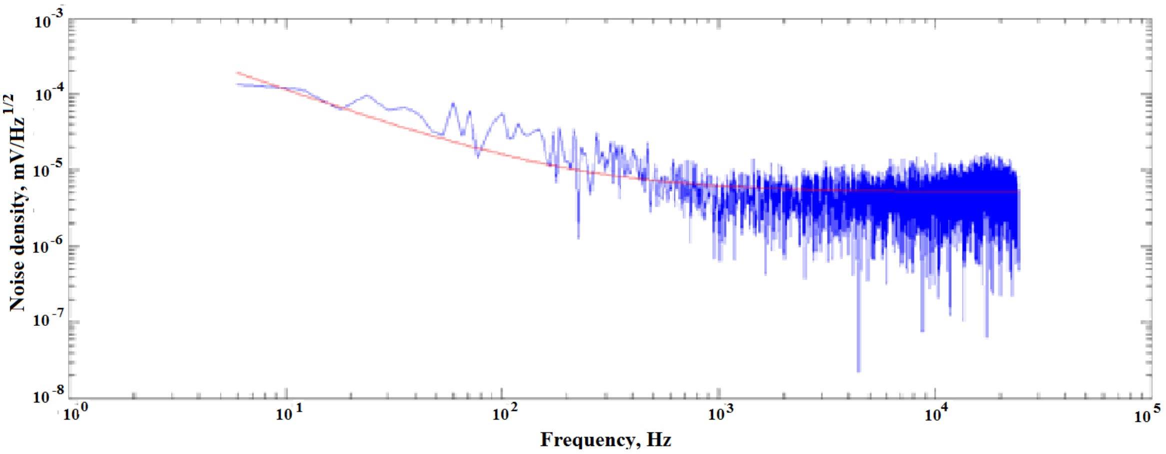

Fig. 7. Noise spectrum of output signal of AMR sensor at 10K

Conclusion

Operation of Honeywell's AMR sensors HMC1001 and HMC1002 has been investigated at low temperature. It has been shown that the sensors can be used to monitor magnetic environment of a processor in a wide temperature range down to 4 K.

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Approved on 29.04.2013.