5. Experimental Contents

1) Measure the sensitivity of a Hall sensor
2) Verify the output voltage of a Hall sensor proportional to the magnetic field intensity inside the solenoid
3) Acquire the relationship between the magnetic field intensity and position inside and at the edges of the solenoid

6. Experimental Procedure

A. Refer to Figure 3 to connect wires: connect the output terminals of the "Current Source" on the left of the panel with the "Excitation Current In" terminals of the solenoid coil, and then insert the plug of the Hall sensor probe into the corresponding socket on the right of the panel.

B. Turn the "Current Adj." knob to minimum position (i.e. the minimum current). Switch on the power and let the apparatus warm up for 10 minutes. Then place the Hall sensor into the middle location of the solenoid ($X = 16.0$ cm). Adjust the "Zero Adj." knob of the Hall sensor to make the digital voltmeter display zero. At this time, the Hall sensor works at the standard state and the residual voltage is compensated.

C. Determination of sensitivity K of the Hall sensor

(1) Remain the Hall sensor at the central location of the solenoid ($X = 16.0$ cm), change the DC current Im of the solenoid to acquire U-Im relationship by recording a series of U-Im data, e.g. Im varies from 0 to 450 mA with a step of 50 mA.

(2) Use the least-square method to process U-Im data, acquire the slope $K=\Delta U/\Delta I_m$ of the straight line and the correlation coefficient R.

(3) For a solenoid of infinite length, the magnetic field is $B=\mu_0 n I_m$ (μ_0 is the permeability in vacuum, n is the number of turns per unit length of the solenoid).

Because the solenoid length is finite, the magnetic field formula must be corrected as

$$B = \mu_0 \frac{N}{\sqrt{L^2 + \overline{D}^2}} I_m$$

The parameters of the solenoid used in the experiment are:

Length $L = 260 \pm 1$ mm

Total turns $N = 3000 \pm 20$

Average diameter $\overline{D} = 35 \pm 1$mm

Permeability in vacuum $\mu_0 = 4\pi \times 10^{-7}$ H/m.

Therefore, the sensitivity of the Hall sensor can be derived as:

$$K = \frac{\Delta U}{\Delta B} = \frac{\sqrt{L^2 + \overline{D}^2}}{\mu_0 N} \frac{\Delta U}{\Delta I_m} = \frac{\sqrt{L^2 + \overline{D}^2}}{\mu_0 N} k \qquad \text{(unit: } V/T\text{).}$$

D. Measurement of magnetic field distribution of a powered solenoid

(a) Acquire the U - X relationship from the solenoid powered by a constant-current *Im* (e.g. 250 mA). X is from 0 to 30.0 cm. Take more data points at each end of the solenoid.

(b) Calculate B - X relationship using sensitivity K acquired above. Plot B - X curve.

(c) Mark the uniform area of magnetic field on the plot (including length and position) and calculate the average magnetic field strength $\overline{B_0^{'}}$. The theoretical value is

$$B_0 = \mu_0 \frac{N}{\sqrt{L^2 + \overline{D}^2}} I_m$$

Assume the range of magnetic field variation <1% is the uniform range, i.e. $-1\% \leq (B_0 - B'_0)/B_0 \times 100\% \leq 1\%$.

(d) The length of the solenoid is known as L = 26.0 cm, so mark the end positions of the solenoid on the plot as points P and P' (usually it is considered that the magnetic field strength at edge point is half of that in the center, i.e. $B_P = B_{P'} = \frac{1}{2}\overline{B_0^{'}}$). Verify that the distance between points P and P' is about 26.0 *cm*.

Note:

i) When measuring $U \sim I_m$, place the sensor at the center of the solenoid (i.e. uniform region).
ii) When measuring $U \sim X$, current I_m applied to the solenoid should remain unchanged.
iii) When $I_m = 0$, the digital voltmeter should display “0”.
iv) After experiment, turn the “Current Adj.” knob in counterclockwise direction to the end.

7. Example of Data Recording and Processing

Note: the following data are for reference purposes only, not the criteria for apparatus performance:

A. The relationship between Hall potential difference and magnetic induction strength

Place the Hall sensor at the central position of the solenoid (i.e. $X = 16$ *cm*). The measured U and I_m are given in Table 1 and plotted in Figure 4 below.

Table 1 Measured Hall potential difference U and magnetization current I_m

I_m (mA)	0	50	100	150	200	250	300	350	400	450
U (mV)	0	21.7	43.4	64.6	86.3	107.6	129.0	150.5	172.0	193.5

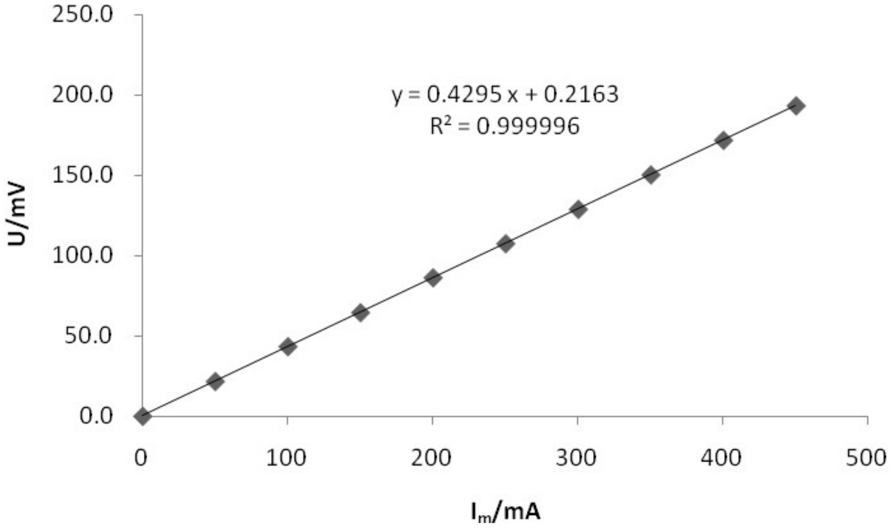

Figure 4 Plot of Hall potential difference U versus solenoid current I_m

B. Magnetic field distribution in powered solenoid (I_m=250 *mA*)

U_1 and U_2 are the output voltages of the Hall sensor with forward and reverse currents applied, respectively. $U = (U_1 - U_2)/2$. (Measuring the Hall voltage with forward and reverse currents and averaging the data eliminate the effect of the geomagnetic field.)

Table 2 Relationship of B and X ($B = U/K$)

X (*cm*)	U_1 (*mV*)	U_2 (*mV*)	U (*mV*)	B (*mT*)
1.00	12.6	-12.8	12.70	0.42
1.50	18.0	-18.2	18.10	0.61
2.00	26.4	-26.6	26.50	0.89
2.50	39.2	-39.4	39.30	1.31
3.00	55.6	-55.8	55.70	1.86
3.50	71.7	-72.0	71.85	2.40
4.00	83.8	-84.0	83.90	2.81
4.50	92.0	-92.3	92.15	3.08
5.00	97.0	-97.3	97.15	3.25
6.00	102.4	-102.7	102.55	3.43
7.00	104.9	-105.2	105.05	3.51
8.00	106.3	-106.6	106.45	3.56
9.00	107.1	-107.4	107.25	3.59
10.00	107.4	-107.7	107.55	3.60
11.00	108.0	-108.1	108.05	3.61
12.00	108.1	-108.3	108.20	3.62
13.00	108.0	-108.3	108.15	3.62
14.00	107.9	-108.2	108.05	3.61
15.00	107.8	-108.2	108.00	3.61
16.00	107.9	-108.1	108.00	3.61
17.00	107.9	-108.0	107.95	3.61

18.00	107.8	-108.0	107.90	3.61
19.00	107.6	-107.9	107.75	3.60
20.00	107.3	-107.6	107.45	3.59
21.00	107.1	-107.4	107.25	3.59
22.00	106.9	-107.2	107.05	3.58
23.00	106.5	-106.7	106.60	3.57
24.00	105.3	-105.5	105.40	3.53
25.00	103.5	-103.8	103.65	3.47
26.00	100.8	-101.0	100.90	3.37
26.50	98.3	-98.4	98.35	3.29
27.00	94.5	-94.8	94.65	3.17
27.50	88.4	-88.6	88.50	2.96
28.00	79.0	-79.3	79.15	2.65
28.50	65.1	-65.2	65.15	2.18
29.00	48.1	-48.4	48.25	1.61
29.50	33.3	-33.4	33.35	1.12
30.00	21.9	-22.2	22.05	0.74

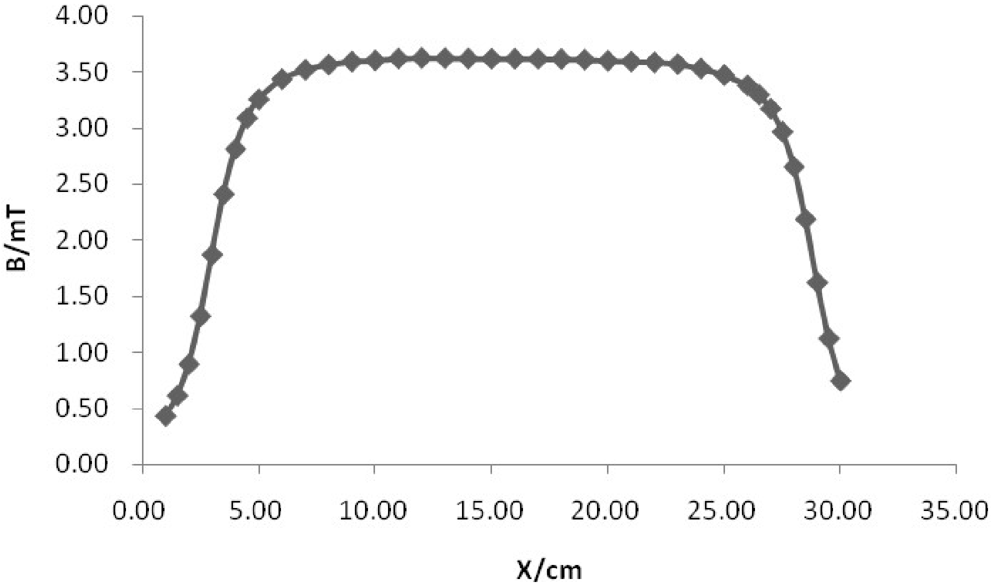

Figure 5 Magnetic field distribution in solenoid

C. Conclusion

1) Study on Hall effect: using the least square method we got $K = \Delta U/\Delta I_m = 0.4295$ *V/A* and correlation coefficient $r = 0.999958$. Since the magnetic induction strength B in solenoid is proportional to the applied current, Hall potential difference U is proportional to magnetic field strength B as demonstrated in Figure 4.

2) Calculate sensitivity K of the Hall element: the magnetic field strength in the center of

the solenoid $B_0 = \mu_0 \frac{N}{\sqrt{L^2 + D^2}} I_m$, N=3000 turns, L=26.00 cm, $\overline{D}$=35.0 mm, therefore:

$$K = \frac{\Delta U}{\Delta B} = \frac{\sqrt{L^2 + \overline{D}^2}}{\mu_0 N} \frac{\Delta U}{\Delta I_m} = \frac{\sqrt{L^2 + \overline{D}^2}}{\mu_0 N} k = \frac{\sqrt{0.260^2 + 0.035^2}}{4 \times \pi \times 10^{-7} \times 3000} \times 0.4295 = 29.9 V / T$$

Since the theoretical sensitivity of the 95A Hall sensor is 31.3±1.3 *V/T*, the experimental result meets with the theoretical value.

3) Determine the uniform region and the length of the solenoid

The theoretical value of magnetic field strength in the center of solenoid is:

$$B_0 = \mu_0 \frac{N}{\sqrt{L^2 + D^2}} I_m = 4\pi \times 10^{-7} \frac{3000}{\sqrt{0.26^2 + 0.035^2}} \times 0.25 = 3.592 \times 10^{-3} \text{ T}.$$

By using 1% as the criteria of uniform region, i.e. $\frac{|B_0 - B_0^{'}|}{B_0} \times 100\% \le 1\%$, we get $B_0^{'} = 3.592 \pm 0.036 mT$. From the plot shown in Figure 5, we get the uniform region is from $X_1 = 8.0$ cm to $X_2 = 23.0$ cm.

By setting B=B_0/2=1.796 *mT* as the magnetic field at edge point of the solenoid, we get $2.50cm < P < 3.00cm$ and $28.50cm < P' < 29.00cm$, leading to the length of the solenoid $P^{'} - P \approx 26.00cm$, which is very close to the theoretical value of 26.0 cm.