Improving the Accuracy of a Magnetic Bio-Sensor – A Novel Approach

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Abstract— **This paper shows a novel approach to improve the accuracy of a magnetic bio-sensor system. In a typical magnetic bio-sensor system, the magnetic beads will be attached to the target molecules and will be immobilized on the substrate. A fixed known magnetic field will be applied to the area, and a planar Hall-Effect magnetic sensor will be used to measure the variation in the magnetic flux density due to the presence of magnetic beads. Such variation is proportional to the magnetic bead density.**

Environmental factors such as temperature, earth's magnetic field, and power supply noise are major sources of errors that affect the accuracy of the measurement. Unlike the use of a DC excitation field, our method utilizes an alternating current excitation at a specific frequency to generate the base magnetic field. The output voltage of the Hall-Effect sensor will then be filtered after amplification to separate the exciting frequency from the noise frequencies. Such systematic environmental noise elimination improves the accuracy of the overall system. This has been verified by simulation. The paper benchmarks the use of alternating current as exciting field over the commonly reported direct current excitation. In addition, such robust system will not require extensive calibration since it is resilient amidst changes in environmental conditions. This is an essential property required for a system to be used in portable and point of care testing.

Keywords— **Magnetic beads, Hall-effect sensor, Bio-sensor, Noise Reduction, Accuracy.**

I. Introduction

Magnetic beads are commonly used as bio-markers in a magnetic bio-sensor system. In a magnetic immunoassay protocol as explained in [1], attachment of magnetic bead is done by several washing processes. An example for such attachment is shown in Fig. 1.

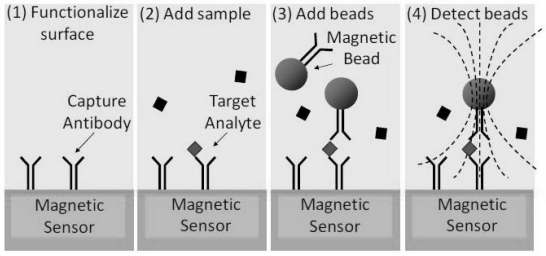


Fig. 1- Magnetic bead attachment [1]

In this method a known base magnetic field is applied to the sensor area [2]. The magnetic beads' presence in this field caused the variation in flux density. A magnetic sensor measures the magnetic field flux density. The difference between the base magnetic field and the measured magnetic field is proportional to the density of magnetic beads in the sensor area.

In this paper different sources of errors and their effects on the measurement are modeled. A typical DC exciting measurement is simulated and the effect of noises on the final result is shown. Then a technique of using AC exciting field is presented. This is by far a novel approach. The simulation results show that the effect of noises in the measurement has been eliminated.

II. System and Modeling

A. Hall-effect magnetic sensor

The magnetic sensor is an N-well planar Hall-effect cell. Fig. 2 shows the basic structure of a Hall-effect sensor.

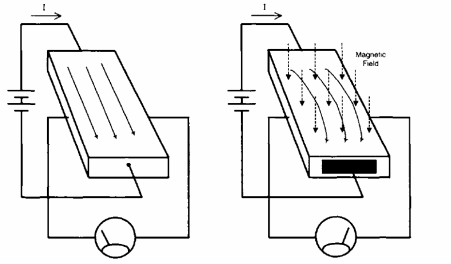


Fig. 2- Hall-effect sensor structure [3]

The Hall-Effect sensor output voltage is shown in Eqn. (1) [3]:

$$V_H = \frac{IB}{q_0 N d} \tag{1}$$

where: B is the magnetic field, I is the excitation current, d is the N-well thickness, and N is the amount of doping.

By applying a regulated fix voltage to the sensor, the current remains constant. The structural parameters are constant for the sensor; as a result the output voltage is propor-

tional to the applied magnetic field only. In the model, any external magnetic field contributes a portion in the Hall voltage.

B. Exciting magnetic field

In order to detect the presence of magnetic beads in the sensor area, an exciting magnetic field is generated by injecting electrical current in two polarization metal lines above and below the Hall sensor [2]. The directions of the current create an additive magnetic field as defined by Biot-Savart's Law and the right-hand-rule for the magnetic field created by a current-carrying wire.

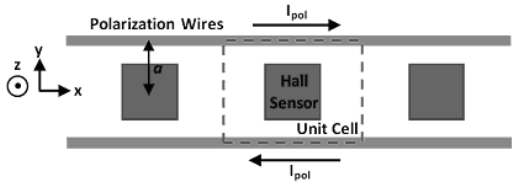


Fig. 3- Exciting magnetic field polarization wire [1]

Fig. 3 shows the arrangement of such metal line around the Hall sensor.

C. Signal, Noise and disturbance model

The exciting magnetic field generated by the polarization wires and other environmental magnetic fields affect the measurement. The model we used is based on the normalized contribution of each source on the Hall voltage measurement.

Exciting field: Two models are used for the exciting field. In the conventional DC excitation, we use a normalized value of 45% for this signal as shown in Eqn. (2).

$$ExcDC = 0.45 \tag{2}$$

In the proposed AC excitation method, a sinusoidal signal with 45% peak and 723Hz frequency is used as model and shown in Eqn. (3). The phase shift does not affect the results of this work; and so in the whole simulation for the signals and filters, a phase shift of zero is assumed.

$$ExcAC = 0.45Cos(2\pi \times 723t) \tag{3}$$

Earth Magnetic field: Since the bio-sensor is measuring the weak magnetic field, the earth's magnetic field causes considerable error in the measurement. The earth's magnetic field is modeled by a DC signal with 30% of normalized value as shown in Eqn. (4).

$$EearthMag = 0.30 \tag{4}$$

Power Supply Noise: The power supply is running on either 50 or 60Hz depending on the country. The 60Hz frequency is chosen for this model with a peak normalized value of 15% as shown in Eqn. (5)

$$PowerPlug = 0.15Cos(2\pi \times 60t) \tag{5}$$

Low frequency: The noise due to variations in temperature and humidity have very low frequencies. It is modeled with a 0.25 Hz signal with peak normalized value of 25% as shown in Eqn. (6).

$$LowFrq = 0.25Cos(2\pi \times 0.25t) \tag{6}$$

High frequency: The noise due to switching is modeled by a white Gaussian noise with 30 dB signal to noise ratio of power.

III. SIMULATION

The system is simulated using MATLAB® in two steps. In the first step, a conventional system that uses a DC current for polarization is simulated. In the next step, the proposed technique using AC current polarization and output filtering is simulated.

DC Exciting field: The Hall output voltage is the sum of the components of different sources. Each magnetic field has its corresponding component of Hall voltage. Fig. 4 shows the component based on the models defined in section II.

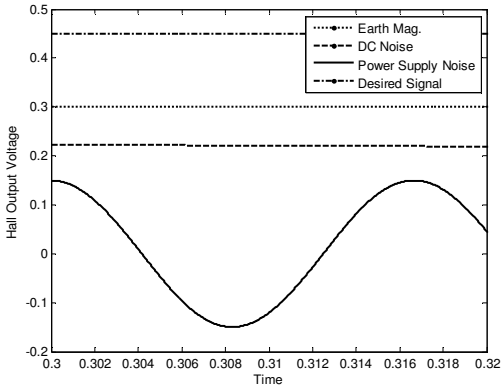


Fig. 4- The components of the Hall output voltage separated by source

The measured Hall sensor output voltage using the DC excitation, as shown in Fig. 5, is noisy and the only way to extract the desired signal from this is by taking its average. Then for each point, there is a need for calibration. Such calibration is valid only for that point and the accompanying environmental condition when the calibration took place. A

device based on this system may go out of calibration when it is being replaced.

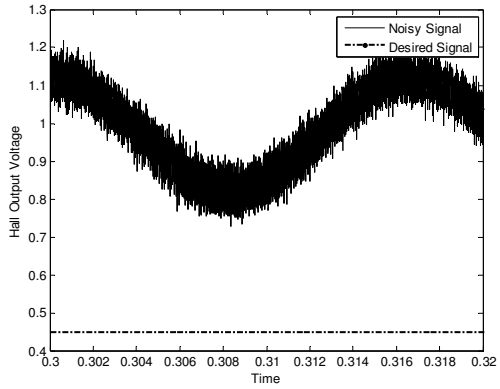


Fig. 5- The Hall output voltage using a DC exciting field

AC Exciting field: In order to eliminate the effect of noise and improve the accuracy of the bio-sensor system, using the AC exciting field is proposed. In this method, the current injected to the polarization wires are sinusoidal. The phase shift is ignored for both signal and filter since the amplitude is the only parameter that is needed for measurement. Fig. 6 shows the individual signals from different sources.

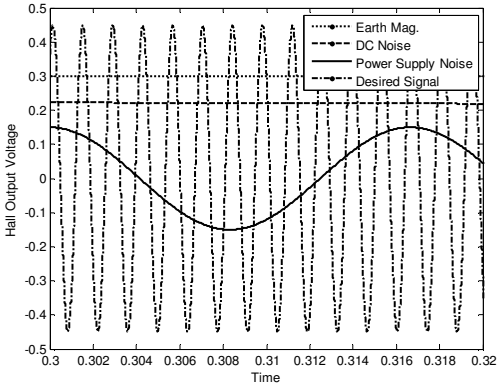


Fig. 6- The components of Hall output voltage using an AC exciting field

Although the frequency of the exciting signal is arbitrary, some practical issues need to be considered. The frequency should be an odd number to avoid conflict with the harmonics of the power supply noise. In addition, it should not be close to the frequency of the other noises and their harmonics so that it can be easily filtered. The frequency should be high enough so that the analog filter can be implemented using smaller capacitors or a digital filter can be designed using a lower order. Furthermore, the frequency should not be so high to exceed the bandwidth of the amplifiers or generate antenna problems in the chip. Based on these considerations, a frequency of 723 Hz is chosen for the AC exciting current.

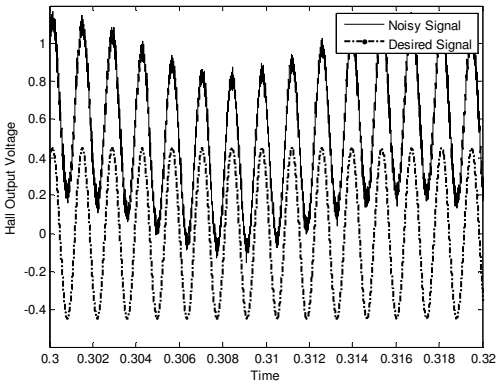


Fig. 7- The Hall output voltage using an AC exciting field

Fig. 7 shows the noisy Hall sensor output voltage with the desired signal using an AC exciting field. The result is a noisy signal that can be readily filtered out to extract the desired signal without the need of extensive calibration.

A digital 24th order Butterworth IIR band-pass filter is used in the simulation. Its specifications are detailed in Table 1.

Table 1 Digital filter specifications

Parameter	Value	Unit
First stop-band frequency	700	Hz
First pass-band frequency	720	Hz
Second pass-band frequency	750	Hz
Second stop-band frequency	770	Hz
First stop-band attenuation	60	dB
Pass-band ripple	1	dB
Second stop-band attenuation	80	dB

The filter is designed using MATLAB®. The sampling frequency has been set to 1 MHz, considering that typical modern ADCs have a conversion time of 200 nS. Using digital filter is preferred compare to analog one. Digital filter could be re-designed by updating the software while analog filters require hardware modification. Analog filters generally require large capacitors which is not a good idea in chip design. In digital filters, achieving better quality and higher order is done by calculation or mathematical formulation, while in the analog filter, the necessary hardware needs to be added. In digital filter, the IIR is preferred compared to FIR since for the same quality, IIR filter has much

lower order. By the way, in the IIR digital filter design, the issue of aliasing, stability and transient time should be addressed properly. For the target application, the phase shift does not have any effect so it could be ignored in the filter design.

Fig. 6 shows the simulated output of the filter. It is a perfect match to the desired signal defined by Eqn. (3), with all of the noises filtered out.

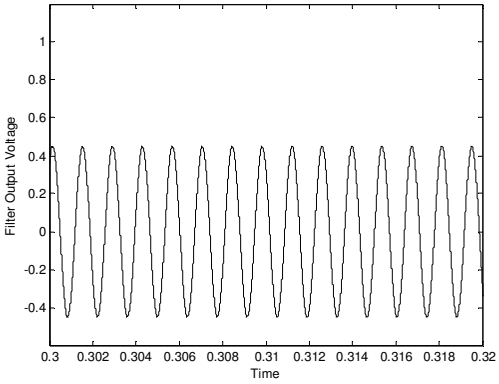


Fig. 8- The filter output showing that the desired signal has been extracted successfully

IV. Conclusions

By MATLAB® simulation, the paper has successfully presented that by using an AC exciting field in Hall-effect based magnetic bio-sensor, the environmental noises such as the earth's magnetic field, power supply hum, temperature and humidity variations will be eliminated in the measurement results. This will increase the accuracy of the measurement.

In addition, the high end product could be used in point of care without the requirement of extensive calibration.

In the future, the same technique will be tested on the actual chip to confirm the result of simulation on the real system. The digital filter can be realized using the digital IC design flow synthesized on a Field Programmable Gate Array.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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