Implementation of the Ferguson and Stoebe's "Hysteresis Loops and Barkhausen Effects in Magnetic Materials" Experiment

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Abstract

A paper presented at the NEW workshop in 1996 described an interesting and economical experiment where one could obtain the B-H curves for magnetic materials. This paper describes an implementation of this experiment which uses an inexpensive USB-based digital oscilloscope to record the B-H curves which can then be analyzed using spreadsheets. In addition, the circuit boards, mechanical drawings, and parts lists will be available from our web site for anyone who wants to build this equipment themselves.

Keywords:
Magnetism, magnetic materials, hysteresis loops, M-H and B-H curves, magnetization, susceptibility, relative permeability, coercivity

Prerequisite Knowledge:
Magnetic properties of materials, operation of an oscilloscope.

Objective:
The objective of this experiment is to gain a understanding of the magnetic properties of materials by measuring and analyzing the M-H curves of several materials.

Equipment and Materials:
Digital oscilloscope, the B-H meter described in this paper, computer (PC), samples of metals and magnetic materials in the form of 0.25 inch diameter x 1 inch long cylindrical rods.

Introduction:
Materials characterization is an important step in understanding the nature and properties of the material in question. In industry and research fields, characterization of magnetic materials is typically conducted using expensive and highly specialized equipments such as Superconducting Quantum Interference Detector (SQUID), Vibrating Sample Magnetometer (VSM), Alternating Gradient Force Magnetometer (AGFM/AGM) and/or Hysteresis Meter (HM). These instruments, though extremely useful and accurate, are difficult to be incorporated in a classroom/laboratory setting for high school and undergraduate students to understand and

observe magnetic materials and their unique behavior. Hence, in order to allow students to understand the phenomenon of magnetization in magnetic materials, Thomas Stoebe presented a paper at the 1996 NEW-Update in Los Alamos [1] describing a simple experimental setup to observe hysteresis loops of magnetic materials that could be made using parts available at Radio Shack. Ever since this introduction, many have been very interested in implementing this setup in the classroom but the cost of the oscilloscopes and the difficulty of building the circuits have been a primary deterrence.

Our plans were hampered by the cost of oscilloscopes, the difficulty of building the circuits and putting them in a suitable box, and finding a way to record the B-H curves. More recently these problems have been eliminated by companies such as ExpressPCB which provides free software that lets you draw up the circuit and design the circuit board, then send the file in using the Internet. ExpressPCB will make the boards and mail them back in about two days. Also, inexpensive digital oscilloscopes are now available that plug into your PC's USB port, allowing one to monitor the B-H loop and to record it. Once recorded, it should be possible to measure practically every feature of the B-H loop.

Last year the authors built and tested a prototype B-H meter. Since then we have revised and built circuit, put it in a study box, built a fixture that holds the magnet and sense and solenoid coils, and demonstrated its operation. We are building three of these systems for use in class this fall. This paper describes the circuits, the construction of the instrument. Ideas for future experiments are also described.

Background for the Circuit:

The circuit performs two functions, generating an external field in which the sample is placed, and sensing the magnetization of the sample. The external field is generated by passing a current through a field solenoid. The field strength generated is detected using a current sensing circuit and sent to the x-axis input of the oscilloscope. The sensing circuit consists of two balanced (with equal number of turns) coils, wound in opposite directions to cancel out the external field when no sample is present. When a sample is inserted into one of the sense coils, and the sense coils are inserted into the solenoid's field, a net voltage is induced in these coils. This voltage is amplified and integrated before sending to the y-axis input of the oscilloscope. A dual-channel oscilloscope set to the X-Y mode function will display and record the B-H curves.

1. Generation of magnetic fields H using a solenoid

In general, for an air cored coil or solenoid, the magnetic field $\boldsymbol{H}$ is given by

$$H = Ci \tag{1}$$

where $\boldsymbol{i}$ is the current flowing within the coil and $\boldsymbol{C}$ is a coil constant which depends on the position of field measurement, the shape of the coils, and the number of turns in the winding. For an infinite coil with $\boldsymbol{n}$ turns per unit length of coil, the field in the center is given by

$$H = ni. \tag{2}$$

For this simple case the field produced in an air cored coil depends on the current and the number of turns per unit length, ***n***. By knowing the predetermined number of turns for the solenoid coils and measuring the voltage across a fixed resistor (in this case R=1 Ω), the magnetic field is

$$H = \frac{n}{R}V. \tag{3}$$

Therefore, the voltage displayed on the oscilloscope is proportional to the magnetic field generated by the field solenoid.

2. Measurement of magnetic flux B using sensing coils
The sense coils consist of two identical coils except that they are wound in opposite directions. For each coil where ***N*** is the number of turns in the coil and the cross-sectional area of the coil is ***A*****,** the voltage across the ends of the coil, V_{sense} is related to the rate of change of the flux of the external field by

$$V_{sense} = -NA\frac{dB}{dt}. \tag{4}$$

The flux density of the sense coil without a sample inserted is

$$B_{sense1} = \mu_0 H \tag{5}$$

where μ_0 in the permeability of air (μ_0=4πx10^{-7}). On the other hand, the flux density of the sense coil with the sample is

$$B_{sense2} = \mu_0(H+M). \tag{6}$$

Hence, the resultant measurement flux density from combination of both sensing coils will cancel out the effects of the flux density in air leaving a true magnetization loop for the material as

$$B = B_{sense2} - B_{sense1} = \mu_0 M. \tag{7}$$

In order to determine the flux, the voltage signal from the sense coil must be integrated

$$B = \frac{1}{RC}\int\frac{V_{sense}}{NA}dt \tag{8}$$

where ***R*** and ***C*** are the values of the resistor and capacitor used in the integrator circuit.

Description of the Circuit:
The original circuit consisted an integrator that received input from the two balanced sense coils and integrated it, and a current limit and sense circuit for the solenoid coil. The op amps could

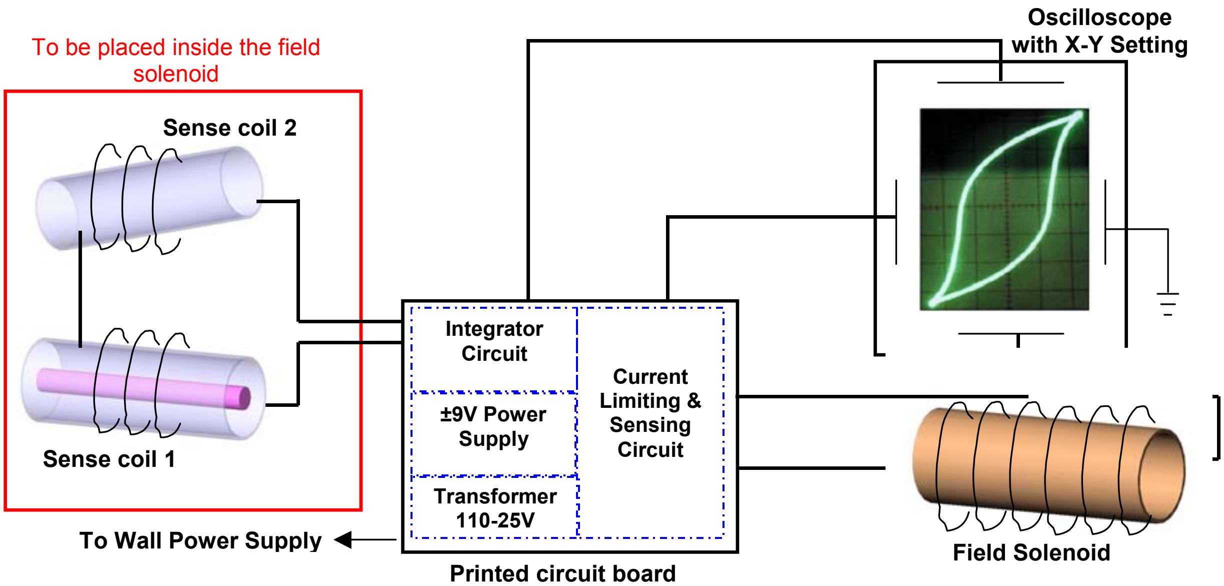


Figure 1. Block diagram showing the main components of the B-H meter.

be powered by two 9 volt batteries and the power for the solenoid coil was provided by a 24 volt transformer whose output current was limited to about 2 amps using four 25 watt resistors.

The authors have added a tracking voltage regulator to provide a balanced ± voltage for the op amps and an difference amplifier that outputs the x-axis signal (current driving the solenoid coil) referenced to ground. In Furgeson and Stobe's original circuit one had to be careful to not short the -leg of this signal to the case, the ground for the oscilloscope, or anything else. All output signals are now referenced to ground. Figure 1 shows a block diagram of this circuit.

Construction of the Instrument:
The circuit was drawn up using ExpressPCB's free software. The main part of the circuit is shown in the appendix. ExpressPCB's free software was also used to design the circuit board. It combines the power supply, sense circuit, integrator, and solenoid coil circuit on a single 6" x 6" double-sided circuit board that fits perfectly into the extruded aluminum box. (This circuit board is shown in appendix.) This file was sent to ExpressPCB via the Internet. A total of four boards were made, shipped, and were received within a week.

After the components were soldered in it, the transformer, connectors, and switches were installed in the aluminum case.

The fixture that holds the magnet, sense coils, and solenoid was made out of plexiglass. This fixture, shown in figure 2, allows the magnet and sense coils to slide into the solenoid. It also provides for safe and reliable electrical connections.

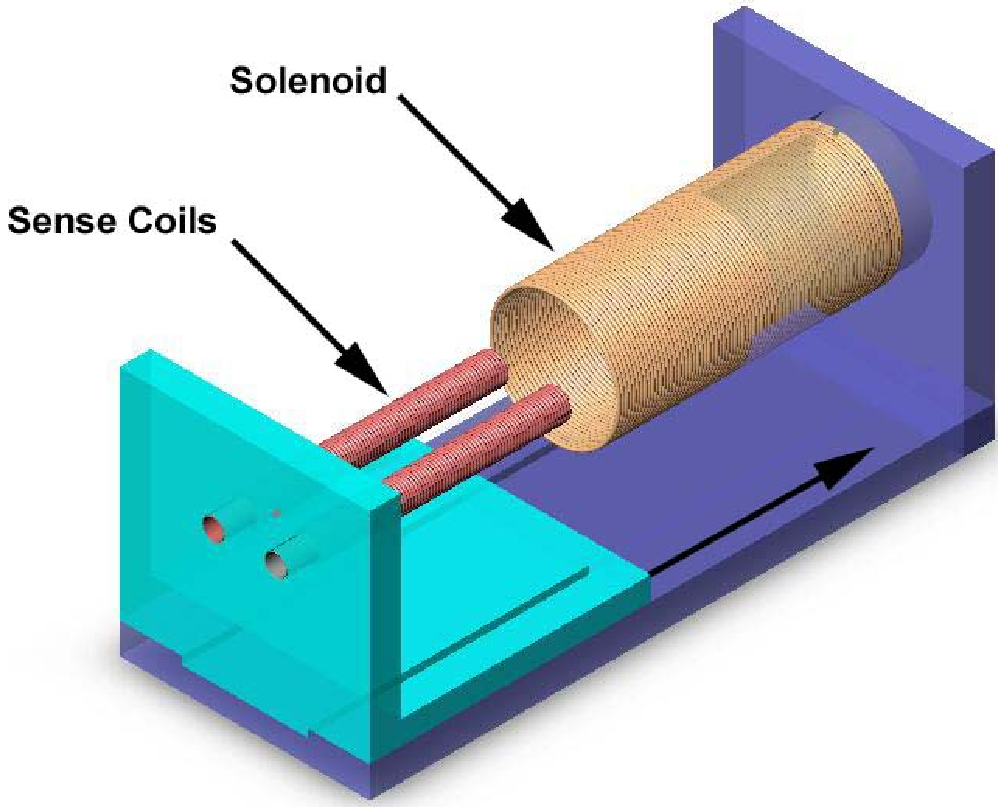


Figure 2. Fixture that holds the balanced sensing coils and solenoid. The sense coils can be slid in and out of the field produced by the solenoid.

Before using this system three adjustments are required. They are:

Balance the power supply: Adjust R2 to obtain the same magnitude in voltage for the + and - legs of the power supply. Monitor pins 4 and 7 of U3, U4, or U5. The tab on U1 is a good place to connect the negative lead of your voltmeter. These voltages may not be equal to ±9 volts, which is OK, but their magnitudes should be equal.

Balance the integrator: Install jumper JP1 and adjust R17 to zero the output of the integrator (pin 6 of U4, or J4). Remove JP1 when done.

Calibrate the x-axis output: Connect the solenoid coil and use an ammeter to measure the solenoid current. Monitor the output of J6 while adjusting R20 to obtain an output voltage equal to the solenoid current.

Procedure:
It is easy to hook everything up. The 2 and 3 connector audio connectors used here make it impossible to connect the electronics to the fixture incorrectly, and the color-coded shrink-wrap

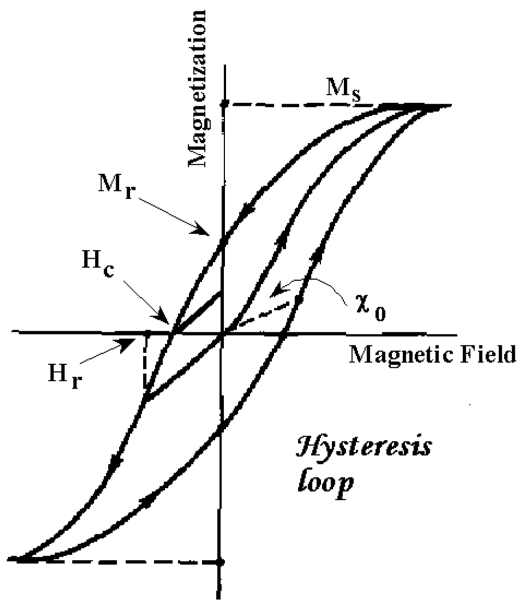


Figure 3. Schematic illustration of a hysteresis loop for magnetic materials. [3]

used on the BNC connectors indicates which one to connect to the x and y axis of the oscilloscope. The oscilloscope must display the M and H signals in X-Y mode.
Place a 0.5" x 1" round bar magnet, iron rod, or other material into the sense coil and slide this into the solenoid. A M-H curve similar to that shown in figure 3 will be displayed on the oscilloscope. By storing about 1 second of data one will have a record of 50 or 60 M-H loops.

Results:
The data can be imported into a spreadsheet and plotted as M versus H for all 50-60 loops, or any one loop, or an average for all loops. One can then obtain the properties shown in figure 4 and listed below:

M_s Saturation magnetization, the maximum magnetic moment.

M_r Remnant magnetization, the magnetization that remains after the external field is removed.

H_c Coercivity, the strength of the magnetic field required to reduce the remnant magnetization to zero.

In addition, one can derive and/or plot the following properties:

Induction magnetization

$$B = \mu_0(H+M) \tag{9}$$

(μ_0 is the permeability of free space)

Relative permeability

$$\mu_r \equiv \frac{\mu}{\mu_0} = \frac{H+M}{H} \qquad (10)$$

(μ is the permeability of the sample)

Susceptibility

$$\kappa = \frac{M}{H} \qquad (11)$$

Mass susceptibility

$$\chi = \frac{\kappa}{\rho} \qquad (12)$$

where ρ is the material's density.

Other properties can also be explored, and much of the above analysis can be done using a B-H curve instead of an M-H curve. In this case, one can plot BH versus H and determine the maximum value for this plot, to measure the hysteresis loss per cycle, a measure of the "hardness" of a magnet.

Discussion:
Preliminary results using last year's prototype looked good but we were unable to digitize the data at that time. A number of the parts for this version are still being fabricated so it was not possible to offer new sample data and an analysis at this time. These will be included in the final paper.

Building this unit was not difficult. Once the parts were found the circuit board was assembled and put in its box in an afternoon. A little machine shop work is required to build the fixtures that hold the coils and to punch the holes in the front and rear panels of the box for the circuit board (www.frontpanelexpress.com can make custom front panels for you.).

Conclusions:
This equipment is now easy to build, is relatively inexpensive, and it works well. It is also easy to use and once built the cost of conducting the experiment is nil. The availability of inexpensive USB-based digital oscilloscopes allows one to record the M-H curve and analyze it to determine a number of properties. This simple system provides a relatively painless way to introduce a magnetic materials experiment into curriculum.

We now have a tool that allows us to investigate the magnetic properties of a number of materials, for example steels with different compositions and different heat treatments, nickel and cobalt alloys, powders, composites, and even nano-materials. For ferromagnetic materials, their magnetic behaviors are functions of temperature and grain size. (The grain size dependence, which is related to the number of domains and the upper limit on the domain size). These factors suggest experiments that allow us to develop demonstrations and experiments that explore the properties-processing-structure theme of materials science and relate to design, materials selection, and even magnetic nanomaterials. Ferguson and Stoebe's paper [1] offered suggestions for several experiments.

A complete parts list, circuit diagram and circuit board, mechanical drawings for the fixtures, can be downloaded from

www.matsci.ucdavis.edu/meier/publications/new2005.htm

This experiment and sample data will be available online at

www.matsci.ucdavis.edu/matscilt/ems-172l/ems-172l

by the time of the workshop in October. A *SAMS* module (Spreadsheet Applications for Materials Science, www.matsci.ucdavis.edu/meier/sams) on this topic is under development.

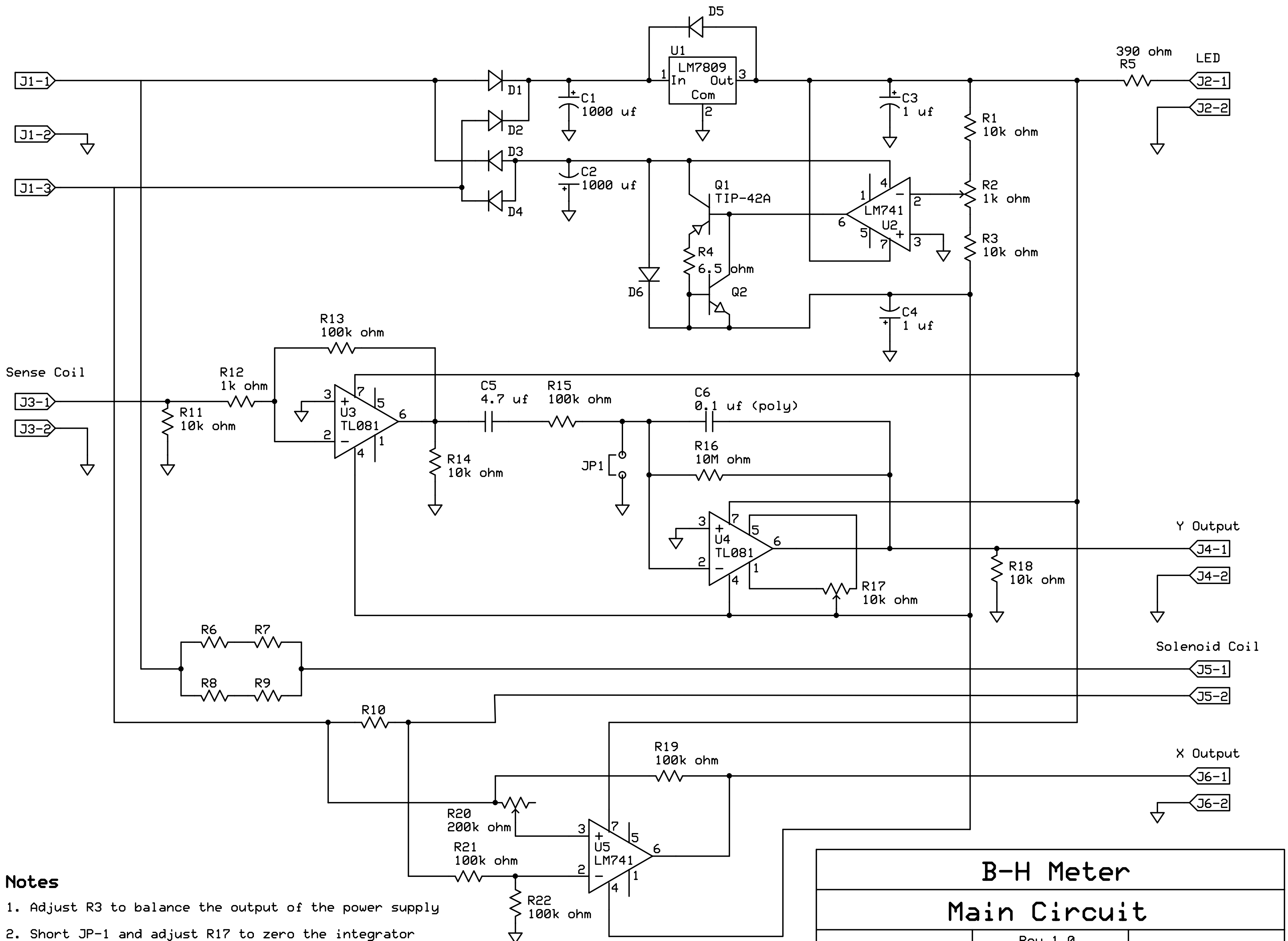
References:
1. L. Furgeson and T. Stoebe, Hysteresis Loops and the Barkhausen Effects in Magnetic Materials, NEW-Update 1996, Los Alamos.
2. Bruce M. Moskowitz, Hitchhiker's Guide to Magnetism, Environmental Magnetism Workshop, June 5-8, 1991 at the Institute for Rock Magnetism. http://www.geo.umn.edu/orgs/irm/hg2m/hg2m_b/hg2m_b.html
3. Bruce M. Moskowitz, Hitchhiker's Guide to Magnetism, Environmental Magnetism Workshop, June 5-8, 1991 at the Institute for Rock Magnetism. http://www.geo.umn.edu/orgs/irm/hg2m/hg2m_index.html

Biography:
Michael L. Meier received his B.S. in Materials Engineering from North Carolina State University in 1979 and his M.S. (1986) and Ph.D. (1991) in Materials Science and Engineering from the University of California, Davis. After a two-year post-doctorate position at the Universität Erlangen-Nürnberg in Erlangen, Germany he returned to UC Davis where he is now the director of Materials Science Central Facilities and is also developing the laboratory teaching program.

M. L. Chan received her B. Eng. and M.Eng degree in Mechanical Engineering from the National University of Singapore, NUS in 2000 and 2002 respectively. After working for two years as a research engineer in the Institute of Materials Research and Engineering, Singapore (IMRE), she is currently pursing her PhD degree in Mechanical and Aeronautical Engineering at the University of California, Davis. Her research interests involve design, modeling and experimental characterization to measure mechanical properties, behavior, motion and forces in MEMS devices for varied applications. Her current research is focused on micromachined magnetic biosensors.

Appendices:

The next two pages show the ExpressPCB software's printouts of the circuit diagram and circuit board (component layout, traces, and silk screen on the top layer).



Notes

1. Adjust R3 to balance the output of the power supply
2. Short JP-1 and adjust R17 to zero the integrator

B-H Meter		
Main Circuit		
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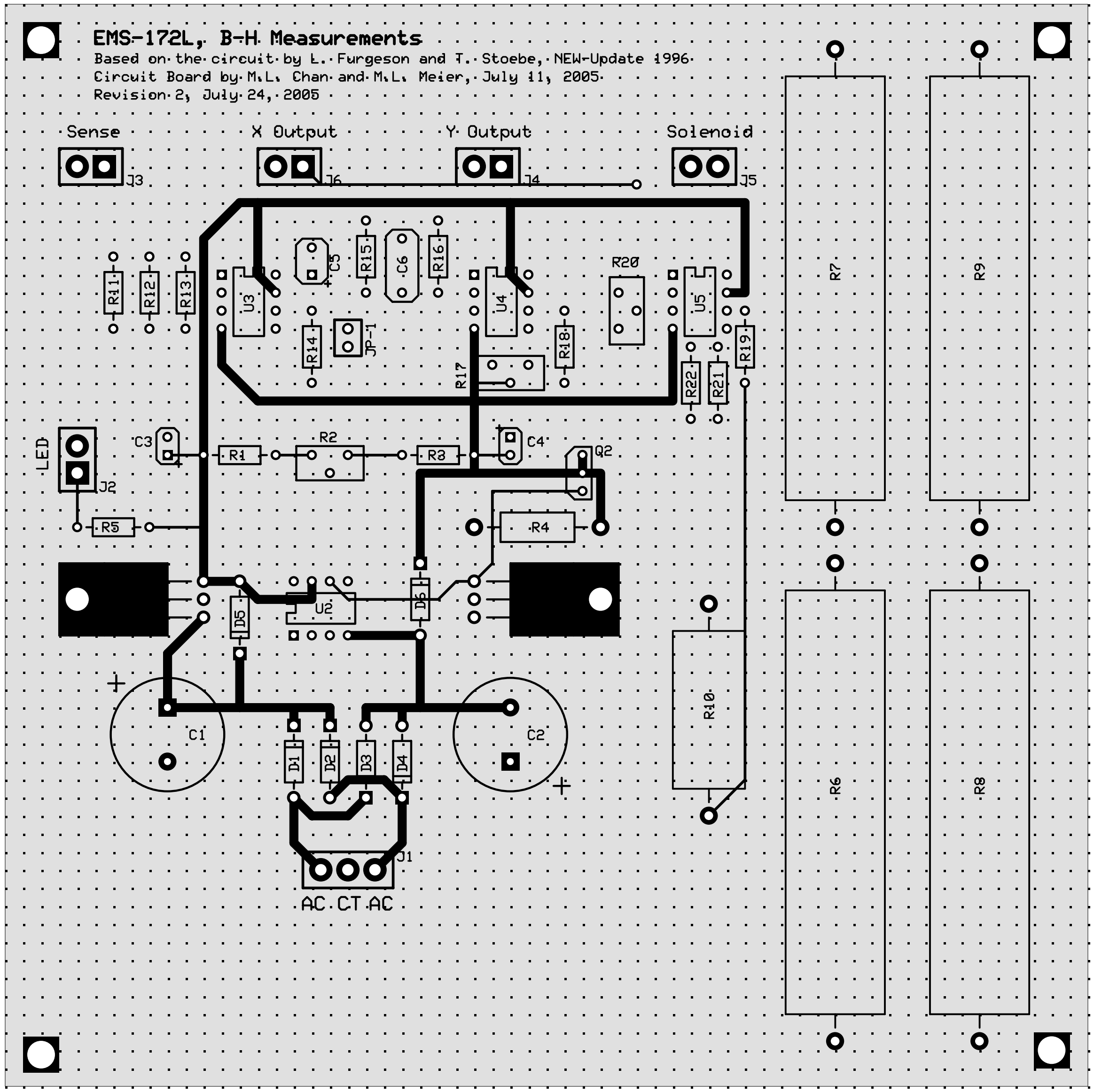

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