STUDY ON MEASURING DEVICE OF AC AND DC WEAK MAGNETIC FLUX DENSITY

Chun-sheng YANG[1], Hong-tao NIU[1,*], Lin-tao YANG[1], Jin XU[1], Jie SU[1], Peng XIAO[1]

Weak magnetic field measurement has important application in navigation system, attitude detection, medical equipment and many other industrial fields. Although there are many applications of magnetic field detection, more research on weak magnetic field detection device is required. Magnetic flux density (MFD) is closely related to the magnetic field intensity. Research on the measurement of frequency and amplitude characteristics of AC weak MFD is still less. Furthermore, there are also many application requirements of the weak MFD measuring devices with good portability. In order to realize the measurement device of AC and DC weak MFD, a measuring device for AC and DC weak MFD signals based on magnetoresistive sensors is developed. The design principle of software and hardware for the measuring device is introduced in this paper. A microprocessor STM32F407 with ARM 32-bit Cortex™-M4 CPU is applied for data processing and preservation of the sampling signals from the sensor in the system which showed good capability of floating-point operation. Fourier transform is applied to analyze the frequency spectrum of the MFD signal for frequency calculation. The least square method is applied to fit the experimental data, and the conversion formulas of MFD with good linearity are obtained. Design of the measuring device is proved to be accurate and stable by the calibration experiments of AC and DC MFD. The measurement range of the designed device is from 0 μT to 600μT. The proposed technique can be used to effectively monitor the ambient MFD and it also has a good application prospect in vibration or rotation speed measurement.

Keywords: AC/DC weak magnetic flux density (MFD), Magnetoresistive sensors, Fourier transform, Least square method, Measuring device

1. Introduction

Magnetic field measurement is closely related to our life and is widely used in navigation system, attitude detection, medical equipment and other industrial fields [1]. In medical field, an alignment method for the magnetic field measurement system of heavy ion medical machine was proposed to improve both the accuracy and efficiency of the magnetic field measurement system [2]. In robotic field, electronic compass was applied to measure the earth's magnetic field and estimate a robot absolute heading with respect to the magnetic north in

[1] National Institute of Measurement & Testing Technology, Cheng du 610021, China
*Corresponding author: 13126925@qq.com

an indoor environment [3]. Development of micro-fluxgate sensors with electroplated magnetic cores for electronic compass was also proposed to measure the magnitude of weak magnetic field [4]. Furthermore, static weak magnetic field measurement was studied based on low-field nuclear magnetic resonance [5]. Although there are many applications of magnetic field detection, more research on weak magnetic field detection device is required. MFD is closely related to the magnetic field intensity. Research on the measurement of frequency and amplitude characteristics of AC weak MFD is still less.

In this work, research on the magnetoresistive sensor to measure the values of AC and DC MFD is carried out. Magnetoresistive sensors can be effectively applied to measure the MFD signal, not only DC signal, but also AC signal. Magnetoresistive sensors have the advantages of accurate measurement and stable performance in weak magnetic field measurement. They can be applied to the measurement and orientation of weak magnetic field [6-7]. In order to realize a portable weak MFD measuring device with the functions of AC and DC measurement simultaneously and a low cost, measurement of AC/DC weak MFD signal by magnetoresistive sensor is proposed and a measuring device is designed in this paper. The weak MFD signal is processed by Fourier transform and least square fitting. The device is calibrated in the AC and DC MFD measurement respectively. The experimental results shows that the designed device has good linearity in the AC and DC MFD measurement, and can accurately and effectively detect the strength and frequency of AC and DC weak MFD. It can be used for the calibration of AC/DC magnetic field transmitter, and also for the detection of magnetic field distribution in the environment such as inside the electric vehicles and near the high-voltage substations. It also has a good application prospect in vibration or rotation speed measurement.

2. Hardware Design

2.1 Overall System Design

The overall block diagram of system hardware is shown in Figure 1, including power module, magnetoresistive sensor HMC1052, set/reset circuit, operational amplifier circuit, AD7606 multi-channel synchronous acquisition module, microcontroller STM32F407 and LCD, etc.

In addition to providing 12V power for operational amplifier circuit, the power supply module provides 3.3V for STM32F407 and 5V for other circuit modules. MCU outputs PWM to the set/reset circuit [8], and set/reset magnetoresistive sensor ensures the sensitivity will not be affected by external strong magnetic field [9]. Magnetoresistive sensor converts the MFD incident along the sensitive axis into differential voltage output. Differential voltage signal is amplified by differential AD620 and converted into a single-terminal voltage signal which relatives to the ground, before it's sent to the AD7606 multi-channel synchronous acquisition module for analog-to-digital conversion. Converted digital quantity is processed by STM32F407 and then output to the LCD monitor.

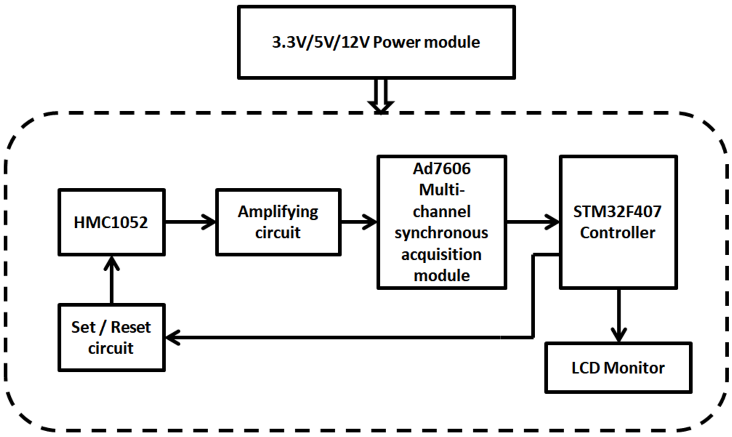


Fig. 1. Block diagram of system hardware.

2.2 Magnetoresistive Sensor

The internal part of the magnetoresistive sensor contains Wheatstone bridge made by four reluctance thin film alloys (equivalent to resistors). If there is no external magnetic field, the resistance values of the four bridge arms are equal and the output voltage of the bridge is close to zero. On the contrary, due to the anisotropic magnetoresistive effect, the resistance values of the arms will change, which results in the differential voltage output [10]. Figure 2 shows the schematic diagram of the magnetoresistive sensor. According to its principle, the corresponding output voltage is given by

$$U_0 = U\left(\frac{R_4 + \Delta R_4}{R_2 - \Delta R_2 + R_4 + \Delta R_4} - \frac{R_3 - \Delta R_3}{R_1 + \Delta R_1 + R_3 - \Delta R_3}\right) \quad (1)$$

In an ideal case, let $R_1 = R_2 = R_3 = R_4 = R$ and $\Delta R_1 = \Delta R_2 = \Delta R_3 = \Delta R_4 = \Delta R$, according to formula (1), it gives

$$U_0 = U\left(\frac{\Delta R}{R}\right) \quad (2)$$

where U is the power supply voltage of the bridge, the output voltage signal U_0 has a linear relationship with the change of resistance ΔR, which is induced by the external magnetic field. When the intensity of external magnetic field is greater, the output voltage is higher, and the symbol of ΔR reflects the applied direction of external magnetic field.

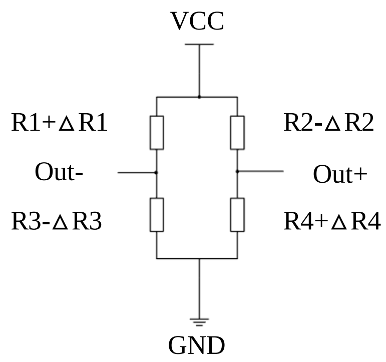


Fig. 2. Schematic diagram of a magnetoresistive sensor.

Honeywell magnetoresistive sensor HMC1052 is selected in this paper. HMCI052 is a biaxial linear magnetoresistive sensor and each sensing axis has a Wheatstone bridge composed of a thin film reluctance alloy [11]. When a 5V voltage is applied to the sensor bridge, the sensor can convert the MFD incident in the direction of the sensitive axis into a differential voltage output [12]. It can sense the AC/DC MFD accurately and effectively, and the measured MFD range is within $\pm 6\times 10^{-4}$T.

2.3 Operational Amplifier Circuit

Figure 3 shows the operational amplifier circuit designed in this paper. The differential voltage of HMC1052 sensor bridges is filtered by RC filter circuit and then sent to the positive and negative input of AD620 amplifier circuit. After differential amplification, the output voltage of single terminal is obtained, which is convenient for data acquisition module to carry out analog-to-digital conversion. The AD620 amplifier circuit uses dual power supply, which has good linear amplification performance and adjustable magnification. It can be adjusted according to the MFD and the voltage acquisition range of AD conversion module.

2.4 AD7606 Multi-channel Synchronous Acquisition Module

AD7606 is applied since the analog-to-digital converter chip is a 16-bit and 8-Channel synchronous sampling analog data acquisition chip. The chip has advantages of built-in analog input clamp protection, second-order anti-aliasing filter, tracking and holding amplifier, 16-bit charge redistribution successive approximation analog-to-digital converter, flexible digital filter, 2.5V reference voltage source, reference voltage buffer and high-speed serial and parallel interface [13]. The AD7606 is powered by a single 5V power supply. It can process ±10V and ±5V true bipolar input signals. At the same time, all channels can sample at a throughput rate of up to 200kS/s. Since the output signal of the sensor is amplified within ±5V by the signal conditioning and amplification circuit, the AD7606 adopts ±5V input mode for sampling in the design.

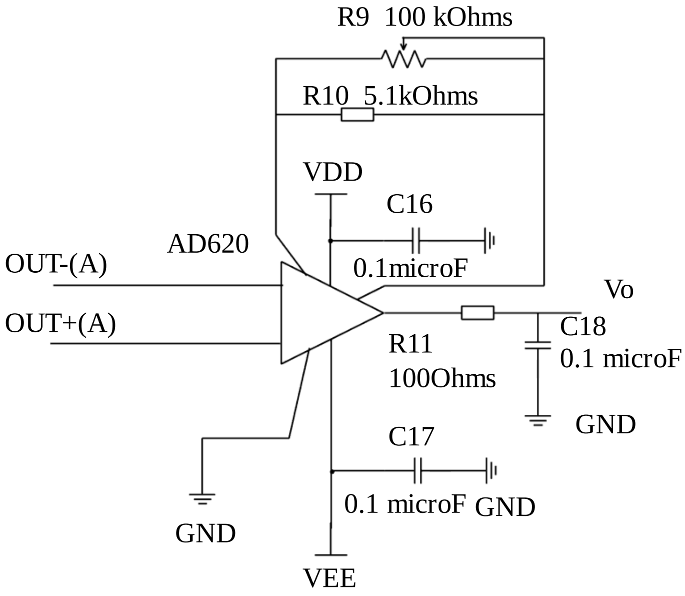


Fig. 3. Operational amplifier circuit of the AD620.

3. Software Design

The software design flow chart is shown in Figure 4. The main control processor of the detection device in the design is STM32F407 chip with ARM framework. The functions of STM32F407 chip include generating PWM input to set/reset circuit, data acquisition, Fourier transform, error compensation, calculating corresponding MFD values, display and so on. The specific functions are as follows:

(1) The PWM pulse signal generated by STM32F407 MCU is sent to the set/reset circuit, and the power supply voltage VCC provides 5V voltage. The set/reset circuit can generate about 500mA instantaneous current, which can effectively set/reset the sensor axis, and ensure that the magnetoresistive sensor always has high sensitivity.

(2) The I/O port of MCU receives the MFD signal sampled by AD7606. The signal flow is that the magnetoresistive sensor senses the measured MFD signal and outputs the weak differential voltage to AD620 instrument amplifier, after its differential amplification, signals are sent to AD7606 multi-channel synchronous acquisition module. And then MCU can read multi-channel signals simultaneously.

(3) The MCU performs Fourier transform on the digital signal collected. The MCU collects 1024 data in a measurement period, and then performs Fourier transform to obtain frequency, average value, peak-to-peak value and other data.

(4) MCU performs the data analysis. According to the frequency obtained by Fourier transform, the measured magnetic field can be judged as DC magnetic field or AC magnetic field. The DC MFD can be obtained from the average value, and the AC MFD can be obtained from the peak-to-peak value. When the AC and DC magnetic fields exist at the same time, the average value of the measured voltage waveform corresponds to the DC MFD, while the peak-to-peak value corresponds to the AC MFD.

(5) MCU sends the values of AC/DC MFD to the LCD monitor. Before sending to the LCD, it shall judge whether the measured MFD exceeds the range firstly. If it exceeds the range, MCU will carry out the error display and be reset [14].

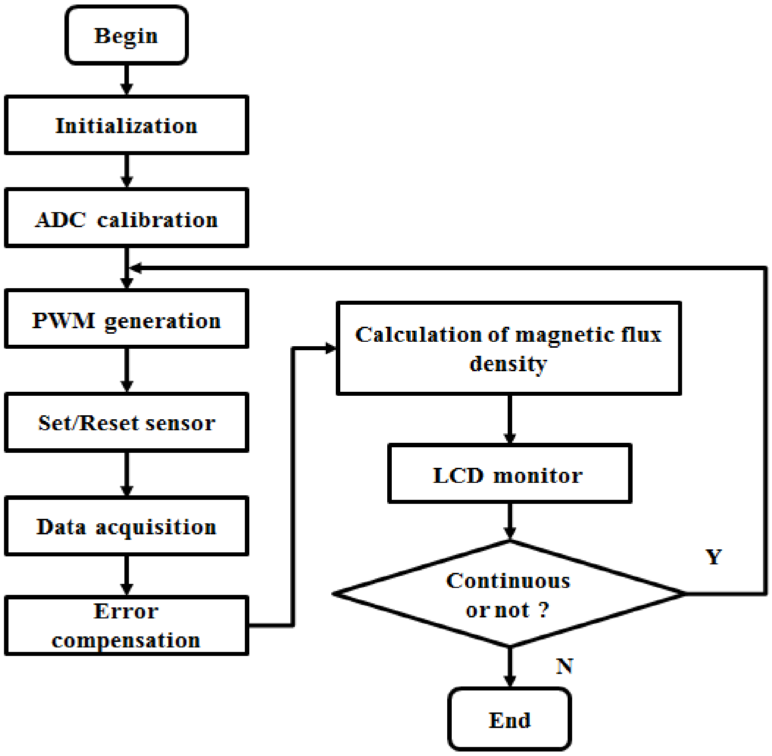


Fig.4. Flow chart of software design.

4. Frequency Spectrum Analysis of MFD Signals

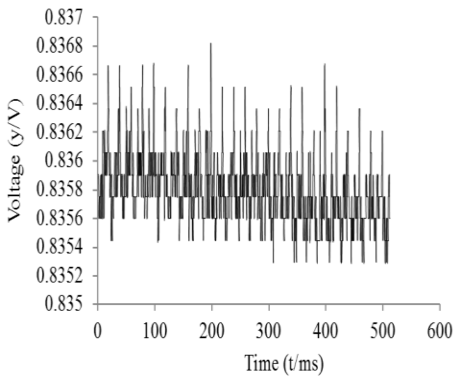
The expression form of the signal in the frequency domain is the Fourier transform. The frequency spectrum reflects the frequency composition of the input signal. Fourier transform is an important means of analyzing and processing signals [15]. In this paper, the MFD signals are sampled at a fixed time interval, the sampled data are processed by discrete Fourier transform, and the fast Fourier transform is applied in the MCU programming to improve the calculation speed.

Let $\{y(0), y(1), y(2), ..., y(N-1)\}$ be N sampling points of the MFD signal $y(t)$, and its discrete Fourier transform is defined as

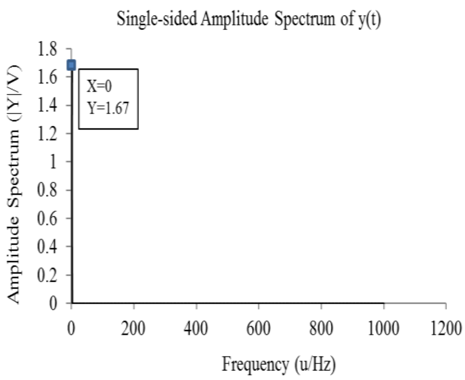
$$Y[y(t)] = Y(u) = \sum_{t=0}^{N-1} y(t) e^{-j2\pi ut/N} \tag{3}$$

where j is the imaginary unit, t is the time-domain variable, u is the frequency- domain variable, t and u =0, 1, 2, …, $N-1$, and N =1000. Since the sampling frequency is 2 kHz, the time-domain sampling interval is 0.5ms.

The frequency and amplitude of AC MFD can be obtained by Fourier transform. In this paper, discrete Fourier transform is used to calculate the frequency value of AC/DC MFD signals, peak-to-peak value of AC MFD signals is calculated by the point-by-point comparison method, and the value of DC MFD is calculated by the multi-point average method. Fourier transform is used to process the collected voltage data, and the frequency information of the measurand can be obtained accurately and quickly. In order to reduce the interference, this paper chooses 1000 data of the 1024 data obtained from a single sampling to calculate the frequency of the signal by Fourier transform. Figure 5 and Figure 6 show the frequency spectrum analysis of the DC and AC MFD signal by using the Fourier transform, respectively. Fig. 5 (a) and Fig. 6 (a) show the waveform diagram of the collected 1024 data, while Fig. 5 (b) and Fig. 6 (b) show the frequency spectrum analysis of the collected data. In the experiment, the DC magnetic field generator adopts adjustable DC current, and the AC magnetic field generator adopts adjustable power frequency current. As shown in Figure 5, the frequency spectrum of DC MFD signal is analyzed by Fourier transform, and its frequency characteristic value is concentrated at 0Hz. From the spectrum analysis in Figure 6, it can be seen that the frequency of the measured power frequency AC MFD signal is concentrated at 48.89 Hz, which is close to 50 Hz.

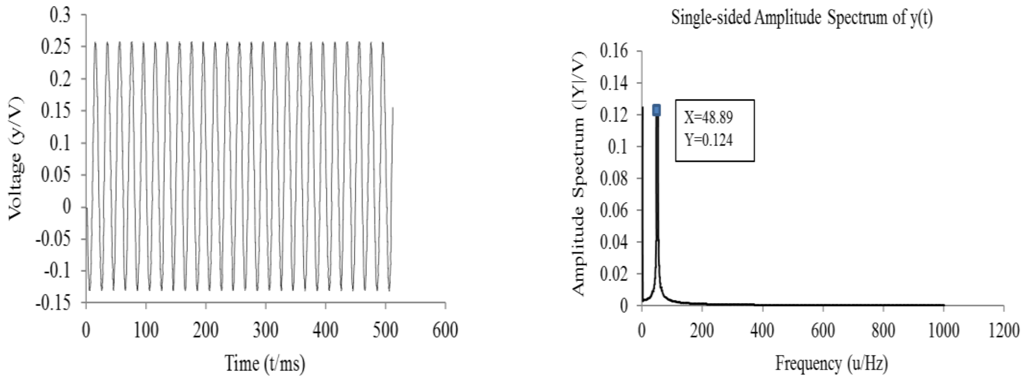


(a)



(b)

Fig. 5. (a) DC MFD signal collected by the magnetic field sensor, and (b) Single-sided amplitude spectrum |Y(u)| of the DC MFD signal y(t) based on Fourier transform.



(a) (b)

Fig. 6. (a) AC MFD signal collected by the magnetic field sensor, and (b) Single-sided amplitude spectrum |Y(u)| of the AC MFD signal y(t) based on Fourier transform.

5. AC/DC MFD Calibration Experiment

The calibration experiment is realized by using Helmholtz coil to generate AC/DC magnetic field with adjustable AC/DC current respectively. Helmholtz coil is composed of a pair of circular coils with radius R and turns M, which are parallel to each other and coaxial in series in the same direction. The distance between the coils is R. HMC1052 is a biaxial magnetoresistive sensor, and only the sensitive axis A is used in the field calibration experiment, the output voltage of the sensitive axis B in its orthogonal direction is almost zero. In the DC MFD measurement experiment, the value of the DC MFD corresponds to the average value of the output voltage signal of the detection device. In the AC MFD measurement experiment, the value of AC MFD corresponds to the peak value of the output voltage signal of the detection device. The least square method is used to fit the measured data, that is, the sum of squares of the difference $\sum(k_i - k_i^{'})^2$ between the measured value k_i and the estimated value $k_i^{'}$ should be minimized. Let y represents the output voltage by the MFD measuring device, and k represents the MFD under test. Assuming that $k = b_0 + by$, the least square method is applied to solve the regression coefficient b_0 and b, the solution formulas are given by:

$$b = \frac{N\sum_{t=1}^{N} k_t y_t - (\sum_{t=1}^{N} k_t)(\sum_{t=1}^{N} y_t)}{N\sum_{t=1}^{N} y_t^2 - (\sum_{t=1}^{N} y_t)^2} \quad (4)$$

$$b_0 = \bar{k} - b\bar{y} \quad (5)$$

where N is the total number of data groups, t is the serial number of data groups, $\bar{y}$ and $\bar{k}$ are the average values of y and k respectively.

The experimental results of DC MFD are shown in Figure 7. The least square method is used for linear fitting of the observation data, the formula for fitting the multi-point mean value y of the output voltage signal of the MFD measuring device and the value k of DC MFD is as follows: $k = 391.03y - 15.32$. The correlation coefficient of goodness of fit R^2 = 0.9966 indicates that the regression line fits well with the observed data.

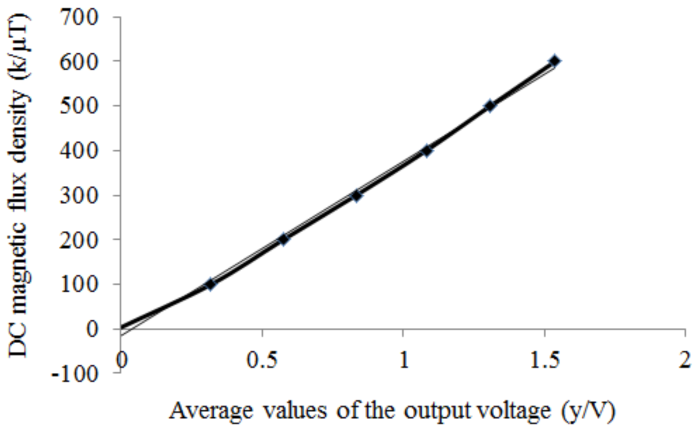


Fig. 7. Diagram of DC MFD versus the average of output voltage signals, where the thick line represents measured values of DC MFD and the thin solid line represents the least square fitting values.

The experimental results of AC MFD are shown in Figure 8.

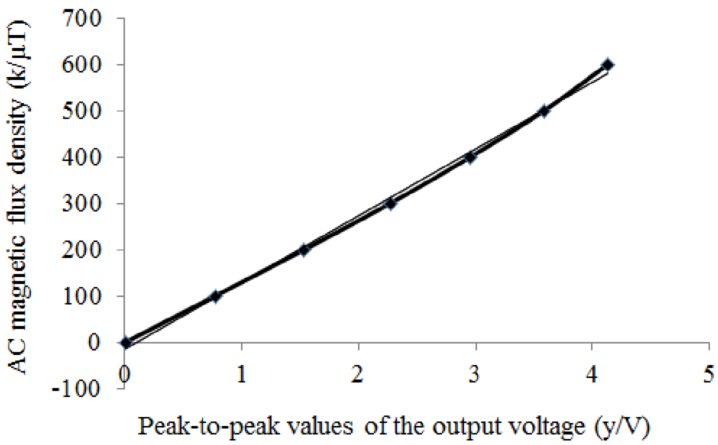


Fig. 8. Diagram of AC MFD versus the Vpp of output voltage signals, where the thick line represents measured values of AC MFD and the thin solid line represents the least square fitting values.

The least square method is also used for linear fitting of observation data, and the fitting formula of peak-to-peak value y of output voltage signal of MFD measurement device and value k of AC MFD can be obtained as follows: $k = 143.61y - 13.07$. The correlation coefficient of goodness of fit R^2 = 0.9968 indicates that the regression line fits well with the observed data.

A diagram of the circuit board of the measuring device of AC and DC weak MFD is shown in Figure 9. As can be seen, a magnetoresistive sensor is mounted on a circuit board of 40mm×22mm. The upper frequency limit of the device for weak MFD measurement is basically limited by the sampling rate and it is set to 20 kHz. The sensitivity of the device is related to the magnetoresistive sensor and it is set to 1 μT. The measurement error of the proposed device is less than 5% which can be improved by further research. The proposed device is able to measure the weak MFD in both x and y directions depending on its applications. In this paper, the method for weak MFD measurement is shown only in the x direction. Since the DC magnetic field of Earth always exists and it will be superimposed to the DC component of the measurand, it has to be mentioned that in the practical application, the MFD introduced by the DC magnetic field of Earth is firstly recorded in the device and it could be suppressed by subtraction of the recorded data after the measurement. Although there are many measuring systems of the weak magnetic field in the market, the proposed device and the methods of weak MFD measurement are able to provide a portable weak MFD measuring technique with the functions of AC and DC weak MFD measurement simultaneously and a low cost. The proposed technique also has potential reference for the application in other industry field.

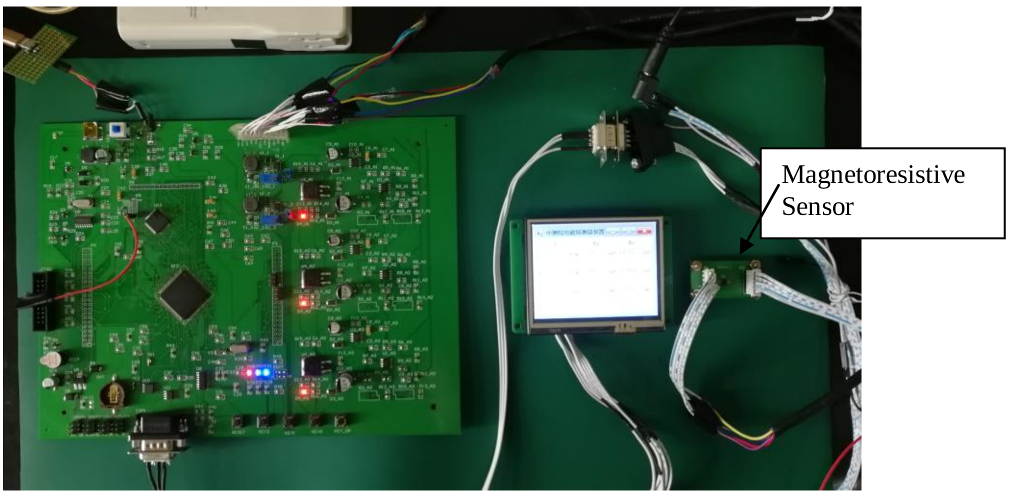


Fig. 9. Diagram of the circuit board of the measuring device of AC and DC weak MFD.

6. Conclusions

A device is designed to measure the AC/DC weak MFD signal in this paper. It applied magnetoresistive sensors to detect the change of AC/DC MFD, and Fourier transform to process the collected data. The feasibility of the design scheme is verified by AC/DC MFD calibration experiment. The AC/DC weak MFD detecting device designed in this paper can detect the AC/DC weak MFD accurately and quickly, which is convenient and reliable.

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