Design and Simulation of a magnetic balance weak current sensor based on TMR

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Abstract—In this paper, a weak current sensor based on TMR is designed. The system structure, principle and conversion process of the sensor are introduced. The voltage current conversion circuit and feedback block diagram are analyzed emphatically. Then ANSYS Maxwell is used to simulate the electromagnetic field of the iron core and the coil. The results show that when the measured conductor and the secondary coil are connected with the current which is inversely proportional to the number of turns, the magnetic field in the air gap reaches a balance, close to the zero flux state. Finally, Multisim software is used to simulate the driving circuit of the system. The simulation results show that for DC and AC signals, the secondary current can track the primary current quickly, and the accuracy can reach 0.7% when measuring 1~10mA weak current.

1. INTRODUCTION
When the current flows through the conductor, a magnetic field will be generated around the conductor, and the intensity of the magnetic field is directly proportional to the current. TMR (Tunnel magnetoresistance) sensor can transform magnetic field intensity signal into voltage signal linearly, so it can be used to develop current sensor. In recent years, with the technical specifications of magnetic sensors greatly improved, the resolution of TMR sensor can reach 0.1mOe, which can measure the weak current of mA level. In this paper, a magnetic balance weak current sensor based on TMR is designed based on the advantages of small volume and high resolution of TMR. The sensor system consists of front-end core, coil and TMR electromagnetic elements, as well as back-end feedback drive circuit. The formatter will need to create these components, incorporating the applicable criteria that follow.

2. STRUCTURE OF MAGNETIC BALANCE SENSOR SYSTEM
In the system, the signal detection and output modules are composed of the ferromagnetic ring and the magnetoresistance sensor. Then, the signal is modulated. The magnetic signal is converted into the voltage signal and sent to the DSP for processing. The voltage is output through the D/A terminal of the DSP, then converted into the current by the voltage current conversion circuit, and the current is fed back to the output module. This structure forms a closed loop feedback system. The feedback current is
proportional to the measured current flowing through the conductor. The measured current can be calculated by extracting the feedback current signal. The design system structure is shown in Fig. 1.

![Figure 1. Structure of magnetic balance current sensor](image)

3. SENSOR PRINCIPLE
In the closed loop control system, in addition to the forward channel, there is a feedback channel. The function of the feedback channel is to feedback the signal from the output to the input. The output of the system is detected directly or indirectly by the feedback channel, and transformed into the same physical quantity as the input value, and then compared with the given value, so the deviation signal is obtained. The closed loop control system uses the amplified deviation signal to control the controlled object. As long as there is a deviation between the output and the given value, there will be a control effect, trying to correct this deviation. In the design system, the magnetic balance closed loop negative feedback control system is adopted, that is, the magnetic field generated by the measured current is compensated by the magnetic field generated by the current of the secondary coil, so that the magnetoresistance sensor is always in the working state of detecting zero magnetic flux. The specific working process is: After the TMR is powered on, the magnetic induction intensity proportional to the primary side current is induced at the air gap:

$$B_1 = \alpha N_1 I_1$$  \hspace{1cm} (1)

Where $\alpha$ is the electromagnetic conversion sensitivity of the iron core; $N_1$ is the number of turns of the primary conductor passing through the iron core coil, and $I_1$ is the measured current at the primary side.

After being amplified, the voltage is input to the A/D terminal of DSP. At this time, there is a voltage signal at the A/D terminal. In DSP, through programming, the D/A terminal outputs the corresponding feedback voltage signal. After the signal passes through the voltage current conversion circuit, the secondary side feedback compensation current $I_2$ is obtained. The secondary side feedback compensation current $I_2$ is wound on the magnetic concentrating ring with wire, which will produce magnetic induction intensity at the air gap:

$$B_2 = \alpha N_2 I_2$$  \hspace{1cm} (2)

Where $N_2$ is the number of turns of the feedback coil on the secondary side, $I_2$ is the feedback current of the secondary side.

When magnetic balance is reached, in the air gap, the primary side magnetic field $B_1$ is equal to the secondary side magnetic field $B_2$, and the direction is opposite. $B_1$ and $B_2$ cancel each other, so the magnetic induction intensity is 0.

$$B_1 = B_2$$  \hspace{1cm} (3)
Therefore, the relationship between the measured current $I_1$ and the feedback compensation current $I_2$ is as follow:

$$I_1 = \left( \frac{N_2}{N_1} \right) \times I_2 \quad (5)$$

4. System Analysis

4.1 Magnetic field measurement

The TMR sensor is placed in the air gap of the magnetic focusing ring. When the current in the conductor is $I_1$, the current generated after the feedback current offsets a part of it is set as $I_d$. The magnetic induction intensity generated in the gap of the magnetic concentrating ring is:

$$B_d = \mu_0 I_d / d \quad (6)$$

Where the permeability in vacuum, $\mu_0=4\pi \times 10^{-7} \text{Tm} / \text{A}$, and $d$ is the width of the air gap.

The internal unit of TMR sensor is the Wheatstone bridge circuit unit. After the bridge voltage is input, the sensor can output the potential difference $V_m$ which is proportional to the magnetic induction intensity $B_d$. The relationship between the sensor output potential difference $V_m$ and the magnetic induction intensity $B_d$ is as follow:

$$V_m = sV_0 B_d / \mu_0 \quad (7)$$

Where $s$ is the sensitivity of TMR magnetic sensor, $s=1(\text{mV/V/Oe})$, $V_0$ is the supply voltage of TMR magnetic sensor.

4.2 Signal conditioning

The voltage $V_m$, generated by the sensor is amplified by instrument differential amplifier AD620, and its magnification can be adjusted. After the voltage generated by the TMR sensor is amplified by differential, the voltage $V_m$ sampled by the A/D terminal of the DSP is:

$$V_{in} = KV_m = KsV_0 I_d / d \quad (8)$$

According to (8), the voltage sampled by DSP is linear with the measured current. At this time, after a series of digital processing, such as digital filtering and PID control, the output voltage at the D/A terminal is basically the same as that at the A/D terminal. After the output voltage passes through the voltage current conversion circuit, the output current $I_2$ of the secondary side is obtained.

4.3 Voltage current conversion

The voltage and current conversion circuit is shown in Fig. 2. $P_1$ and $N_1$ are the positive and negative terminals of the amplifier $A_1$. $P_2$ and $N_2$ are the positive and negative terminals of the amplifier $A_2$. 

$$N_1 I_1 = N_2 I_2 \quad (4)$$
Figure 2. Voltage current conversion circuit

The figure above shows the voltage and current conversion circuit with load grounding. Due to the introduction of negative feedback, \( A_1 \) forms the in-phase summation circuit, and \( A_2 \) forms the voltage follower. In Fig. 2, \( R_1 = R_2 = R_3 = R_4 \).

\[
U_2 = U_1 \quad (9)
\]

\[
U_{p1} = \frac{V_{out} R_4 + U_{p2} R_3}{R_3 + R_4} = 0.5V_{out} + 0.5U_{p2} \quad (10)
\]

\[
U_1 = \left( 1 + \frac{R_2}{R_1} \right) U_{p1} = 2U_{p1} \quad (11)
\]

Replace (10) with (11):

\[
U_1 = U_{p2} + V_{out} \quad (12)
\]

Voltage at \( R_6 \):

\[
U_{R_6} = U_1 - U_{p2} = V_{out} \quad (13)
\]

Therefore, the secondary current:

\[
I_2 = \frac{V_{out}}{R_6} \quad (14)
\]

It can be seen from (14) that the output voltage of D/A terminal has a linear relationship with the secondary current. As mentioned above, the output voltage of the D/A terminal is the same as the sampling voltage, and \( V_0 = 5V \). Therefore, the relationship between the sampling voltage \( V_{in} \) at the A/D terminal and the secondary current \( I_2 \) is as follow:

\[
I_2 = \frac{V_{in}}{R_0} \quad (15)
\]

By substituting (8), we can get the following result:

\[
I_2 = \frac{V_{in}}{R_0} = \left( \frac{247k\Omega}{R_g} + 5 \right) \frac{I_d}{dR_0} \quad (16)
\]
4.4 Closed loop structure block diagram

The feedback current $I_f$ is obtained by winding the secondary current $I_2$ on the magnetic concentrating ring for $N_2$ turns. The relationship between feedback current $I_f$ and secondary current $I_2$ is as follows:

$$ I_f = N_2 I_2 \quad (17) $$

Through artificial setting, the direction of the magnetic field generated by the feedback current $I_f$ is opposite to the direction of the original side magnetic field, so as to cancel the original side magnetic field to achieve the magnetic balance state, and the system forms a closed loop negative feedback structure. To sum up, the overall closed-loop structure diagram of the system is shown in Fig. 3.

![Closed loop structure block diagram](image)

Figure 3. Closed loop structure block diagram

From Fig. 3, the magnetic field generated by the feedback current cancels out the original magnetic field, and finally achieves the magnetic balance. In this case, $I_f$ is equal to the measured current $I_1$ minus the feedback current $I_f$, that is:

$$ I_d = I_1 - I_f \quad (18) $$

After processing by amplifier and DSP, the output secondary current:

$$ I_2 = A I_d \quad (19) $$

According to (16), the Amplification factor $A = (247k\Omega / R_0 + 5)/d\cdot R_0$. Because the output voltage of the sensor is tens of mV, it only needs to be amplified 100 times by the amplifier. So the resistance can be set to 500 $\Omega$ and $K = (494k\Omega / R_0) + 1$. In the voltage current conversion circuit, the resistance value is 1k$\Omega$, and the air gap width $d$ of the ferromagnetic ring is a few millimeters. It is found that the amplification factor $A$ is much greater than 1.

By substituting (17) and (19) into (18), the following result can be obtained:

$$ \frac{I_2}{I_1} = \frac{A}{1 + A N_2} \quad (20) $$

Since the amplification processing factor $A$ is much greater than 1, so:

$$ I_1 = N_2 I_2 \quad (21) $$

Therefore, the secondary output current has a linear relationship with the measured current. When the measured current has a certain value $I_1$, the input sampling voltage $V_n$ measured at the A/D terminal of the DSP is processed by DSP, and the digital quantity is output at the D/A terminal. The secondary magnetic field is generated by the feedback current converted from voltage and current to counteract the primary magnetic field until the magnetic balance of the system is achieved. At the time of magnetic balance, the secondary output current is $I_2$. According to the relationship between the measured current $I_1$ and the feedback compensation current $I_f$, the value of the measured current $I_2$ can be obtained.
5. **Simulation of Electromagnetic Field**

The core is made of permalloy with high permeability, and its typical saturation value is 0.68T. The design of the coil adopts the method of uniform winding. The schematic diagram is shown in Fig. 4.

![Coil Winding Diagram Loop](image)

It can be seen from Fig. 4 that the coil is wound with 20 turns to cover the whole circumference of the iron core. According to the size of the iron core and the coil, the simulation model of the iron core and the coil is established in the ANSYS Maxwell software (see Fig. 5). After selecting the automatic sectioning unit of the model, the current density load is applied to the tested conductor and the compensation coil respectively, and the air interface meets the parallel boundary condition of the magnetic line.

![Simulation Model of Iron Core and Coil](image)

During the simulation, the air gap width is 4mm and the number of turns is 20. The current of 5mA is applied to the conductor, and the current of 0.24–0.26 mA is applied to the feedback coil at the same time. The secondary coil current with the air gap magnetic field of TMR element of 0 is found by scanning calculation. The finite element simulation results are shown in TABLE I.

| Secondary Coil Current / mA | Air Gap Magnetic Field / mGs  |
|-----------------------------|-------------------------------|
| 0.2400                      | -0.628980039169752            |
| 0.2425                      | -0.471157030018872            |
| 0.2450                      | -0.314609759064089            |
It can be seen from TABLE I that the secondary coil current of TMR element with air gap magnetic field of 0 is about 0.25mA, which is consistent with the theory. The magnetic field distribution in the iron core and air gap is shown in Fig. 6, and the magnetic field display range is $0 \sim 1.85 \times 10^{-3}$ mGs.

From Fig. 6, it can be seen that the magnetic field generated by the current offset during the magnetic balance is mainly concentrated in the air gap, while in the iron core, the magnetic field is not an ideal zero flux, which is caused by the fact that the original side cable is not an ideal infinite straight wire model and the coil has magnetic leakage. It can be seen from the simulation results that the measurement error caused by this is very small and can be ignored.

**6. SIMULATION OF SYSTEM DRIVING CIRCUIT**

Multisim has powerful circuit analysis and simulation ability, which is suitable for the design of analog/digital circuit board at board level. Therefore, Multisim is used to build the simulation model of driving circuit and analyze it. The signal conditioning module needs to respond and amplify the TMR voltage quickly, which can be realized by the instrument differential amplifier AD620. DSP processing module is used as PID regulator in the whole feedback system. It can adjust the air gap magnetic field quickly together with TMR element. So the hardware PID circuit is used to simulate the DSP processing process. The hardware circuits of signal amplification and PID are shown in Fig. 7. IO1 and IO2 are used to collect the differential signals output by TMR components, and then they are output to current voltage conversion circuit through IO3 after processing. The voltage and current conversion module is built as described in Section IV, which will not be described here.
Since there is no corresponding magnetic control component in Multisim, it is a key problem to use circuit to embody iron core coil and TMR component. The structure of iron core coil is similar to transformer, so a transformer model can be used to equivalent. In the model, parameters such as core and coil resistance can be set according to the actual situation. Considering that the voltage of TMR is driven by magnetic field and magnetic field is driven by current, and the factor of magnetic field has been included in the modeling of iron core coil, so the magnetic field can be ignored in the modeling of TMR element, and the controlled voltage source controlled by current can be used to equivalent. The simulation model of the whole system is shown in Fig. 8.

![Figure 8. System simulation model](image)

In Fig. 8, the current source $I_1$ generates the primary side current and drives the controlled voltage $V_1$ to simulate the TMR voltage generated by the current magnetic field. The transformation ratio of transformer $T$ simulates the turn number relationship of secondary coil. The reduced secondary current drives the controlled voltage source $V_2$ to simulate the TMR voltage generated by the current magnetic field of the secondary coil. They are respectively used as positive and negative output terminals of TMR components and connected with the positive and negative input ends of operational amplifier. After differential amplification and PID regulation, the current formed by voltage and current conversion is fed back to the primary side of transformer $T$. The current amplitude of secondary side can be obtained by using a meter, and the voltage signal monitored by oscilloscope can be used to observe whether the measured signal can follow the signal to be measured.

Multisim provides abundant current sources and virtual components of oscilloscope. Two current waveforms of 5mA DC and AC are selected for simulation to test the performance of the designed sensor. The simulation test waveforms are shown in Fig. 9 and Fig. 10, in which red is the primary side current and blue is the secondary side current with 10 times amplitude (one half of the primary current).

![Figure 9. DC signal](image)
According to the simulation results in Fig. 9 and Fig. 10, the designed magnetic balance weak current sensor works normally and can quickly follow the DC and AC current waveforms in amplitude, phase and frequency.

Changing the output amplitude of the current source from 1 to 10mA and every 1mA is a measuring point. The measured current value of each measuring point is shown in TABLE II.

| Primary current /mA | Secondary side current /mA | The secondary side is reduced to the primary side current /mA | Absolute error /mA | Relative error |
|---------------------|----------------------------|-------------------------------------------------------------|-------------------|---------------|
| 1                   | 0.049671                   | 0.99342                                                     | 0.00658           | 0.6580%       |
| 2                   | 0.099976                   | 1.99952                                                     | 0.00048           | 0.0240%       |
| 3                   | 0.149995                   | 2.99990                                                     | 0.00010           | 0.0033%       |
| 4                   | 0.199656                   | 3.99312                                                     | 0.00688           | 0.1720%       |
| 5                   | 0.249951                   | 4.99902                                                     | 0.00098           | 0.0196%       |
| 6                   | 0.299972                   | 5.99944                                                     | 0.00056           | 0.0093%       |
| 7                   | 0.349933                   | 6.99866                                                     | 0.00134           | 0.0191%       |
| 8                   | 0.399933                   | 7.99866                                                     | 0.00134           | 0.0167%       |
| 9                   | 0.449719                   | 8.99438                                                     | 0.00562           | 0.0624%       |
| 10                  | 0.499976                   | 9.99952                                                     | 0.00048           | 0.0048%       |

According to the simulation results in TABLE II, the current sensor designed in this paper has high accuracy in measuring weak current, and the error is only within 0.7% when measuring 1~10 mA current.

7. CONCLUSION
The magnetic balance weak current sensor based on TMR is designed in this paper. The closed loop design has strong anti-interference ability. The measured current and the secondary side current cancel each other when working. The actual magnetic flux in the core is close to 0, which is not affected by the nonlinearity of the iron core and has high precision. Due to the need for magnetic field signal to generate voltage and drive voltage current conversion circuit, there is a current deviation for excitation, which makes the secondary side current after reduction will be smaller than the measured current in theory, but this current is very small and can be ignored in general. It can also be seen from the simulation results that the sensor designed in this paper can measure both DC and AC weak signals, and the secondary side current can accurately and quickly track the measured current signal, which can reach 0.7% when measuring the weak current of mA level.
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