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DESIGN OF MAGNET MEASUREMENT SYSTEM BASED ON MULTI-HALL SENSOR

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Abstract

High-precision magnetic field measurement and control technique significantly guarantees the accurate realization of the magnetic confinement of accelerators. Using real-time magnetic field intensity as the feedback to adjust the magnetic field current input can be a promising strategy. However, the measurement accuracy of the Hall-sensor is hard to meet feedback requirements because of multiple affection from external factors. Meanwhile, the NMR(Nuclear Magnetic Resonance sensor), which can provide high-precision magnetic field measurement, can hardly meet the requirements against the real-time control due to its strict requirements on the uniformity of the measured magnetic field, as well as its low data acquisition speed. Therefore, a magnetic field measurement system based on multi-Hall sensors is designed to solve this problem. Four Hall-sensors are used to measure the target magnetic field in this system. An Adaptive fusion algorithm is used to fused collected values to obtain the best estimate of the magnetic field intensity. This system effectively improves the accuracy of magnetic field measurement and ensures the instantaneity of the measurement.

INTRODUCTION

Magnetic confinement plays a decisive role when stabilizing the accelerator beam. At present, the control of magnetic confinement is mostly based on the feedback of the power supply current to implement of the current input of magnet [1], which indirectly ensures the stability of the magnetic field. However, this method is difficult to ensures the effect of the control of the magnetic field, due to magnet's own factors such as magnet eddy current and iron core aging. Therefore, directly using magnetic field strength, as a feedback signal becomes a more promising solution. Nevertheless, it is limited by the sampling rate and accuracy of magnetic field measurement, which makes the progress of this solution relatively slow.

Present main methods of magnetic field measurement and their accuracy are shown in Fig. 1 [2]. The feedback signal of magnetic field control requires high precision and wide range of measurement. So, NMR, hall, and fluxmeter meets the requirement. However, the NMR sampling frequency is than expected, and it needs a certain period of time to lock the value of non-uniform magnetic field. For instance, the sampling frequency of Metrolab PT2026 is only 33 Hz, and the search time is approx [3]. Thus, NMR is difficult to meet the magnetic field control requirements. Fluxmeter is commonly used for dynamic measurement. But its size is large, which makes it difficult to be broadly deployed on site. Hall sensor advantages of high sampling rate, excellent dynamic characteristics, small volume and easy deployment. So, it is the most suitable magnetic field measurement scheme for feedback control.

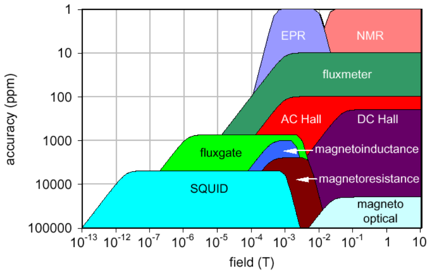

Figure 1: Magnetic field measurement range and accuracy.

SYSTEM DESIGN

Signal Preprocessing

The main noise of the measurement system includes the offset voltage and thermal error of Hall element [4], as well as the gain error, offset voltage and accidental high-frequency noise of the measurement module [5]. To eliminate these noises, the single-channel measurement signal is preprocessed. The high-frequency noise and offset voltage are mainly filtered by pre-filter and differential algorithm within the measurement module. The pre-filter distinguishes signals according to the frequency of the signal and blocks the high-frequency noise. On this basis, differential operation is performed on the input signal. The offset voltage of each ADC in the measurement module is approximately same. Equations (1) and (2) represents signal V_m.

$$V_{m^+} = V_{id} + V_{of} \tag{1}$$

$$V_{m^-} = -V_{id} + V_{of} \tag{2}$$

Where V_{of} is the offset voltage, V_{id} is the ideal signal. V_{m^+} and V_{m^-} represents a pair of measurements with opposite phases.

As shown in Eq. (3), an ideal input signal without offset voltage can be obtained by subtracting the input with opposite phase.

$$V_{m^+} - V_{m^-} = 2V_{id} \tag{3}$$

For Hall thermal error and measurement module gain error, the corresponding calibration parameters need to be obtained and compensated by software. Calibrating gain

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error of measurement module with high precision calibration source. By comparing the calibration source with the measured voltage, the compensation coefficient α can be obtained. For the compensation of the Hall thermal error, it needs to be divided into two situations to calibrate the correction coefficient of Hall which are constant temperature with plus different magnetic field and constant field with plus different temperature. The correction value corresponding to different gradient magnetic fields at 25 °C is shown in Fig. 2.

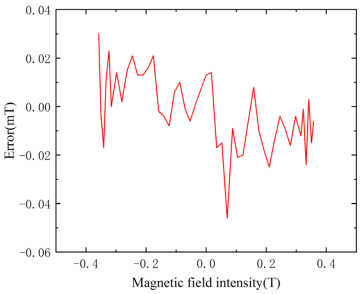

Figure 2: the correction value corresponding to different gradient magnetic fields at 25 °C.

Adaptive Weighted Fusion Algorithm

The offset voltage of Hall element is a kind of random noise which is it difficult to remove through common frequency-domain filter. Therefore, the offset voltage needs to be filtered by time-domain method. For a single sensor, the variance of the sensor cannot be changed, and the posterior error can be only reduced by increasing the measurement data. But this method increases the amount of computation and reduces the convergence rate. The method of multi-sensor adaptive fusion will not only improve the accuracy of measurement value, but also reduce the amount of measurement and accelerate the convergence rate.

For the adaptive weighted fusion algorithm, the fused value and adaptive weighting factor shall meet Eq. (4).

$$X = \sum_{n=1}^{4} W_n X_n, \sum_{n=1}^{4} W_n = 1 \tag{4}$$

Where X, X_n and W_n are respectively fused value, measured value of hall sensors and adaptive weighting factor.

The measured value of any sensor has the structure shown in Eq. (5).

$$X_n = ide_n + nis_n \tag{5}$$

Where the ide_n is measured value without noise. nis_n is offset noise, its variance is σ_n^2.

Then the weighting factor should satisfy Eq. (6). After weighting, the observation noise should be 0 or *constant*. So that the signal exclude noise can be obtained directly through linear correction. .

$$\sum_{n=1}^{4} W_n nis_n = 0 \; or \; constant \tag{6}$$

From the analysis above, the optimal weighting factor is determined by the variance of each sensor. However, the variance of sensors is often uncertain and will be affected by many factors. Therefore, directly calculating the sensor variance through the measured value and adaptively changing the weighting factor can reduce the noise to the greatest extent. When there are multiple sensors, the measured data can be used to obtain [6]. Take Hall sensors 1 and 2 as an example, where k is the sampling period, and the solution formula is represented as Eq. (7).

$$\sigma_1^2 = R_{1,1} - R_{1,2} \tag{7}$$

The $R_{1,1}$, $R_{1,2}$ solution algorithm is shown in Eqs. (8) and (9).

$$R_{1,1}(k) = \frac{k-1}{k} R_{1,1}(k-1) + \frac{1}{k} X_1(k) X_1(k) \tag{8}$$

$$R_{1,2}(k) = \frac{k-1}{k} R_{1,2}(k-1) + \frac{1}{k} X_1(k) X_2(k) \tag{9}$$

And through δ^2 can be solved the optimal weighting factor, where p is one of the four sensors, and its algorithm is shown in Eq. (10).

$$W_p = 1/(\delta_p^2 \sum_{n=1}^{4} \frac{1}{\delta_n^2}) \tag{10}$$

Thus, an adaptive fusion filter for four-way hall sensors is implemented. After the filtered signal is calibrated by NMR, the magnetic field intensity with few noise can be obtained.

Testing Platform Construction

The overall structure of the system is shown in Fig. 3. A standard dipole magnet is used as the detection object and NMR is used as the measurement datum. At the center of the pole of the bipolar magnet, four Hall sensors are deployed on both sides of the NMR probe. NI CompactRIO (CRIO) is used for data acquisition and processing of four-way Hall sensors. The host is responsible for collecting NMR and processed Hall data. And it also has the function of adjusting the power supply output to control the magnetic field.

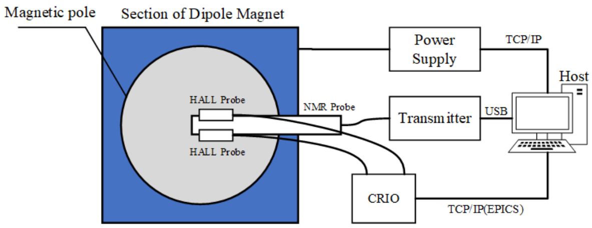

Figure 3: Overall structure of multi-hall magnetic field measurement experimental platform.

The host connects with CRIO and power supply through TCP/IP and carries out commands such as data reading and

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current output. The CRIO runs the EPICS program to publishes PVs. PVs includes four HALL readings and the magnetic field values after algorithm processing. Magnetic field measurements of NMR are directly transferred to the host through USB.

SIMULATION TESTING

Four independent groups of zero mean noise were used to simulate the observation error of hall sensor. The variance of white noise in each group were 0.001, 0.002, 0.0025, 0.0015, and the true value was 0.35 T. True value and white noise were added together to simulate four groups of sensor measurement data.

Figure 4 shows measured value of hall sensor with minimum variance and adaptive fused value. The measurement value of a single Hall sensor fluctuates around 0.35 T. The estimated value of adaptive fusion will have a short-term drift at the beginning due to insufficient data. As the number of data increases, the magnetic field data will become stable and converge to the true value.

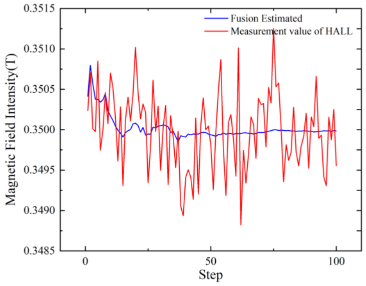

Figure 4: Comparison of minimum variance Hall magnetic field data with the estimated value after adaptive fusion.

The result of comparing errors between measured value of Hall sensor and fused value shows that the adaptive fusion algorithm can greatly reduce the measurement errors. As shown in Fig. 5, after using the adaptive filtering algorithm, the error quickly converges to the minimum with the step size. After 20 steps of data fusion, the error converges to 0. Accurate measurement of magnetic field is achieved.

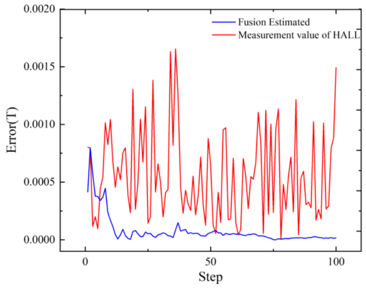

Figure 5: The estimation error of adaptive fusion and the error of Hall measurement with minimum variance.

In Fig. 6, the mean filter was a method that directly averaging the measurements of the four sensors. The effect of mean filter is obviously worse than that of the adaptive fusion algorithm because it simply sets the weighting factor of all Hall sensor measurements to 0.25.

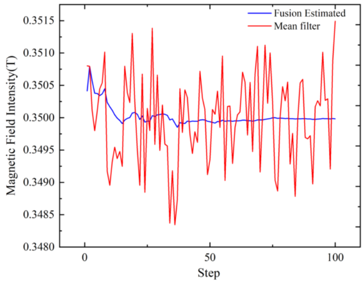

Figure 6: Comparison of adaptive fusion filter and mean filter.

CONCLUSION

In this paper, a measurement system is designed with multiple Hall sensor. A filtering scheme is designed for the noise of hall and measurement module. It includes pre-processing the HALL measurement value, which are weakening the high-frequency noise and offset voltage through filter and differential algorithm. The correction of thermal error of hall sensor and gain error of measurement module is also implemented. Eventually, the offset voltage of Hall sensor is eliminated by the adaptive fusion algorithm of multi-hall sensor. The final simulation results show that the measurement error of the magnet measurement system can be significantly reduced by using the adaptive fusion algorithm of multi-hall sensors.

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