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Article

Design of magnetic field sensor with software for a wide range of applications

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Abstract. The work of the paper outlines a highly efficient wirelessly magnetic field-based information transmission method, enabling real-time data acquisition. Emphasizing stringent demands on magnetic devices for high sensitivity across a wide range of field strengths, it highlights the need for rapid response times and minimal power consumption. The paper introduces a prefabricated magnetic sensor programmed on an Arduino board using Hall's Effect. This principle exploits electron transfer within a conductor under a magnetic field, inducing a transverse potential difference. Meticulously chosen solid-state materials and geometries generate detectable pulses, subsequently amplified for measuring various magnetic field components. Operating within a voltage range of 2.7-6.5V, aligned with the Arduino's 5V standard, the sensor demonstrates zero signal levels at 2.25-2.75V. Sensitivity ranges from 1.0-1.75 mV/gauss, mandating pre-calibration for accuracy, facilitated by a pre-calibration function or reset button. Output voltage ranges from 1.0-4.0V when powered by 5V, suitable for analog-to-digital conversion. With a minimum measurement range of ±650 gauss, typically extending to ±1000 gauss, and a swift response time of 3 ms, the sensor allows measurements up to tens of kHz. Operating currents between 6-10 mA are suitable for battery-powered applications, while a temperature-induced error of 0.1%/°C equates to 3 mT. Notably, the sensor measures magnetic fields along and perpendicular to the axis. To enhance accessibility and accuracy, a specialized Python-based software tool has been developed, featuring automatic sensor identification. This work encapsulates the paper's focus on advancing magnetic field measurement technology with practical implications for diverse applications.
Keywords: hall effect, sensor, magnetic field, calibration, software.

1. Introduction

In the modern age, sensors designed to measure magnetic fields, including Hall sensors, Wiegand sensors, magnetoresistive sensors, and similar devices, are widely used in a variety of applications including home appliances, magnetometry systems, navigation, automation, and medicine [1]. It is particularly important for medical magnetic field sensors to have high sensitivity, as many living organisms produce magnetic fields with low intensity levels, yet measurable, which can reach values on the order of 10 nT [2].

A promising strategy is based on the principle of discrete application of Ampere's law using a ring array of sensors designed to measure magnetic fields. When choosing the radius of the ring array, the linear operating range of the magnetic field sensors must be taken into account, which may lead to an increase in size to ensure sufficient space when dealing with large current values. The authors of the study [3] propose a method of creating a compact broadband current sensor based on the combination of tilted tunneling magnetoresistance sensors and Rogowski coil. These tunneling magnetoresistance sensors are characterized by the possibility of increasing the linear range with tilting and can be used as current sensors. The basic principle is to change the sensitivity of the sensor depending on its tilt angle. Nevertheless, the application of the proposed sensor can sometimes be non-trivial and cause some difficulties.

Researchers [4] seek to solve the current problem of improving the accuracy of magnetic field measurements by optimizing their placement. In the presented magnetic field sensor arrangement scheme, pairs of sensors are installed symmetrically, but their positions relative to the center are shifted along each axis.

The authors [5] presented a compact two-axis magnetometer equipped with a fluxgate and with a high sensitivity of up to 92 V/T. In contrast, magnetoresistive detectors typically have a resolution on the order of 10 nTL [6]. Another studies [7-8] reports the development of a polysi microchall device that provides sensitivities in the range of 5 to 6 mV/T and has a resolution of less than 10 nTl. These all sensors, in order to operate, require current to be passed through the excitation coil, which leads to an increase in power consumption. In addition, they use optical, capacitive and piezoresistive techniques to measure the displacement of resonant structures, which requires a sophisticated sensing system.

As a result, there was a need to create new approaches or technologies that could overcome these limitations and challenges.

2. Methods

A highly convenient and efficient means of information transmission involves wirelessly utilizing magnetic fields, enabling real-time acquisition of magnetic field data. This method imposes stringent demands on magnetic devices, necessitating high sensitivity to accurately measure magnetic fields across a broad spectrum of strengths. Furthermore, these devices must exhibit rapid response times and minimal power consumption to meet operational requirements effectively.

This paper presents a prefabricated magnetic sensor that meets all requirements and is programmed on an Arduino board using the Hall's Effect. This effect is harnessed for the measurement of magnetic fields, wherein electron transfer occurs within a conductor positioned in the magnetic field. Consequently, a transverse potential difference arises across the conductor owing to electron attraction. Through meticulous selection of solid-state conductor material and geometry, a detectable pulses are generated, which may subsequently be amplified to yield measurements across various components of the magnetic field.

When building the sensor, we selected an operating voltage of 2.7-6.5V, which is perfectly in line with the standard 5V voltage for the Arduino platform (Figure 1). The zero signal level was in the range of 2.25-2.75V, which is almost midway between the 0V and 5V levels. The sensitivity range was 1.0-1.75 mV/gauss, hence pre-calibration is required to get accurate results. A pre-calibration function or otherwise a reset button was also provided.

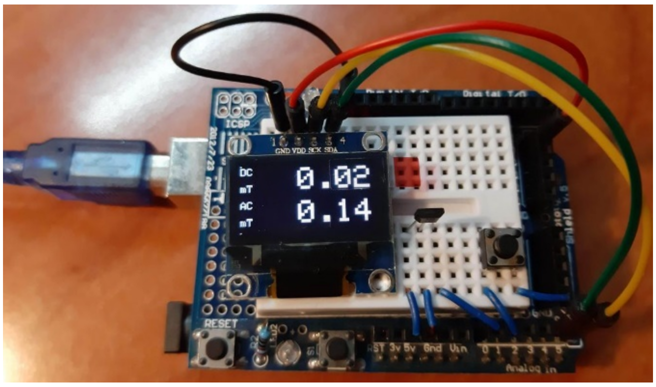

Figure 1 – Internal sensor connection on the Arduino board

When operating from 5V, the output voltage is 1.0-4.0V, which allows reading data using an analog-to-digital converter on the Arduino platform. The minimum measurement range was ±650 gauss, typically increasing to ±1000 gauss. The response time of the device is 3 ms, allowing measurements up to tens of kH. The operating current consumption is between 6 mA and 10 mA, which is a small value suitable for battery-powered applications. The measurement error for a temperature change of 0.1%/ºC seems negligible, but this corresponds to an error of 3 mT.

The sensor has the ability to measure the magnetic field both along the axis and in the direction perpendicular to it. For a more accessible and accurate determination of values, we have created a special software tool based on Phyton that includes automatic sensor identification (Figure 2).

```
sensor:
  - platform: template
    sensors:
      total_magnet_pump:
        unit_of_measurement: mT
        value_template: "{{ state_attr('sensor.0x842e14fffe1393a2_power', 'magnet') }}"
```

Figure 2 – A fragment of the Python sensor programming

3. Results and Discussion

Developed sensor enables simultaneous measurement of both radial and axial magnetic fields. The use of dynamic variable oversampling significantly reduces noise at low sampling rates. Figure 3 shows a graph of the special software developed for this sensor, which provides quick and easy data acquisition from the sensor, as well as its subsequent analysis on the appropriate platform.

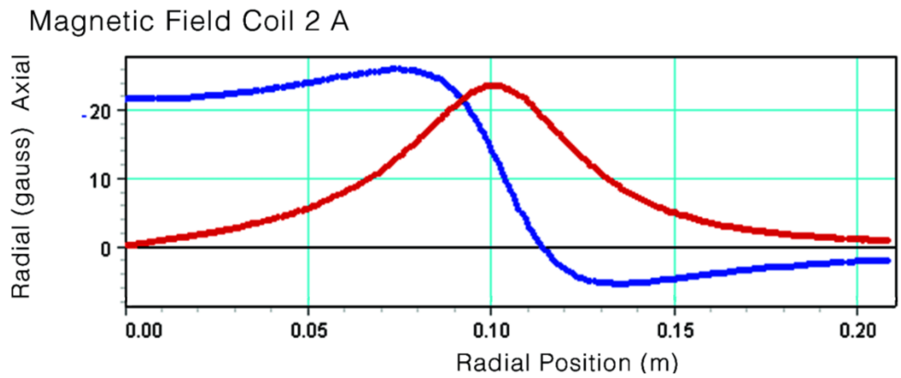

Figure 3 – Visualization of collected data Magnetic field of the coil measured by the sensor

One important aspect of this code is the repeated measurement of the magnetic field 2000 times sequentially. This process takes a time interval of 0.2 to 0.25 seconds. By tracking the sum and square of the measurements' sum, the possibilities of calculating the average values and standard deviation, represented as constant and variable components have been adjusted. By averaging the values over a large volume of measurements, it is possible to increase the accuracy according to theoretical expectations, by about √2000, which is equivalent to about 45. Thus, when using a 10-bit analog-to-digital converter, we achieve a level of accuracy comparable to that of a 15-bit ADC. This fact is of practical importance considering that one ADC step is 4 mV, which is approximately 0.3 mT. By averaging the values, the error can be reduced from 0.3 mV to 0.01 mV.

An additional advantage is that standard deviation information can be obtained, allowing changes in the magnetic field to be monitored. Given that the alternating magnetic field typically oscillates at a frequency of 50 H, going through approximately 10 cycles per measurement period, a measurement of the alternating component can be made.

After compilation, my code occupies the following memory space: 17613 bytes (61%) of program storage space is used. The maximum value is 29867 bytes. Global variables use 401 bytes (18%) of dynamic memory, leaving 1705 bytes for local variables. The maximum value is 2048 bytes.

The code provides a calibration constant corresponding to the value specified in the documentation (1.4 mV/gauss), but the allowable range of this value in the documentation is 1.0 to 1.75 mV/gauss. To ensure the accuracy of measurements, the sensor must be calibrated.

The simplest method of producing a magnetic field of a given intensity is to use a solenoid. The magnetic induction in a solenoid is determined by the formula $B = \mu_0 * n * I$, where μ_0 is the magnetic constant (or magnetic permeability of vacuum), equal to 1.2×10^{-6} Tl/m/A, n is the density of the solenoid winding, and I is the current flowing through the solenoid. This formula is a good approximation for the field at the center of the solenoid, provided the ratio of its length to diameter is greater than 10.

To make precise signal a hollow cylindrical tube have been taken with a length 9 times its diameter and wind an insulated wire around it. A plastic pipe with an output diameter of 23 mm, on which 566 turns of wire were wound, stretching for 20.2 cm, which corresponds to a winding density of n = 28 turns/cm or 2800 turns/m have been used. The length of the wire was 42 m and the resistance was 10 Ohms.

By energizing the coil and measuring the current with a multimeter, either a regulated current source or a variable resistor can be used to control the current. The magnetic field should then be measured for different values of current and the results compared.

Before calibration, a value of 6.04 mT/A was obtained, although a value of 3.50 mT/A was theoretically expected. Therefore, the calibration constant in line 17 of the code was multiplied by 0.6. Thus, sensor was successfully calibrated.

4. Conclusions

The developed sensor allows simultaneous measurement of radial and axial magnetic fields. The use of dynamic variable oversampling significantly reduces the noise level at low sampling frequency. Special software simplifies data acquisition from the sensor and their subsequent analysis.

The main feature of the code is repeated measurement of the magnetic field 2000 times in a row with subsequent calculation of the mean and standard deviation. This increases the accuracy of the measurements compared to theoretical expectations.

Calibration of the sensor is necessary to ensure measurement accuracy within the acceptable range of values. It is recommended to use a solenoid to create a magnetic field of a certain intensity. After calibrating the sensor, its accuracy is confirmed by comparing theoretical and actual values.

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