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Design and Fabrication of IC Based Magnetic Hysteresis Loop Tracer Sensitive to Low Fields

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1.0 Abstract:
In paper the design and fabrication of an IC OP-07 based magnetic hysteresis loop tracer for low magnetic field up to 10 Oe. The high loop gain of IC OP-07 is able to amplify even the minute changes in the magnetic flux which is needed for accurate working of a B-H loop tracer. The circuit is found to be sensitive to feeble signals. Compared to the conventional B-H loop tracer a separate phase shifter has been used along X-channel providing more circuit flexibility. The designed instrument has been used to measure the apparent coercivity, apparent retentivity and saturation magnetization using minor loops for Ferromagnetic (Fe) and Ferrimagnetic (Mn-Zn) samples. The instrument works at a frequency of 50Hz and the cylindrical samples with a diameter to length ratio of 10 which is seen to minimize the demagnetizing field factor. Hysteresis loss is found to decrease with the decrease in the current of the solenoid. Lowering of magnetic field shows the formation of Rayleigh's loop.

2.0 Key words: Magnetic, Hysteresis, Integrated Circuit, Loop Tracer, Low field

3.0 Introduction
The magnetic properties of materials are measured by number of techniques one among it being variation of magnetic induction within the magnetic material with the externally applied magnetic field. Theses variation brings internal structural changes in the magnetic materials which are measured in terms of permeability, coercivity, retentivity, saturation magnetization etc. Different magnetic materials exhibit different limiting loops. The limiting loop is the saturating response of a magnetically ordered material showing extreme behavior. Along with the limiting loop there exist infinitely many minor loops [1] for a magnetically ordered material and in various scientific, technical and industrial field minor hysteresis loop of the magnetic material under low magnetic field is desirable. Although the B-H loop tracer have been constructed by using different operational amplifiers [2], we have used IC OP-07 [3,4] for its construction as it has a very low input offset voltage (75µV max) and high open loop gain(200V/mV) which makes it an excellent candidate for high gain instrumentation [5]. A digital and computer-based hysteresis loop tracers for studying soft magnetic materials has been reported [6, 7] In this paper first the block diagram of B-H loop tracer then the design of each block, next the calibration of the instrument and finally the result from the measurement of apparent retentivity apparent coercivity and saturation magnetization for minor loops and discuss them.

4.1 Instrument Design and Calibration

The block diagram of the proposed B-H loop tracer is shown in figure 1 with the introduction of all pass filter in the X-channel itself which provides the flexibility for phase correction in the X-channel.

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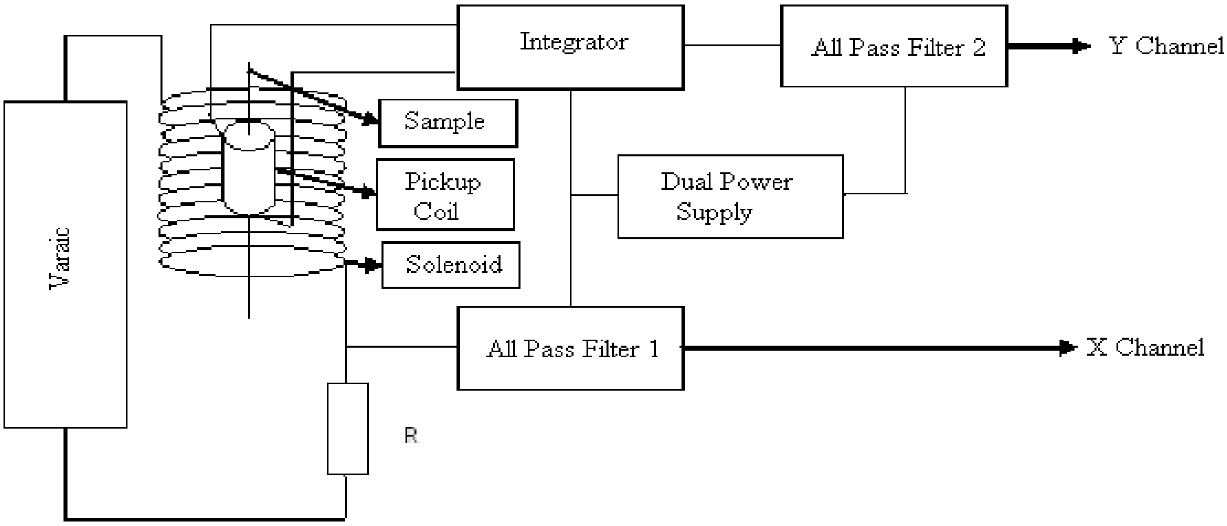

Figure 1: Block diagram of B-H Loop Tracer.

4.2 Solenoid

The field strength at the centre of the solenoid is calculated from the formula given by D.Bruce Montgomery [4],

$Ho = (HI/a_1)\ [1/2\beta(\alpha-1)]F(\alpha,\beta)$ (1)

The field strength H_0 at the centre of the solenoid is calculated so that the maximum field intensity H_m at the centre of solenoid is known which is used in the calibration of the X-axis of the B-H hysteresis loop graph. The above formula requires following parameters, length of solenoid (2b) = 0.0838 m, number of turns =38, inner diameter of coil = 0.058 m and diameter of wire = 2mm = 0.002 m.Thus inner radius of solenoid (a_1) = 0.058/2=0.029m; outer radius of solenoid (a_2) =0.031m, 2b=0.0838m and b=0.0419 cm. Since $\alpha=a_2/a_1$ $\beta=b/a_1$ therefore α=0.031/0.029 = 1.069 and β = 0.0419/0.029=1.445.The figure 2 [4]indicates various parameters, given in equation 1.

The term $F(\alpha, \beta)$ in equation 1 is called ***field factor*** which is constant for a given solenoid depending on the dimensions of the solenoid. It is calculated from geometrical parameters like a_1 ,a_2 and ***b*** ,shown in figure 2,of the solenoid.

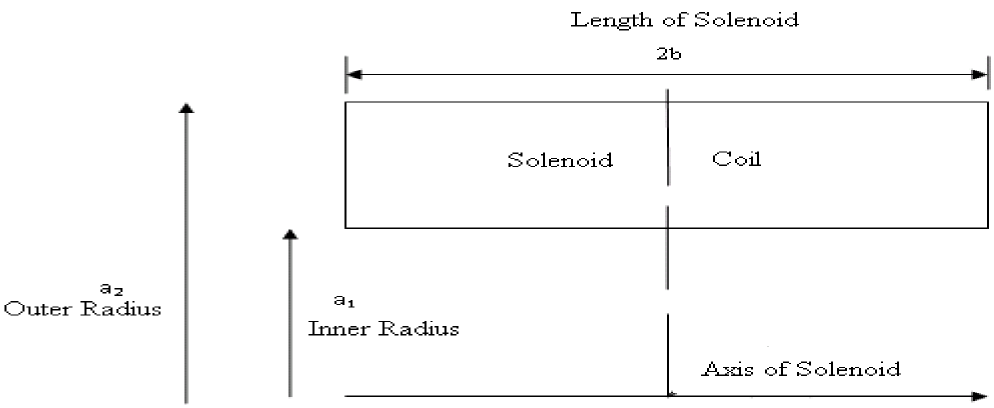

Figure 2: Schematic diagram of a solenoid

Now the field factor[4] for the solenoid is calculated as,

$F(\alpha,\beta) = (4\pi\beta/10)[\sinh^{-1}(\alpha/\beta) - \sinh^{-1}(1/\beta)]$ (2)

Thus the magnetic field strength[4] at the centre of the coil is,

$H_o = (HI/a_1)[1/2\beta(\alpha-1)]\, F(\alpha,\beta) = 6.9785\, I$ (3)

In the above equation r.m.s current is to be substituted as the current is sinusoidal**.** However the maximum field at the centre of the solenoid for peak value of corresponding current is

$H_o = 6.9785 I_{rms} \sqrt{2}$ (4)

4.3 Pickup Coil

Pickup coil is one of the most effective ballistic methods of measuring the magnetic field. The pickup coil is made up of copper wire coated with an insulating paint and wound on a wooden former. The plane of the pickup coil is placed perpendicular to the magnetic field. When a magnetic sample is inserted in the pickup coil a voltage is developed across it which is proportional to the rate of change of intrinsic magnetic induction of the sample with respect to time. This voltage is picked up and fed to integrator circuit of the B-H loop tracer. The dimensions of the pickup coil are as follows, length:- 0.027m, diameter:- 0.01.5m and number of turns:-20.

The diameter of the pickup coil is selected such that the sample which is of diameter 1cm just fits in it and the airflux correction is reduced. Also the length of the pickup coil is kept 0.027m as the samples are 0.1m long and the pickup coil has to only cover the central region of the solenoid. The turns are kept 20 because it can easily cover the length of 0.027m of the solenoid.

4.4 B-H Loop Tracer

The B-H loop tracer circuit designed consists of two parts:-i) X-Channel of B-H Loop Tracer and ii)Y-Channel of B-H Loop Tracer. The first part interfaces the solenoid with the X-axis input of the Digital Storage Oscilloscope and the second part interfaces the pickup coil with the Y-axis input of the Digital Storage Oscilloscope.

4.4.1 X-Channel of B-H Loop Tracer

The X-Channel of the B-H loop tracer is designed according to the following circuit analysis. The current in the solenoid, supplied by transformer or varaic in the block diagram 1, is sinusoidal given by the relation

$I(t) = I_o \sin\omega t$ (5)

According to equation 3 the magnetic field intensity of the solenoid is directly proportional to the current through the solenoid, therefore the magnetic field in centre of the solenoid is changing by the relation,

$H_o(t) = H_m \sin\omega t$ (6)

The signal corresponding to the field at the sample is given by the equation $e_1 = C_1 H_0$ where e_1 is the input signal voltage corresponding to magnetic field at the sample

Substituting for H_0 from equation 6 the signal e_1 becomes

$e_1(t) = C_1 H_m \sin\omega t$ (7)

where H_m is the maximum field intensity at the centre of the solenoid in terms of peak current value, as shown in equation 4.

The circuit diagram for the X-channel of the B-H loop tracer is shown in figure 3. The voltage across the resistor 'R' is proportional to current in the circuit of figure 3. Hence the voltage across resistor 'R' is representing the magnetic field intensity .This voltage is given as input to the ***all pass filter 1*** of the block diagram 1.The ***all pass filter 1*** provides phase shift to the input signal obtained across the resistor R in figure 3.This is done to provide correction in the phase shift of input signal during its transmission from solenoid to the digital storage oscilloscope. The values of various components used in the circuit are given in the figure 3. The ***all pass filter 1*** is built with IC OP07 [3].

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4.4.2 All Pass Filter

An all pass filter processes phase with predictable changes without attenuation to amplitude. The phase angle [5] by which the output wave is shifted from the input wave is given by equation

$$\varphi = -2\tan^{-1}(2\pi fRC) \quad (8)$$

The operating frequency of the solenoid is 50Hz, the resistance R is 100 kΩ and the capacitance C is 0.01µF. The maximum possible value of the phase shift between the input and the output wave is $\varphi = -179.63^{\circ}$

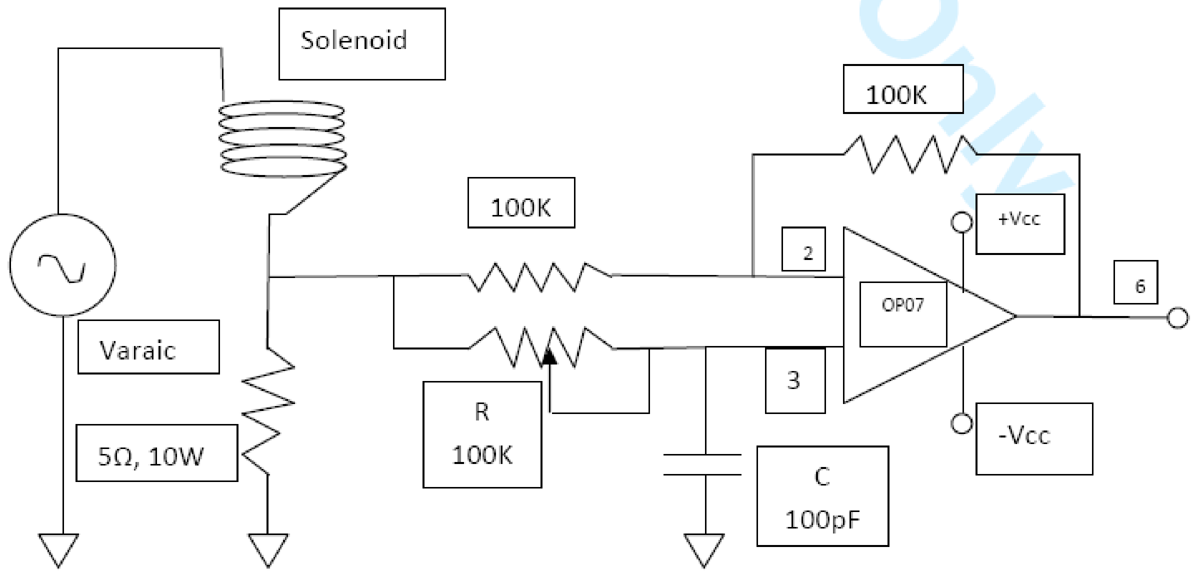

Figure 3: Circuit Diagram of X-channel of B-H Loop Tracer

The negative sign indicates the output signal lags behind the input signal. Thus the output phase angle changes from 0^0 to -179^0 with the change in the value of R in the circuit shown in figure 3. This range gives us complete flexibility in adjusting phase angle of output wave with respect to input wave. The 5Ω resistor connected in series with the solenoid is of 10W rating all the other resistors are of 0.25 W. Electrolytic & ceramic capacitors are used in the circuit of rating 25V.

4.4.3 Y-Channel of B-H Loop Tracer

The Y-Channel of the B-H loop tracer is designed according to the following circuit analysis. According to D.H. Howling [8] the voltage induced in the pickup coil, shown in the block diagram 1, is given by the equation

$$e(t) = 10^{-8}\, NA\, [dH(t)/dt] \quad (8)$$

,where H is the magnetic field intensity at the sample.

The component of magnetizing field intensity H along any principal axis inside an ellipsoid is given by the relation [9]

$$H_i = (H_o) - N_i M_i \qquad i = x,y,z,$$

,where H_o is the applied field, N_i is the demagnetizing factor and M_i is magnetization.

In the present case ballistic demagnetizing field factor is being considered as average is taken over a median cross section perpendicular to the field direction of the sample. Therefore above equation becomes

$$H = H_o - N_z M$$

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For the calculation of demagnetizing field in the present case ballistic demagnetizing field factor is used and the samples are selected such that diameter to length ratio is 10 for which the demagnetizing [10] factor is 0.00492.Hence $H \approx H_0$, therefore the voltage induced in the pickup coil in the central region is

$$e(t)=10^{-8}NA[(dHo)/dt]=10^{-8}\,NAH_m\omega.\cos\omega t \quad (9)$$

This voltage is given as input to the ***integrator circuit***[5], shown in the block diagram 1, whose output v_0 is given by the equation 10, excluding constant C, as we assume there are no other voltages except the voltage given from pickup coil,

$$v_o(t) = -(1/R_1C_F)\int e(t)dt \quad (10)$$

Substituting from equation **9** in equation **10**, the output v_0 of the integrator becomes

$$v_o(t) = -(1/R_1C_F)\,10^{-8}\,NAH_m\omega\,(\sin\omega t/\omega) \quad (11)$$

This voltage is given as input to phase shifter circuit which is designed such that its amplitude [5] of v_0/v_{in} is one (i.e. $|v_0| = |v_{in}|$).

The ***Integrator*** frequency [5] is designed for Y Channel of B-H loop Tracer with following values R_1= 100 kΩ and C_F= 0.01µF

$$f= 1/(2\pi R_1C_F) = 159\text{ Hz} \quad (12)$$

The integrator circuit is designed well above the operating frequency of 50Hz of the B-H Loop tracer. The circuit diagram for Y-Channel of the B-H loop tracer is shown in figure 4.

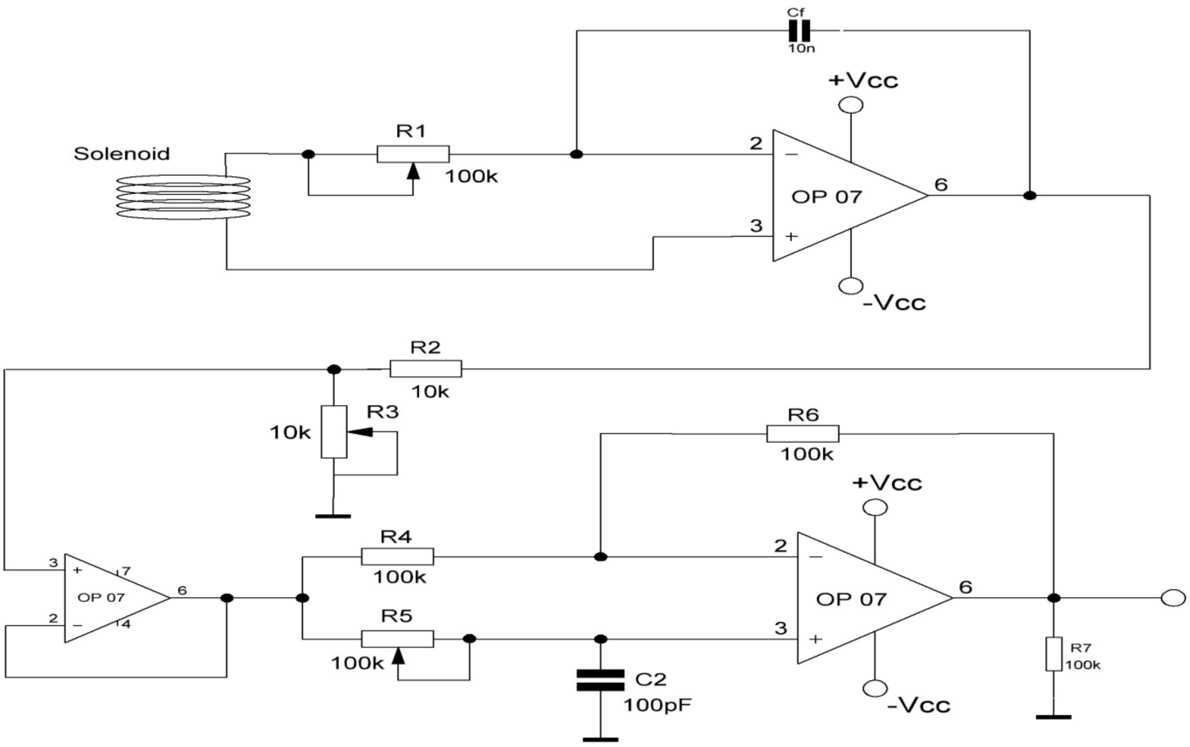

Figure 4: Circuit diagram for Y-Channel of the B-H loop tracer

The ***all pass filter 2*** is designed using equation **$\emptyset = -2\tan^{-1}(2\pi fRC)$** with same values as in equation 8 so that changes similar to that of in X-channel can be produced in the Y-Channel. This is done to compensate any loss to the phase of input signal during its transmission from pickup coil through the integrator to digital storage oscilloscope.

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The ***integrator*** as well as ***all pass filter 2*** in this part is built with IC OP07.The IC OP07 is powered with the dual power supply built onboard.

The experimental setup for B-H loop tracer is shown in the figure 5

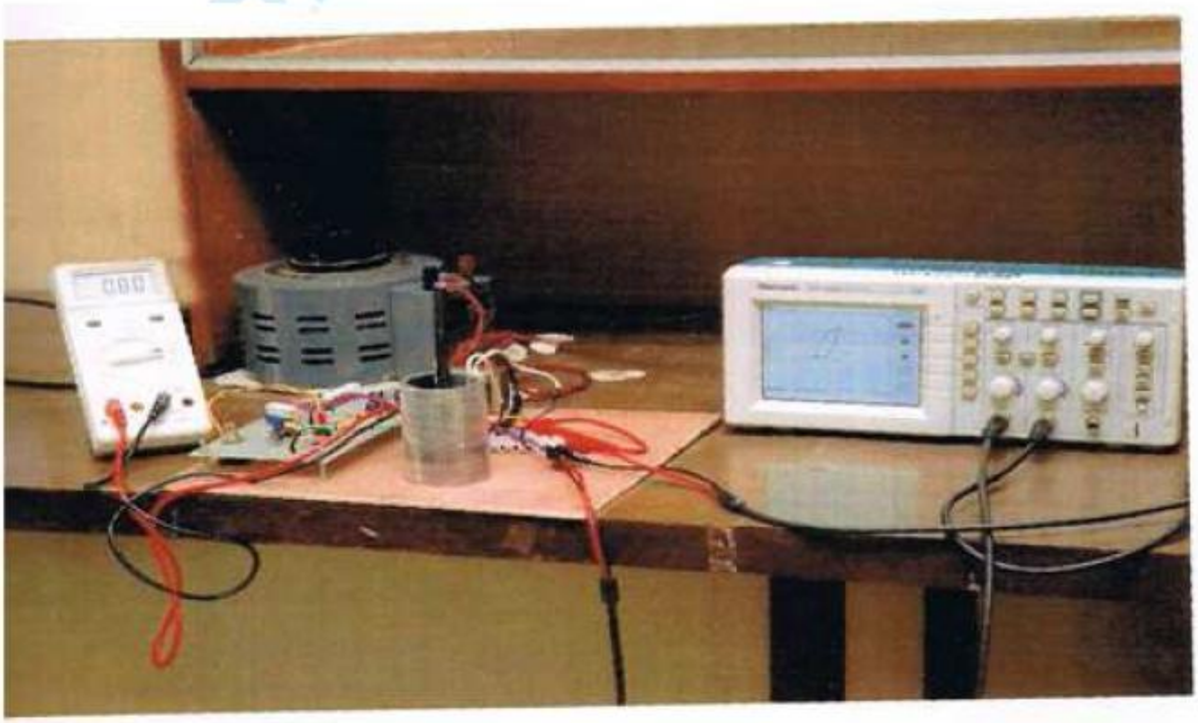

Figure 5: Experimental setup for B-H Loop tracer.

4.5 Calibration of B-H Loop Tracer

It is convenient to measure the magnetic parameters if the divisions of the X-axis and Y-axis on the digital storage oscilloscope are calibrated in magnetic units. In the present case magnetic field intensity (***H***) is shown on the ***X-axis*** of oscilloscope for which we have used unit as ***A/m***. The magnetic induction (***B***) in the sample is shown on the ***Y-axis*** of oscilloscope for which we have used the unit as ***V-s/m²***.

The calibration of the X-axis as well as Y-axis requires the peak values of the maximum field intensity H_m at the centre of the solenoid and the magnetic induction B at the central cross section of the magnetic sample.

The maximum field intensity at the centre of the solenoid at the current of I_{rms} equal to 1 ampere is calculated using the formula of equation 4.

$$H_m = 6.9785\ I_{rms}\sqrt{2} = 784.1302\ A/m \qquad (13)$$

In presence of air 1Oe = 1 gauss, therefore the field strength at the centre of the specimen is taken same as 9.853642 but the unit is replaced as gauss.

4.5.1 Calibration for H (x-axis)

The maximum Magnetic Field Intensity H_m at the centre of the solenoid from equation (13) is H_m= 784.1320 A/m

Total number of division corresponding to maximum Magnetic Field intensity H_m on X-axis is (N_x) is 37mm.

Magnetic field intensity per division (in mm) is

$$H_m/N_x = (784.1320\ A/m)/37\ mm = 21.193\ (A/m)\ mm^{-1}$$

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Therefore 10mm on the graph corresponds to magnetic field intensity of

H =10mm x 21.193(A/m) mm^{-1} = 211.93(A/m)

The relative permeability[14] of iron is 5000.

The magnetic induction for the given iron rod is

$$B_m=\mu H_m \qquad (14)$$

$$=5000 \times 9.853642 \text{ gauss} = 49268.2 \text{ gauss} = 4.92682 \text{ V-s/m}^2 \qquad (1\text{V-s/m}^2 = 10^4 \text{gauss})$$

4.5.2 Calibration for B (y-axis)

The maximum magnetic induction at the centre of the solenoid according to equation (14) is B_m=4.92682 V-s/m^2

Total division (in mm) corresponding to maximum magnetic induction on Y-axis is (N_y) 20 (mm).

Magnetic induction per division (in mm) is

$(B_m /N_y) = (4.92682 \text{ V-s/m}^2)/20(\text{mm}) = 0.246341 (\text{V-s/m}^2)/\text{mm}$

Therefore 10mm on the graph corresponds to magnetic induction of

$B=10\text{mm} \times 0.246341(\text{V-s/m}^2)/\text{mm} = 2.46341 \text{ V-s/m}^2$

4.5.2 Experimental observations

The figure 7 shows the waveforms at the X-channel and Y-Channel of the B-H Loop tracer withou the sample in the pickup coil where it is observed that the amplitude of wave form at the Y channel is considerably reduced.This is due the fact that the pickup coil respond to the magnetic field in and and around the central part of the solenoid and consequently the current induced in it is very small leading to a small amplitude signal.The figure 8 shows the waveforms at the X-Channel and Y-Channel of the B-H Loop tracer with the sample in the pickup coil.Also it is observed now that the amplitude of the waveform at the Y Channel is increased. This is due to the fact that the Iron and Mn-Zn ferrite materials have relative permability as 5000 and 6333.3 respectively, whch increases the magnetic induction at the pick up resulting greater induced currrent.The figure 10 shows the hysterisis loop generated by the designed B-H loop tracer.

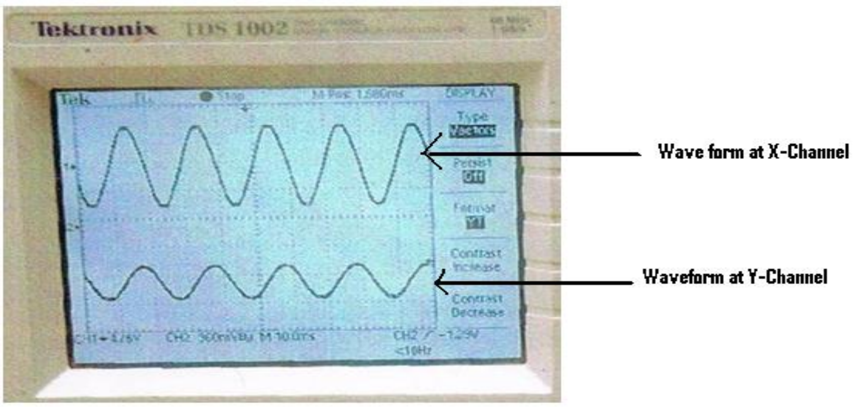

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Figure 6 :- Waveform at X-Channel and Y-Channel of the B-H Loop tracer circuit without sample in the pickup coil.

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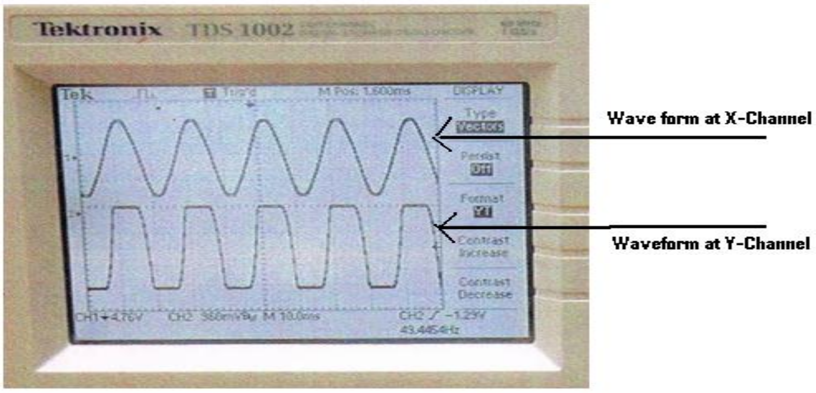

Figure 7:- Waveform at X-Channel and Y-Channel of the B-H Loop tracer circuit with sample in the pickup coil.

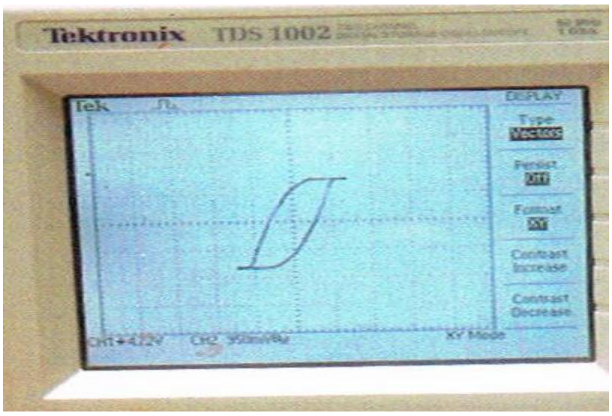

Figure 8: Hysteresis loop generated by the designed B-H Loop tracer.

The minor hysteresis loops for Iron and Mn-Zn ferrite which have been taken as standard samples are shown in figure 10 and figure 11 respectively at currents corresponding to (a)0.80A (b) 0.60A and (c) 0.40A.

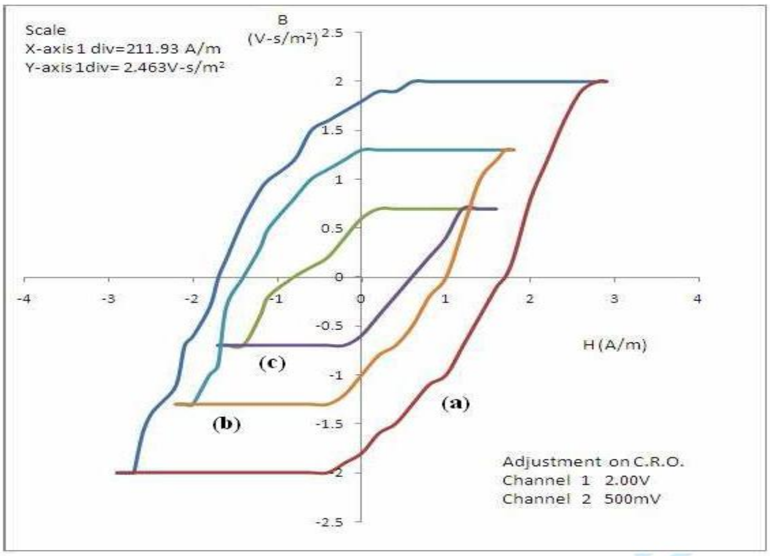

Figure 9 B-H hysteresis at (a) Irms = 0.80 A (b) Irms = 0.60 A and c) Irms= 0.40 A

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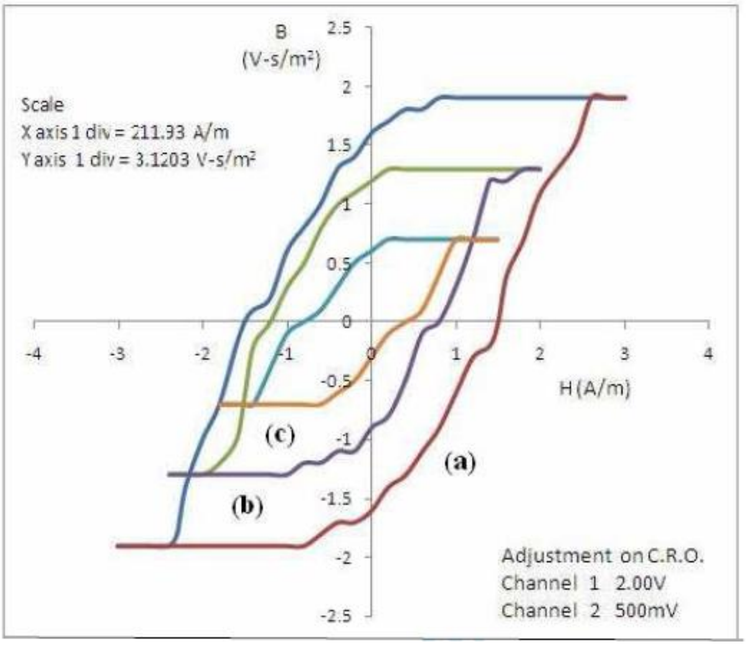

Figure 10 B-H hysteresis for Mn-Zn ferrite at (a) Irms = 0.80 A (b) Irms = 0.60 A and c) Irms= 0.40 A.

The values of, from B-H graphs, apparent retentivity B_r, apparent Coercivity H_c and saturation for Minor Loop B_s for Iron and Mn-Zn ferrite are given in table 1 and table 2 respectively.

TABLE 1 Apparent retentivity B_r, apparent Coercivity H_c and saturation for Minor Loop B_s for Iron

Obs No	I_{rms} (A)	H_m (A/m)	B_r V-s/m^2	H_c (A/m)	B_s V-s/m^2
1	0.8	628.193	4.0641	349.686	4.9262
2	0.7	549.668	3.4483	296.702	3.9409
3	0.6	471.144	2.9557	254.316	3.2020
4	0.5	392.065	1.9705	190.737	2.4631
5	0.4	314.096	1.4779	148.351	1.7242

TABLE 2 Apparent retentivity B_r, apparent Coercivity H_c and saturation for Minor Loop B_s for Mn-Zn ferrite

Obs No	I_{rms} (A)	H_m (A/m)	B_r V-s/m^2	H_c (A/m)	B_s V-s/m^2
1	0.8	628.193	4.6805	317.895	6.2046
2	0.7	549.668	4.0563	254.316	5.3045
3	0.6	471.144	3.4323	211.93	4.0564
4	0.5	392.065	2.1842	148.351	3.1203
5	0.4	314.096	1.5601	105.965	2.1842

Thus it has been observed that:
1. The apparent retentivity (Br), apparent coercivity (H_c) and the saturation magnetization (Bs) values for minor loops decrease with the decrease in the magnetic field around the iron sample (Table 1) which is ferromagnetic in nature.
2. The apparent retentivity (Br), apparent coercivity (H_c) and the saturation magnetization (Bs) values for minor loops decrease with the decrease in the magnetic field around the Mn-Zn sample (Table 2) which is ferrimagnetic in nature.
3. The area of the hysteresis loop measures the hysteresis loss of a magnetic sample. The hysteresis graphs show decreases in the size of the loop which are in close agreement with studies carried out by I.C. Heck.

4.6 Conclusion

A simple and low cost B-H loop tracer using IC OP-07 has been developed for measuring apparent coercivity, apparent retentivity and saturation magnetization using minor loops for cylindrical samples up to a magnetic field of 10 Oe. Use of IC OP-07 eliminates the need for any external nulling thereby eliminating requirement of associated cumbersome circuitry. The high loop gain of IC OP-07 is able to amplify even the minute changes in the magnetic flux which is needed for the successful and accurate working of a B-H loop tracer. In conventional B-H loop tracers circuit the all pass filter is employed only at Y-channel but in the present loop tracer the all pass filter has been used also along X-channel providing circuit greater flexibility. Minor hysteresis loops for ferromagnetic (Fe) and ferrimagnetic (Mn-Zn) have been successfully demonstrated and hysteresis loss is found to decrease with the decrease in the current of the solenoid. The introduction of the sample in the pickup coil results in the amplification of the input signals which takes the output of ICOP 07 to saturation in positive as well as negative half cycle resulting in clipping of the output wave form. This clipped output wave form along with the input wave form gives rise to the characteristic hysteresis shape in the X-Y mode of the C.R.O. Further lowering of magnetic field shows formation of the Rayleigh's loop as in this case although there is amplification but the output waveform does not go to saturation level and hence there is no clipping in the output wave form.

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