The Design and Implementation of Magnetic Field Positioning and Detecting System

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Magnetic sensor has a great advantage when it is used in high dusty environment for measuring and positioning. This paper introduces a digital magnetic field positioning detection system, which adopts the magnetic signal detecting technology and embedded technology. This system can judge the location of the locomotive and send out the controlling signal properly according to the displacement of the device in the magnetic field. We set up the model for the spatial characteristic of the cylindrical permanent magnet first, and then finish the theoretical analysis and emulation. According to the emulating results, we design the concrete detecting method and the electric circuit of Hall sensor. It also adopts high-performance MCU to do the real-time computation, the results of which are passed on to top controller through serial communication bus or current loop .Because the detected side is passive, so it can be placed outside in the hostile environment and it is hard to be influenced by the weather conditions and the variation of light and temperature. This system can be widely used in the complicated environment with high temperature and high dust such as coking plant and mines and it is of great importance for realizing industrial automation.

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NOMENCLATURE

a = radius of cylinder
h = height of cylinder
$R_{1,2}$, r = distance between 2 points
θ = angle between 2 lines

1. Introduction

Reliable mechanical automatic control have not been realized in many special fields in the process of modern industrial control, such as the coking plant with complicated environment, and manual and semi-automatic system are put to use in the field of distribution services or coal delivery with locomotives to many fire doors in the factory. Therefore, the design of digital magnetic field positioning and detecting system in this paper is of great importance to applying the magnetic signal detection technology in many fields, such as locating and displacement measurement of sensor technical application.

Magnetoresistance sensors of Honeywell company are widely applied in the fields of traffic flow detection, distance detection, drilling underground, navigation system, and mining. This small volume magnetoresistance sensor possesses high resolution and accuracy in the magnetic domain of -0.2mT~+0.2mT, and it can distinguish 4nT magnetic signal, but the output signal is extremely weak. There is much dust in the factory and the temperature in site is very high, what's more, the impulse interference which is produced when starting and stopping by locomotives and the signal which is interfered by power frequency have a great influence on magnetoresistance sensors. Geomagnetic field will also exert a profound influence on its output production. So Honeywell company hall sensor is adopted to detect the magnetic signals.

Hall sensor, whose sensitivity is lower than that of magnetoresistance sensors, is also is a high sensitivity sensor, and it is hard to be disturbed. This paper firstly sets up the model for the spatial characteristic of the cylindrical permanent magnet, and then finishes the theoretical analysis and emulation. According to the emulating results, we design the concrete detecting method and the electric circuit of Hall sensor.

2. The analysis of spatial characteristic of the cylindrical permanent magnet [1]~[3]

Figure 1 is motion paths model of Honeywell sensor's relative motion of cylindrical permanent magnet. As chart one shows, the dashed line represents the motion paths, the location of permanent magnet is settled, the distance between permanent magnet center and dashed line is d meter, cylindrical permanent magnet with the radius(a) and length(h) magnetizes along the axis uniformly, and the intensity of magnetization is $\boldsymbol{M} = M_0\boldsymbol{e_z}$. The following part will analysis the spatial characteristic of the cylindrical permanent magnet.

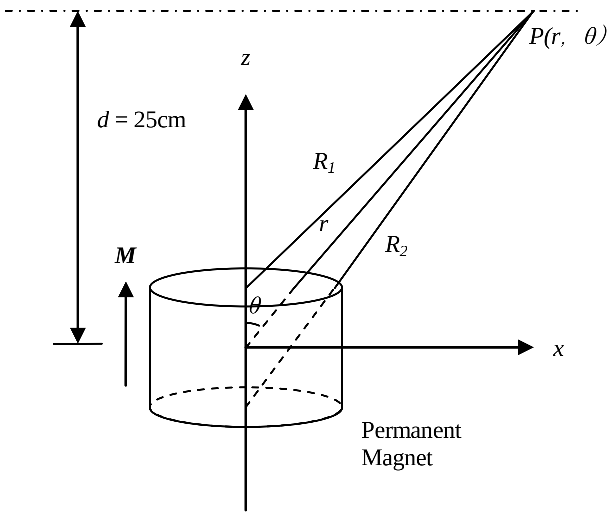

Fig. 1 Magnetic field model of cylindrical permanent magnet

When it comes to the magnetic field produced by permanent magnet, there are two methods: one is to solve with the method of Equivalent Magnetic Charge(EMC), first, scalar magnetic potential φ_{m} is got according to Equivalent Magnetic Charge(EMC), and then $\boldsymbol{B}$ is got according to $\boldsymbol{B}=-\mu_0\nabla\varphi_{\mathrm{m}}$; and the other one is to solve with the method of magnetizing current, vector magnetic potential $\boldsymbol{A}$ is got according to magnetizing current, and then $\boldsymbol{B}$ is got according to $\boldsymbol{B}=\nabla\times\boldsymbol{A}$. Because φ_m is a scalar and $\boldsymbol{A}$ is a vector, so the method of equivalent magnetic charge is much easier and this paper adopts this method to demonstrate.

In the spherical coordinate system, because $\boldsymbol{M}$ is a constant vector, and bound magnetic charge is $\rho_{\mathrm{m}}=-\nabla\cdot\boldsymbol{M}$. There exists surface magnetic charge on the top and bottom side surfaces of permanent magnet: $\sigma_{\mathrm{mUP}}=\boldsymbol{M}\cdot\boldsymbol{e_z}=M_0$, $\sigma_{\mathrm{mDW}}=-\boldsymbol{M}\cdot\boldsymbol{e_z}=-M_0$, but on the facade, there exists $\sigma_{\mathrm{m}}=\boldsymbol{M}\cdot\boldsymbol{e}_{\perp z}=0$. When far zone magnetic field is needed, because of r>>h, it can be considered that equivalent magnetic charge is centralized on the center of the top and bottom side surfaces, the whole magnetic charge are $Q_{\mathrm{mUP}}=\pi a^2\sigma_{\mathrm{mUP}}=\pi a^2 M_0$, $Q_{\mathrm{mDW}}=\pi a^2\sigma_{\mathrm{mDW}}=-\pi a^2 M_0$.

Scalar magnetic potential produced by magnetic charge Q_{mUP} and Q_{mDW} is

$$\varphi_{\mathrm{m}}=1/(4\pi)\cdot\left(Q_{\mathrm{mUP}}/R_1+Q_{\mathrm{mDW}}/R_2\right) \tag{1}$$

In the equation:

$$R_1=\left(r^2+(h/2)^2-r\cdot h\cdot\cos\theta\right)^{1/2}$$
$$R_2=\left(r^2+(h/2)^2+r\cdot h\cdot\cos\theta\right)^{1/2}$$
$$r^2=x^2+z^2$$

For the far zone magnetic field, there exists r>>h, then

$$1/R_1=1/r+h/\left(2r^2\right)\cdot\cos\theta \tag{2}$$

$$1/R_2=1/r-h/\left(2r^2\right)\cdot\cos\theta \tag{3}$$

We turn (2) and (3) into formula (1) and got

$$\varphi_{\mathrm{m}}=\left(a^2M_0h/4r^2\right)\cos\theta \tag{4}$$

So $\boldsymbol{B}=-\mu_0\cdot\nabla\varphi_{\mathbf{m}}=-\left(\mu_0a^2M_0h\right)/4\cdot\nabla\left(\cos\theta/r^2\right)$

$$=\left(\mu_0a^2M_0h\right)/\left(4r^3\right)\cdot\left(2\cos\theta\cdot\boldsymbol{e}_x+\sin\theta\cdot\boldsymbol{e}_\theta\right) \tag{5}$$

According to coordinate transformation of spherical coordinate system and rectangular coordinate system between unit vectors:

$$\boldsymbol{e_r}=\boldsymbol{e}_x\sin\theta\cos\varphi+\boldsymbol{e}_y\sin\theta\sin\varphi+\boldsymbol{e}_z\cos\theta \tag{6}$$

$$\boldsymbol{e_\theta}=\boldsymbol{e}_x\cos\theta\cos\varphi+\boldsymbol{e}_y\cos\theta\sin\varphi-\boldsymbol{e}_z\sin\theta \tag{7}$$

Because flat surface of hall sensor and XOZ flat surface are vertical and the sensor stands upright along the direction parallel to X axis, so it comes that $\varphi=0$, $\sin\varphi=0$

And
$$\boldsymbol{e_r}=\boldsymbol{e}_x\sin\theta+\boldsymbol{e}_z\cos\theta \tag{8}$$

$$\boldsymbol{e_\theta}=\boldsymbol{e}_x\cos\theta-\boldsymbol{e}_z\sin\theta \tag{9}$$

We turn (8) and (9) into (5) and got

$$\boldsymbol{B}=\mu_0a^2M_0h/\left(4r^3\right)\cdot\left(\left(2\cos^2\theta-\sin^2\theta\right)\cdot\boldsymbol{e}_z+3\sin\theta\cdot\cos\theta\cdot\boldsymbol{e}_x\right) \tag{10}$$

Supposing that

$$\boldsymbol{B}_z=\mu_0a^2M_0h/\left(4r^3\right)\cdot\left(2\cos^2\theta-\sin^2\theta\right)\cdot\boldsymbol{e}_z \tag{11}$$

$$\boldsymbol{B}_x=\mu_0a^2M_0h/\left(4r^3\right)\cdot3\sin\theta\cdot\cos\theta\cdot\boldsymbol{e}_x \tag{12}$$

So
$$\boldsymbol{B}=\boldsymbol{B}_z+\boldsymbol{B}_x \tag{13}$$

Because the actual effective magnetic intensity acted on hall sensor is just the component with the direction of sensor geometric plane surface normal, so the magnetic field component's direction which is vertical with the normal has no contribution to the output voltage of hall sensor.

When the geometric plane surface of hall sensor and Z axis are vertical, the actual effective magnetic intensity acted on hall sensor is the component with the direction of $\boldsymbol{e}_z$, the component with the direction of $\boldsymbol{e}_x$ has no contribution to the output of sensor, so

$$\boldsymbol{B}=\boldsymbol{B}_z=\mu_0a^2M_0h/\left(4r^3\right)\cdot\left(2\cos^2\theta-\sin^2\theta\right)\cdot\boldsymbol{e}_z \tag{14}$$

When the geometric plane surface of hall sensor and X axis are ve rtical, the actual effective magnetic intensity acted on hall sensor is th e component with the direction of $\boldsymbol{e}_x$, the component with the dire ction of $\boldsymbol{e}_z$ has no contribution to the output of sensor, so

$$\boldsymbol{B}=\boldsymbol{B}_x=\mu_0a^2M_0h/\left(4r^3\right)\cdot3\sin\theta\cdot\cos\theta\cdot\boldsymbol{e}_x \tag{15}$$

3. System Scheme Design

Though Hall sensor has high sensitivity, output amplitude is still weak when magnetic signal is detected beyond 25cm from the permanent magnet. It goes against the data handling of subsequent circuit, and brings much error to the system. There are two methods to solve this problem, one method is to choose the best permanent magnet in order to strengthen the magnetic induction density of the space; the other one is that every signal is differential signal which is made up of two relative placement hall sensor output signals in order to double the amplitude of output signal. This design helps to double the sensitivity of sensor on its intrinsic basis.

According to the derivation above, magnetic signals produced in this system choose NdFeB materials to make up of permanent magnets with the shape of flat and cylinder. The magnet's radius a is 0.05m, the height is 0.05m, and the remanence indicators is 1T. According to the conversion relation of A/m and T, $1\mathrm{T}=80\times10^4$ A/m, so the magnetizing intensity of magnet steel M_0 is 8×10^5 A/m. And the vacuum magnetic permeability is $\mu_0=4\pi\times10^{-7}\,\mathrm{N/A^2}$.

According to the theoretical derivation formula (14) and (15), make use of MATLAB7.0 software to emulate the process model, and the model is the relative motion of hall sensor to the permanent magnet. The purpose is to observe the evolution of the magnitude and direction of the magnetic signal in the model and offers a favored theoretical support to the further proposal design. The result of emulation, as shown in Figure 2

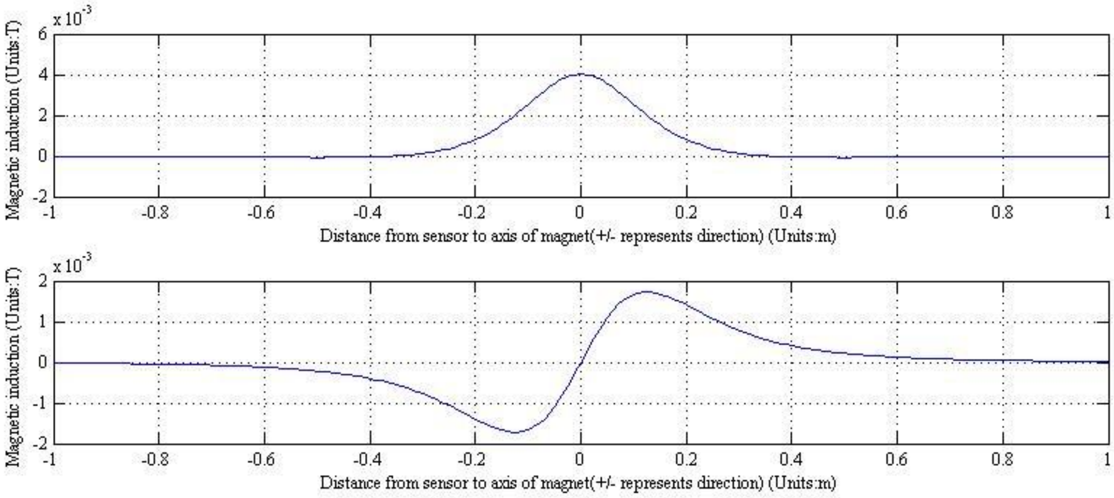

Fig. 2 Emulation diagram

According to the emulation diagram of MATLAB, the magnetic field distribution has its own feature. The first chart shows the magnetic field magnitude of permanent magnet in the direction of $\boldsymbol{e}_z$ along the track of hall sensor. The distance is much closer between the track and the permanent magnet, the magnetic signal is much stronger in the direction of $\boldsymbol{e}_z$, and the maximum is got on the central position; the second chart shows the magnetic field magnitude of permanent magnet in the direction of $\boldsymbol{e}_x$ along the track of hall sensor, and plus-minus represents the opposite direction of the magnetic field. The magnetic field intensity in the central position is zero.

Thus, if we choose a hall sensor of linear output, and put the surface normal in the direction of $\boldsymbol{e}_x$ or $\boldsymbol{e}_z$, then we can sample the output of hall sensor and deduce relative position of Honeywell sensor to the permanent magnet, and determine whether we should provide the corresponding motion control signals. If the normal of hall sensor is laid along the direction of $\boldsymbol{e}_z$, because of the linear input, so the shape of output voltage waveform is similar to the first simulation diagram of MATLAB and we can provide corresponding control signals when sampling the maximum point; if the normal of hall sensor is laid along the direction of $\boldsymbol{e}_x$, because of the linear input, so the shape of output voltage waveform is similar to the second simulation diagram of MATLAB and we can provide corresponding control signals when sampling the zero point(the point on the axis of magnet).

This system puts hall sensor in both directions mentioned above, and it makes the surface normal directions of two sensors are laid along the directions of $\boldsymbol{e}_x$ and $\boldsymbol{e}_z$ respectively, thus we can sample the two sensor output signals at the same time. When the sensor output sample which the normal direction of hall sensor is laid along $\boldsymbol{e}_x$ direction is zero point, and the other sensor output sampling value is close to the maximum, we can judge the position of the vehicle is definitely on the axis of permanent magnet, at this time, we can provide motive control signals according to the actual conditions.

4. System Hardware Structure

The design of the system must meet the requirements of complicated environments and the general characteristics, and realize a certain distance of non-contact passive locating and measurement function. We design the system into four modules: the module of magnetic field signal production and magnetic sensor detection, the module of signal conditioning and ADC, the hardware platform based on the experimental development board of MCU and the microprocessor output controlling module. Figure 3 shows the system structure.

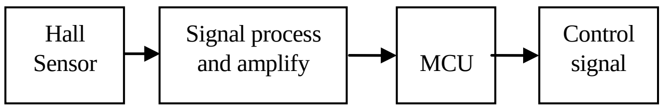

Fig. 3 System Structure

The magnetic signal detection module adopts the hall sensor of Honeywell company, the module of signal conditioning and ADC adopt filters, differential amplifiers and 12 bit digital output ADC(Analog to Digital Converter)respectively, the hardware platform of the system mainly uses STC MCU with many functions, such as display and function keys. And the control signal module is mainly made up of the current loop output circuit.

In the software design, we adopt the integrated development environment Keil using the assembly language. It realizes some functions, such as communicating with ADC, processing the sampled data and outputting the corresponding control signal.

5. Experiment and Test Data

After the system circuit design above, if we want to evaluate whether the design can achieve the desired goal, we should carry out some experiments to verify it. Figure 4 is the experimental equipment scheme to verify the design.

In this scheme, we control the toy car to drive along the rail and scale, which is vertical to the axis of permanent. And the car carries 2 pairs of sensor with each pair laying along the directions of $\boldsymbol{e}_x$ and $\boldsymbol{e}_z$ respectively. During the car movement, we take down the voltages of some key points reading from the LCD in order to observe the trend of change.

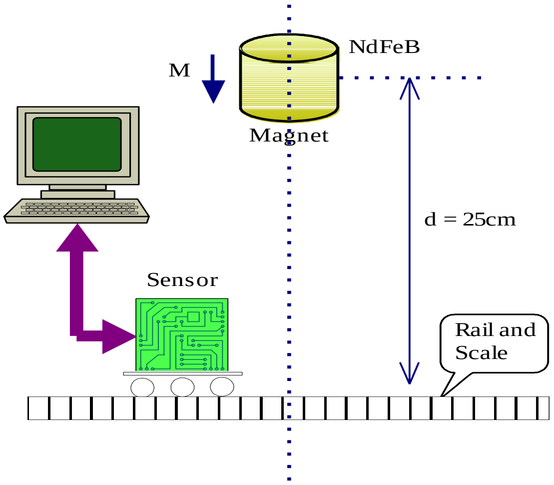

Fig. 4 Experimental Device Scheme

Table 1 shows some voltages on the system test circuit in different positions of the magnetic field.

	No magnet (V)	5cm left of magnet (V)	On the axis of magnet (V)	5cm right of magnet (V)
hall(+Z)	2.50	2.52	2.55	2.51
hall(-Z)	2.50	2.47	2.45	2.47
hall(+X)	2.51	2.53	2.51	2.48
hall(-X)	2.51	2.49	2.51	2.54
Amp(Z)	0.33	3.15	3.68	3.03
Amp(X)	0.37	3.90	0.36	0.30

Table.1 Some voltages on the system test circuit in different positions of the magnetic field

According to the test results and theoretical analyses, it is clearly to see that output voltage of each point remains some error, and there are several reasons. First, in the course of system testing, we did not do the signal processing through low pass filter to the sensor output voltage, and we did not use reference power supply chip in the actual testing, but it basically meets the needs of the results of theoretical analyses through the data in the table, therefore the magnetic field positioning and detecting system in this paper can be adopted not only theoretically but also realizably.

5. Conclusion

This paper introduces the magnetic filed positioning and detecting system in detail from the aspect of theoretical analyses to modeling, and then to system design. It also carries out the scheme verifying according to testing circuit. It can be seen clearly according to the results that this system can operate around the distance of 25cm of permanent magnet, and the communicating distance is far enough to meet the needs of expected targets. It can also be suitable in many other fields such as the detection and control in industry.

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