Design of Underground Displacement Measurement System Based on Mutual Inductance and Hall Effect

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Abstract. Deep displacement monitoring of rock and soil is important for landslide warning. By using mutual inductance effect and Hall Effect, the author designed the underground displacement sensing unit through the solenoid and permanent magnet and the Hall sensor. The author designed the Hall voltage measurement circuit and installation device, and used the mutual inductance voltage measurement circuit that the laboratory has realized, which can accurately collect the mutual inductance voltage and the Hall voltage in real time. Through the 485 communication, the collected data is transmitted to the upper computer, the mathematical model established by the curve fitting method can be used to measure the real-time displacement of the deep part of the rock and soil. The experimental result shows that the horizontal displacement measurement range is 0-40mm, and the measurement accuracy can reach 1.5mm. It can measure the underground displacement within a reasonable error range.

1. Overall Plan

1.1. System introduction

As shown in Fig. 1, the entire system consists of a measurement part and a control part, which communicate via RS-485. The control part is the upper computer. The upper computer sends a command to the measurement part through RS-485, collects the real-time Hall voltage and the mutual inductance voltage. And then we can get the relative displacement of adjacent sensing units through querying the data collected.
1.2. Introduction to Measuring Unit

The measuring part is composed of $N$ identical sensing units. Each sensing unit is composed of a mutual inductance coil, the measuring circuit of voltage, MCU control circuit, and permanent magnet and Hall sensor. When the actual installation is used, the bottommost sensing unit is buried in the bedrock of the rock and soil. From the bottom to the top, each sensing unit is numbered 1 to $N$. Adjacent sensor measuring unit constitutes a measuring unit, such as: 1# measuring unit is composed of sensing unit 1 and sensing unit 2, ... $N-1$# measuring unit is composed of sensing unit $N-1$ and sensing unit $N$. There are a total of $N-1$ measuring units. When the relative displacement of adjacent sensing units occurs, mutual inductance voltage and Hall voltage will change. At this point, the upper computer sends the instruction of measuring voltage to the MCU. Then, the MCU sends the mutual inductance voltage and Hall voltage collected to the upper computer, which analyzes the displacement through the data in the query table. By accumulating the displacement value of $N-1$ measuring units, the underground displacement of the whole system can be calculated.
2. Sensing Unit Design

2.1. Sensing Unit Structure Design
The sensing unit measures the deep deformation base on the mutual inductance and the Hall Effect. This paper proposes to add a Hall sensor and a permanent magnet to the mutual inductance coil on base of our previous research on the mutual inductance effect, and measure both the mutual inductance voltage and Hall voltage that change with the displacement of adjacent sensing unit by using mutual inductance and Hall Effect. As shown in Fig. 2, a permanent magnet, magnetized in the thickness direction, with diameter of 25mm and thickness of 10mm, is added to the upper end surface of the coil. The Hall sensor SS94A1F is installed on the lower end surface of the coil to sense the magnetic field of the permanent magnet and output the corresponding Hall voltage. The middle part of the coil is the PCB board for data acquisition and transmission. The PCB mainly contains the measuring circuit of mutual inductance voltage and Hall voltage and RS485 communication circuit. The control chip adopts MSP430F169 [11] with low power consumption. As shown in Fig. 3, it is structure chart of SS94A1F, the sensor has the characteristics of high stability and high sensitivity, and its internal amplifier circuit is integrated, so the voltage level can be output without external voltage amplifier circuit.

![Figure 2. Experimental Device](image1)

![Figure 3. SS94A1F structure chart](image2)

2.2. Hall Voltage Acquisition
1) Hall Measurement Principle and Permanent Magnet Selection: The measure system for the deep displacement of rock and soil is mainly divided into mutual inductance voltage measurement and Hall voltage measurement. The mutual inductance voltage measurement has been successful in the preliminary research of our research group. This paper mainly describes the Hall measurement. According to the Hall Effect [12], the magnitude of the Hall potential is
Where $R_H$ is the Hall coefficient, $K_H$ is the sensitivity coefficient, $d$ is the thickness of the Hall element, and $I$ is the current through the sensor, $B$ is the magnetic field strength that passes vertically through the sensor.

It can be seen from the above equation that when the current $I$ through the sensor is constant, since the sensitivity coefficient $K_H$ of the same Hall sensor is constant, the Hall voltage is proportional to the magnetic field strength through the Hall sensor. Due to the displacement of the rock and soil, the position between the permanent magnet and the Hall sensor changes, so that the magnetic field strength of the sensor changes, the output voltage of the sensor changes accordingly, thereby obtaining the relationship between the Hall output voltage and the displacement.

It is desirable that the measurement range of the sensing unit is as large as possible, so that a large-sized permanent magnet is selected, and at the same time, the magnetic field is completely symmetrical for the convenience and accuracy of measurement, so the permanent magnet of the cylinder is selected and magnetized in the thickness direction. We have conducted a large number of experiments in the laboratory, and selected a cylindrical permanent magnet with diameter of 25mm and thickness of 10mm according to the farthest horizontal distance and the actual size limit measured by the experiment. With this permanent magnet, the maximum horizontal displacement that can be measured at a tilt angle of 0 is 55 mm.

2) Hall Measurement Circuit: The measurement for the space magnetic field of the permanent magnet is measured by the Hall sensor SS94A1F on this system. The Hall sensor SS94A1F power supply voltage is 8VDC, and its output characteristics are shown in Fig. 4.

![Figure 4. Hall voltage output characteristics](image)

When the magnetic field strength of the sensing surface perpendicular to the Hall sensor is 0-100 Gauss, the output voltage range of the sensor is 4-6.5V. The sampling reference voltage of the MSP430F169 microcontroller is set to 3.3V, and the Hall voltage measurement circuit is designed to convert the sensor output voltage range to 0-3V. The output voltage $V_h$ of the Hall sensor is connected to the addition and subtraction operation circuit after being divided by 1/2, and the reference voltage of the addition and subtraction circuit is $V_{ref}=2V$, and the amplification factor is 2. The output of the addition and subtraction circuit is amplified by a circuit with a magnification of 1.2. The voltage $V_{out}$ is connected to the A/D sampling pin of the MSP430F169 for AD sampling. The schematic diagram of the Hall voltage measurement circuit is shown in Fig. 5.
3. Soft Design

The entire experimental process is controlled by the host computer software. The works of host computer mainly contains three modules. Firstly, control the 7SC405 sports console to move. Secondly, send a command to enable the MCU to collect data and upload it. Finally, save the data to Excel. The software design of data acquisition is written in Visual Studio 2015 using C# language. The Windows Forms Application program written based on this software is very simple and easy to develop PC program [13]. The main function of the upper computer is to collect the mutual inductance voltage and Hall voltage value of adjacent sensing units at different positions and save them in Excel to establish a mathematical model. The main idea of software design for data acquisition is shown in Fig. 6.

**Figure 5.** Hall voltage measuring circuit.

**Figure 6.** Measurement program Flow Chart
4. Mathematical Modeling

4.1. Experimental Data Collection

The experiment uses the points A and B where the edges of the upper and lower sensing units intersect as the reference point, as shown in Fig. 7. In the data acquisition process, firstly, the host computer sends instruction to the reference end (Sensing unit 1) of the sensing unit to generate a sine wave. Next, the upper computer sends the measuring end (Sensing unit 2) a commend to measure the mutual inductance voltage. Then the upper computer sends a command to the reference end to turn off the sine wave output, reducing the interference of the Hall measurement. And then the host computer sends a command to the measurement end to measure the Hall voltage. After one measurement of mutual inductance voltage and Hall voltage is completed, a displacement command is sent to the 7SC405. Each displacements is 1 mm, whether in horizontal or vertical direction.

Figure 7. Schematic diagram of the initial position of the sensing unit

The experiment takes a set of data under each tilt angle, each group of data moves up 40mm in the vertical direction and 40mm in the horizontal direction. The entire experiment is controlled by the host computer. Fig. 8. Shows a three-dimensional graph of the mutual inductance voltage and Hall voltage data measured at a tilt angle of 0 degrees.

Figure 8. Voltage Acquisition Data with 0 Degree
4.2. Data Modeling

Through many experiments and calibration of benchmark experimental data, the tilt angle $\theta$, the horizontal displacement and vertical displacement pairs $(x, y)$ and corresponding mutual inductance voltage and Hall voltage pairs $(U_r, U_h)$ are stored in the database, and the tables of $(\theta-x-y-U_r-U_h)$ are obtained. When the deep displacement measurement system works, the database is queried according to the real-time tilt angle $\theta_0$, mutual inductance voltage and Hall voltage pair $(U_{r0}, U_{h0})$, and the corresponding horizontal displacement and vertical displacement $(x_0, y_0)$ are obtained. Laboratory data acquisition is under the condition of constant angle, so each angle corresponds to a database table. When querying the database table, each mutual inductance voltage and Hall voltage correspond to some discrete points. Discrete points mean that at this point, the voltages are equal, this curve is called a voltage contour line. The discrete points of mutual inductance voltage and Hall voltage are fitted with two curves. The intersection point of the two fitting curves is the horizontal displacement and vertical displacement of adjacent sensing units. As shown in Fig. 9, these are two contour lines when $\theta$ equals to 10 degrees, horizontal and vertical displacements are equal to 15mm.

The following equation is the fitted curve equation, $y_m$ is the mutual inductance voltage contour line equation, $y_h$ is the Hall voltage contour line equation.

$$y_m = -0.0000014333x^4 + 0.000042242x^3 - 0.00817x^2 - 0.05816x + 17.65$$

$$y_h = -0.00002442x^4 + 0.0009238x^3 - 0.0247x^2 + 0.004652x + 18.75$$

Solve the two equations, the solution is:
x=15.859mm, y=14.752mm.

5. Conclusion

The system designed the deep displacement measurement device and measurement model of rock and soil based on mutual inductance effect and Hall Effect. By using the acquired mutual inductance voltage and Hall voltage, by calculating the intersection of the contour and the two contours, the real-time displacement can be uniquely determined. Real-time online measurement of rock and soil can be performed, and remote monitoring can be achieved by combining wireless network communication. The measurement error is less than 1.5mm, and the system uses wireless measurement, which effectively avoids the situation that the cable measuring device is damaged due to excessive displacement of the rock and soil body and cannot continue to measure. It provides strong data support for rock and soil landslide disaster monitoring and early warning and forecasting, and also provides a strong basis for disaster prevention and mitigation.

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