PH4103: Condensed Matter Laboratory

Hysterisis Loop

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1 Aim

In this experiment we aim to understand the working of a magnetic hysterisis loop tracer and calculating coercivity, saturation magnetisation and retentivity for the given sample (Hard Steel).

2 Experimental Setup



Figure 1: The setup at the laboratory

Our experimental setup (see Fig 1) consists of a hysterisis loop tracer, a solenoid with variable AC supply, Pickup coil, Hall Probe, a digital oscilloscope and the sample - a cylindrical steel rod. It must be noted that, 1 full pot of α (or `AREA RATIO`) knob corresponds to 1.00, while for N (or `DEMAGNETISATION`) is 0.10.

3 Theory

Let us define some quantities, $\mathbf{H}$ is the external magnetic field intensity (that we control, by changing current through the solenoid), $\mathbf{B}$ is the resultant magnetic field induction in the material, $\mathbf{I} = \chi\mathbf{H} \equiv$

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$d\vec{m}/dV = \mathbf{M}/V$ is called Intensity of Magnetization or Magnetization vector or Total Magnetic Volume per unit volume, and finally $\mathbf{J} = \mu_0\mathbf{I}$ as magnetic polarisation (that we measure!). Mathematically, we can write them as,

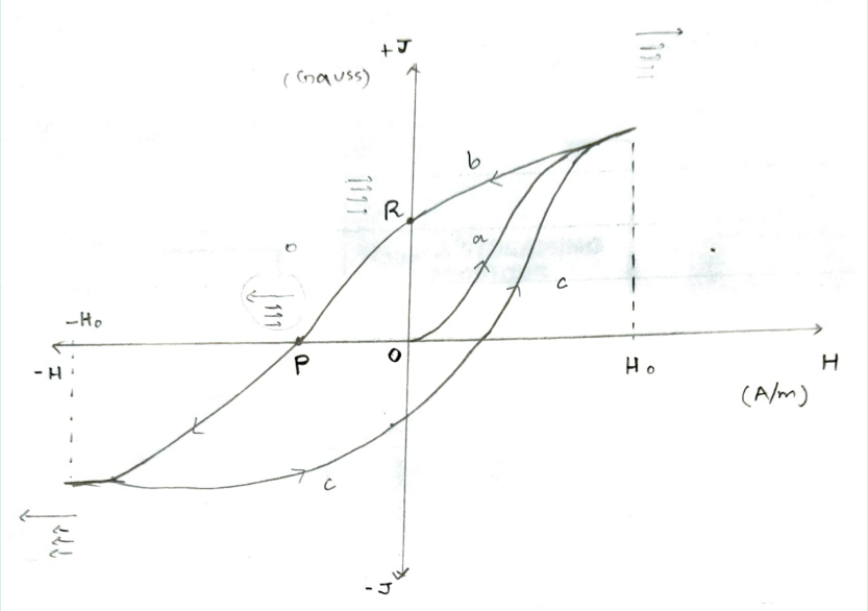
$$\mathbf{B} = \begin{cases} \mu_0\mathbf{H} & \text{(in vaccuum)} \\ \mu\mathbf{H} = \mu_0\mathbf{H} + \mathbf{J} & \text{(otherwise)} \end{cases} \tag{1}$$

where $\mu_r = \mu/\mu_0 = 1 + \chi$

Motivation When a magnetic field is applied to a material (in this case through AC currents in pick-up coil), the material gets magnetised. The actual magnetic field in the material is the sum of the applied magnetic field (H), and the magnetic field due to magnetisation.

$$\mathbf{H} = \frac{\mathbf{B}}{\mu_0} - \mathbf{I}$$

Loop *er byapare* – About the Loop



1. At the beginning (pt. O) current is zero, and sample has no magnetisation $\therefore H = 0, J = 0$.
2. As the current is increased, H increases & magnetisation increases (along curve a). When H reaches H_0 (Maximum - that we set by rotating the dial); J saturates. This is called **saturation magnetisation**.
3. Now when, we gradually decrease H, & J also decreases, but NOW along path b. As current $= 0$, $\therefore H = 0$, but, we observe, $J \neq 0$ (at R). This non-zero value of J (at $H = 0$) is called **Retentivity** of sample.
4. Now current direction reverses, until at point P, when $J = 0$, (along curve b). This value of H is known as **coercivity** of the sample.
5. Similarly increasing H in opposite direction causes J to saturate again till $-H_0$. Decreasing current again, from this point causes the path to trace curve c back to the top.

If we repeat the current cycle, so that H changes between $H_0 \to -H_0 \to H_0$; the curve $b \to c$ is traced again. This loop made by repeated oscillations of the field is called a **hysteresis loop**. The area of the hysteresis loop is proportional to *thermal energy* developed per unit volume of the sample as it goes through the hysteresis cycle.

4 Working Formula

In this section we shall derive the working formulae that are required in order to understand this experiment,

$$\boxed{H = G_0 \frac{e_x}{(\alpha - N)}} \tag{2}$$

$$\boxed{G_0 = \frac{1}{n\mu_0 g_x g_1 A_c}} \tag{3}$$

$$\boxed{J = \mu_0 (g_x/g_y) \frac{e_y}{(\alpha - N)}} \tag{4}$$

Let H_a be the uniform magnetic field produced by the solenoid. The effective magnetic filed H acting in the cylindrical sample can be written as

$$H = H_a - \frac{N}{\mu_0} J$$

where N is called the *normalised demagnetisation factor*[1] and $B = \mu_0 H + J$. To begin with let us define some (more) quantities.

H'	Magnetic Field in the pickup coil outside the sample
l	Length of sample (rod)
A_s	$= \pi D_s^2/4$ is the sample area
A_c	$= \pi D_c^2/4$ is the pickup-coil area
α	$= A_s/A_c$
ΔD_s	$= 0.01$ mm, Least count of screw gauge

The signal corresponding to the applied field is,

$$e_1 \propto H_a \quad \Rightarrow \quad e_1 = c_1 H_a \tag{5}$$

Further the flux linked with of area A_c due to sample of area A_s will be

$$\phi = \mu_0 (A_c - A_s) H' + A_s B$$

Note that, since $l/D_c \simeq 11.5 > 10 \Rightarrow H \approx H'$.

$$\therefore \phi = \mu_0 A_c H + A_s (B - \mu_0 H) \tag{6}$$

$$= \mu_0 A_c H + A_s J \tag{7}$$

The signal e_2 that is induced in the pickup coil, is exactly the induced electric potential difference due to change in magnetic flux ($\frac{\mathrm{d}\phi}{\mathrm{d}t}$).

i.e.

$$e_2 = n \frac{d\phi}{dt} \qquad (n \to \text{No. of turns in pickup coil}) \tag{8}$$

$$= n\mu_0 A_c \left(\frac{\mathrm{d}H}{\mathrm{d}t}\right) + n A_s \left(\frac{\mathrm{d}J}{\mathrm{d}t}\right) \tag{9}$$

However to obtain J, we have to pass e_2 to an adjustable gain (g_1) integrator.

$$-e_3 = -g_1 \int e_2 dt = -g_1 n \mu_0 A_c H - g_1 n A_s J + \Delta\varphi$$

$\Delta\varphi$ is the additional phase introduced due to capacitive coupling of pickup coil and solenoid. This can be adjusted to 0, by rotating the *phase knob*.

$$\therefore \; -e_3 = -g_1 n \mu_0 A_c H - g_1 n A_s J \tag{10}$$

[1] it is dependent upon the geometry and spatial dimensions of the sample

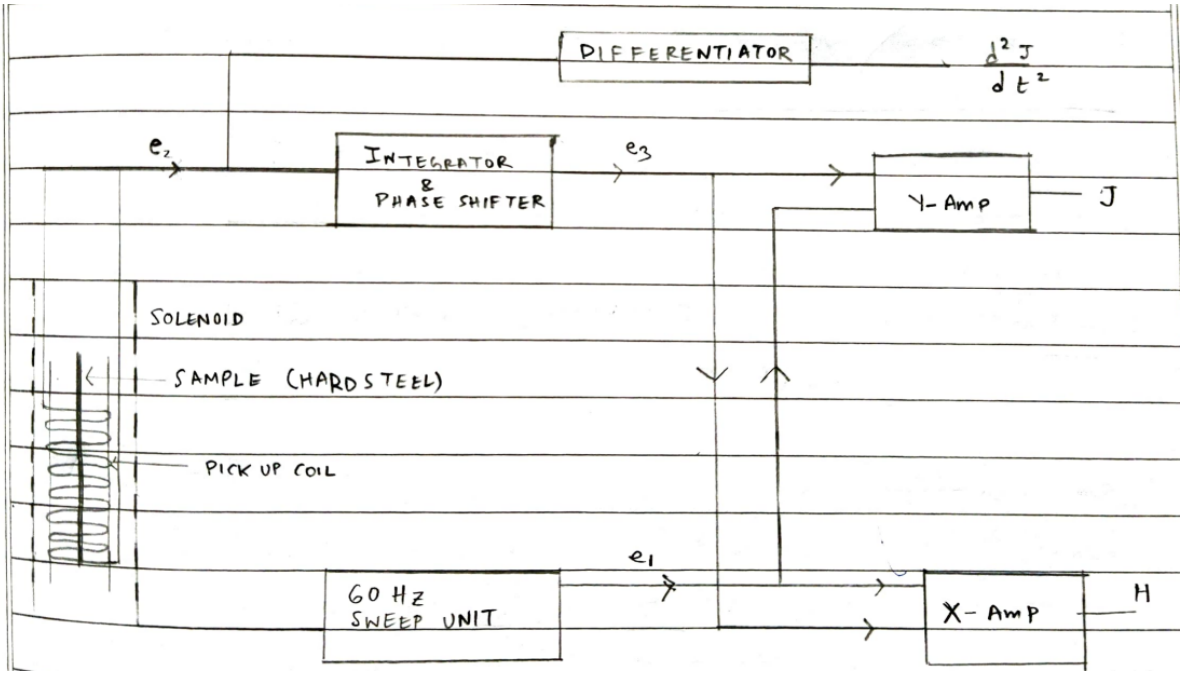


Figure 2: The block diagram of the hysterisis loop tracer

The magnetic field within big coil is proportional to current, we get

$$H_a = Ki \qquad [i = \text{current}, K \to \text{constant}]$$

and, $e_1 = R_1 i$.
From eq (5), $e_1 = c_1 H_a = c_1 K i = R_1 i \implies c_1 = R_1/K$.

The out of phase signals e_1 and $(-e_3)$ are added to get corresponding X-axis & Y-axis signals- e_x/T and e_y/T where $e_x \sim H$ and $e_y \sim J$.

The sum of e_1 & $(-e_3)$ after amplification becomes

$$e_y = -g_y(e_1 - e_3) \tag{11}$$
$$= -g_y(c_1 H_a - -g_1 n\mu_0 A_c H - g_1 n A_s J) \tag{12}$$
$$= -g_y\left(c_1 H - g_1 n\mu_0 A_c H + \frac{c_1 N J}{\mu_0} - g_1 n A_s J\right) \tag{13}$$

Now we tune the *H-balance knob*, to set

$$c_1 = g_1 n\mu_0 A_c$$

This gives,

$$\boxed{e_y = g_y g_1 n A_c\left(\frac{A_s}{A_c} - N\right) J} \tag{14}$$

Now, channel 1 of oscilloscope picks up e_x which is a measure of the magnetic field applied by the big solenoid. This field has to be corrected for demagnetization. So we subtract the magnetic response from the applied field.

$$e_x = g_x(\alpha e_1 - \beta e_y)$$
$$\alpha, \beta \to \text{to determine}$$

We have,

$$e_x = g_x[\alpha c_1 H - \frac{\alpha c_1 N J}{\mu_0} - \beta g_1 n\mu_0 A_c H - \beta g_1 n A_s J] \tag{15}$$
$$= g_x\left[H(\alpha g_1 n\mu_0 A_c - \beta g_1 n\mu_0 A_c) + J\left(\frac{\alpha g_1 n\mu_0 A_c N}{\mu_0} - \beta g_1 n A_s\right)\right] \tag{16}$$

Now, if we take, $\alpha = \frac{A_s}{A_c}$ and $\beta = N$, the coeff. of J vanishes (which is what we want!)

$$\boxed{e_x = g_x g_1 n \mu_0 A_c \left(\frac{A_s}{A_c} - N\right) H} \tag{17}$$

Finally from eq (14), (17) we obtain the desired formulae in eq (2), (3) and (4).

5 Data Analysis

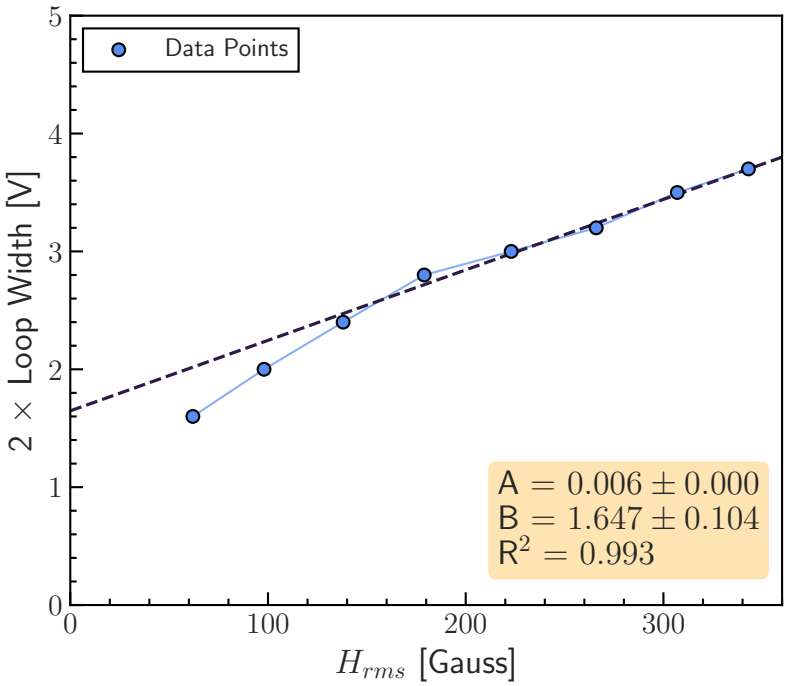


Figure 3: The figure shows a straight line fit ($Y = A + BX$) performed in the linear part of the graph, between 2× Loop width (Y-axis) and rms value of the applied field H_{rms} (X-axis). The R^2 value of the fit and the corresponding fitting parameters are quoted in the yellow box.

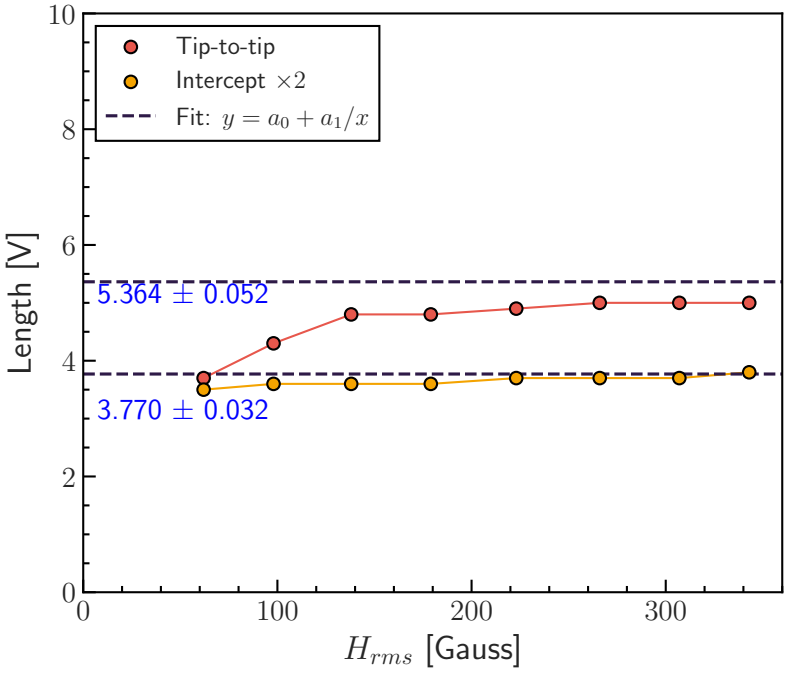


Figure 4: The figure shows an asymptotic fit ($y = a_0 + a_1/x$) in the graph, between 2× Intercept, Tip-to-Tip distance (Y-axis) and rms value of the applied field H_{rms} (X-axis). The corresponding asymptotic values of the fits are quoted in blue.

5.1 Calibration

Before beginning calibration process make sure [2] the `AR. RATIO` knob (α) is set to 1 and `DEMAG. RATIO` knob (N) is set to 0. Then press the `Autoset` button in YT mode of the oscilloscope and observe the yellow (e_x)[3] and blue (e_y) signals A calibration is performed by tuning the `DC BALANCE`, `H-BALANCE` and `PHASE` knobs until we get a flat e_y v/s time signal. This corresponds to $e_y \approx 0 \implies J = 0 \implies H = H_a$.

When an empty pickup coil is placed in the solenoid field, the signal e_2 will only be due to the flux linking the coil area. In this case $N = 0$ and $\alpha = A_s/A_c = 1$[4]

$$\therefore H = G_0\left(\frac{e_x}{\alpha - N}\right) \implies G_0 = H_a/e_x$$

where e_x is the peak-to-peak distance in XT signal.

H_a (rms) [G]	e_x [V]	G_0 (rms) [G V^{-1}]
179	65.6	2.73
224	80.0	2.80

Table 1: Calibration Readings (without sample)

So, G_0 (peak-to-peak) $= \left(\frac{2.73+2.80}{2}\right) \times 2\sqrt{2} = 7.82$ G V^{-1}.

In the following calculations, we quote the diameter of the pick-up coil $D_c = 3.21$ mm as given in the manual. The measurements of the sample properties are tabulated in the Appendix.

5.2 Computations

From the straight line fit in graph in Fig (3), we have

$$\bar{e}_x = (1.647 \pm 0.104)/2 = 0.824 \pm 0.052 \text{ V}$$

Similarly, asymptotic fits in the graph in Fig (4) gives

$$(e_y)_s = (5.364 \pm 0.052)/2 = 2.682 \pm 0.026$$

$$(e_y)_r = (3.770 \pm 0.032)/2 = 1.885 \pm 0.016$$

5.3 Calculations

In CGS units $\mu_0 = 1$ and $g_x = 100,\ g_y = 1$.

Coercivity

$$H_c = \frac{G_0 \bar{e}_x}{(A_s/A_c - N)} = \frac{2.765 \times 0.82369 \times 2\sqrt{2}}{(0.137 - 0.0136)} = 52.202 \text{ Gauss}$$

Saturation Magnetisation

$$\mu_s = \frac{J_s}{4\pi} = \frac{G_0 \mu_0 g_x (e_y)_s}{4\pi g_y (A_s/A_c - N)} = \frac{2.765 \times 1 \times 100 \times 2.68183 \times 2\sqrt{2}}{1 \times 4\pi(0.137 - 0.0136)} = 1353.216 \text{ Gauss}$$

Retentivity

$$\mu_r = \frac{J_r}{4\pi} = \frac{G_0 \mu_0 g_x (e_y)_r}{4\pi g_y (A_s/A_c - N)} = \frac{2.765 \times 1 \times 100 \times 1.885 \times 2\sqrt{2}}{1 \times 4\pi(0.137 - 0.0136)} = 950.663 \text{ Gauss}$$

[2] remove the sample too!! [3] ideally this signal should be a perfect sinusoid due to AC current, but in our set-up we got a *triangular wave* which we expect to have been caused by ineffective grounding in the circuit. [4] since sample is now the air inside the pickup coil which has the same cross section area!

6 Error Analysis

Calibration Constant (G_0)

$$G_0 = H_a/e_x$$
$$\left|\frac{\Delta G_0}{G_0}\right| \leq \left|\frac{\Delta H_a}{H_a}\right| + \left|\frac{\Delta e_x}{e_x}\right|$$

However due to insufficient readings, we do not report their errors.

Coercivity

$$H_c = \frac{G_0 \bar{e_x}}{(A_s/A_c - N)}$$
$$\left|\frac{\Delta H_c}{H_c}\right| \leq \cancel{\left|\frac{\Delta G_0}{G_0}\right|} + \left|\frac{\Delta \bar{e}_x}{\bar{e}_x}\right| + \cancel{\left|\frac{\Delta A_c}{A_c}\right|} + \left|\frac{\Delta A_s}{A_s}\right| + \cancel{|\Delta N|}$$
$$= \left|\frac{\Delta \bar{e}_x}{\bar{e}_x}\right| + 2\left|\frac{\Delta D_s}{D_s}\right|$$
$$= 0.052/0.824 + 2 \times 0.01/1.19 = 0.007991$$

Therefore,

$$\boxed{|\Delta H_c| \leq 0.00799 \times 52.202 \simeq 4.172}$$

Saturation Magnetisation

$$\mu_s = \frac{J_s}{4\pi} = \frac{G_0 \mu_0 g_x (e_y)_s}{4\pi g_y (A_s/A_c - N)}$$
$$\left|\frac{\Delta \mu_s}{\mu_s}\right| \leq \left|\frac{\Delta (e_y)_s}{(e_y)_s}\right| + 2\left|\frac{\Delta D_s}{D_s}\right|$$
$$= 0.026/2.682 + 2 \times 0.01/1.19 = 0.0265$$

Therefore,

$$\boxed{|\Delta \mu_s| \leq 0.0265 \times 1353.216 \simeq 35.860}$$

Retentivity

$$\mu_r = \frac{J_r}{4\pi} = \frac{G_0 \mu_0 g_x (e_y)_r}{4\pi g_y (A_s/A_c - N)}$$
$$\left|\frac{\Delta \mu_r}{\mu_r}\right| \leq \left|\frac{\Delta (e_y)_r}{(e_y)_r}\right| + 2\left|\frac{\Delta D_s}{D_s}\right|$$
$$= 0.016/1.885 + 2 \times 0.01/1.19 = 0.02529$$

Therefore,

$$\boxed{|\Delta \mu_r| \leq 0.02529 \times 950.6626 \simeq 24.050}$$

7 Discussions and Sources of Error

- The manual advised us to calibrate at H_a = 200 G. However, this was not possible due to the limitation of instrument. Therefore we took two readings at 179 G and 224 G and took their average.
- At high magnetic fields (H_a), it was observed that $J - H$ curve had a small loop in the saturation portion. This is due to difference in phases for the forward paths, caused by induction of eddy currents in the sample. This affected the measurement of tip-to-tip and intercept values of the loop.

- The samples might not be entirely pure, and may contain impurities as was observed in plots of $\mathrm{d}J/\mathrm{d}t$ and $\mathrm{d}^2J/\mathrm{d}t^2$.
- The nearby magnetic material was affecting the field uniformity inside the coil, and that might have caused a deviated hysteresis loop.
- The demagnetisation factor's (N) exact value was not available corresponding to the exact dimensions of sample. This led to an error ΔN, which we neglected.
- Voltage fluctuations and additional instrumental errors inherent in electronic circuits, which might have added to some noise in our hysteresis loop measurement.

The loop width graph was extrapolated to zero magnetic field, because from definition of coercivity the measure of width should be under no shielding effects. The μ_s, μ_r are derived from asymptotic extensions of the corresponding plot because these refer to the situation when shielding effects are insignificant.

8 Conclusion

From our experiment we conclude the following values of magnetic properties of *hard steel*,

- Coercivity: $H_c = 52.202 \pm 4.172$ Gauss.
- Retentivity: $\mu_r = 950.663 \pm 24.050$ Gauss.
- Saturation Magnetisation: $\mu_s = 1353.216 \pm 35.860$ Gauss.

References

- Lab manual

Appendix

A) Sample Properties measurement

Material	D_s [mm]	$\alpha = \frac{A_s}{A_c} = \left(\frac{D_s}{D_c}\right)^2$	**Sample length** l [mm]	l/D_s	N (from Appendix)
Nickel (Drill)	1.48	0.213	39	26	0.0180
Hard steel	1.19	0.137	37	31	0.0136
Soft Iron	1.18	0.135	36	30	0.0137

B) Hysterisis Loop measurements (Hard Steel)

H_a (rms) [G]	2× Loop width [V]	Tip-to-Tip Height [V]	2× Intercept [V]
62	1.6	3.7	3.5
98	2.0	4.3	3.6
138	2.4	4.8	3.6
179	2.8	4.8	3.6
223	3.0	4.9	3.7
266	3.2	5.0	3.7
307	3.5	5.0	3.7
343	3.7	5.0	3.8