STP526-EB/Feb. 1973

D. I. Gordon[1]

Introduction

Historical Development

The use of continuously recording instruments for obtaining magnetization curves and hysteresis loops is becoming more widespread both in research laboratories and in manufacturing quality tests. The number of magnetics research workers and technicians who obtain magnetic materials properties data from point-by-point measurements is dwindling, despite the fact that it is the official ASTM test method.

This reference manual attempts to present a picture of the present state of the art of d-c recording hysteresigraphs. It is not comprehensive, but the five papers presented here describe the better-known approaches to the problem and the particular successful solutions of the authors. Other d-c recording hysteresigraphs have also been devised. Those that have been brought to our attention are listed in the bibliography. A bird's eye view of the historical development and current status follows. No attempt is made to pass judgment on the merits and disadvantages of these instruments. Rather, we would like the papers in this manual and the reference bibliography to speak for themselves and to provide the readers with enough source information to dig deeper and to arrive at their own evaluations for their particular needs.

Haworth's paper [*1*][2] (1931) is probably the first publication on d-c hysteresigraphs. This paper describes the use of a galvanometer with balanced restoring torque by a photoelectric current proportional to the galvanometer displacement. Magnetization curves and hysteresis loops were traced on photographic paper by a beam of light reflected from the mirror of the galvanometer and from a mirror mounted on the movement of an ammeter measuring the magnetizing current.

Edgar [*2*] (1937) described a hysteresigraph using a photocell-galvanometer integrator with a feedback nulling circuit utilizing a mutual inductor. His paper states that discrimination and stability are better than 30 maxwell turns. Output was displayed on an oscillograph with photographic recordings. Dicke [*3*] (1948) described a variation of the above in which an R-C circuit was substituted for the

[1] Naval Ordnance Laboratory, Silver Spring, Md. 20910.

[2] The italic numbers in brackets refer to the list of references appended to this paper.

mutual inductor in the feedback loop.

Cioffi's paper [4] describing his recording fluxmeter of high accuracy and sensitivity was published in 1950. However, he had previously given a talk on the subject at a meeting of the American Physical Society in 1945. Popularly referred to as the Cioffi fluxmeter, his instrument has been copied many times. This instrument was the first precision recording fluxmeter for tracing accurately and rapidly magnetization curves and hysteresis loops directly on standard rectangular coordinate paper to any desired scale for direct reading of the data. During the development of Cioffi's instrument (1940-1950) the X-Y recorder was unknown. In cooperation with Leeds and Northrup an X-Y recorder was developed in 1942 for use with the Cioffi fluxmeter. This X-Y recorder combined two single ordinate scale recorders and subsequently came into use in various measuring instrument systems. Overall error of the Cioffi hysteresigraph can be reduced to 0.2 percent by calibration of the overall system with a precision search coil of certified accuracy and a magnetic field accurately determined by means of a nuclear magnetic resonance magnetometer [33].

Other d-c hysteresigraphs based essentially on the Cioffi system have been described by Paine and Becker [5] (1951), Tebble [34] (1953), Bockemuehl and Sargeant [6] (1960), Callarotti [7] (1966), and Cohen [8] (1968).

Following Dicke's variation of using resistance-capacitance instead of inductance in the feedback loop of the photo-galvanometer are the hysteresigraphs by Brockman and Steneck [9] (1954), Tompkins and Young [10] (1957), and Mygren [11] (1963).

Gall and Watson [12] (1956) described an instrument for automatic recording of hysteresis loops, which employed electromechanical integration of the induced voltage by means of a miniature electric motor having accurate proportionality between its speed of rotation and the applied voltage.

Steingroever [13] (1962) also used an "electromechanical" integrator, comprised of a large d'Arsonval meter containing a sensing coil and a power torque coil. A d-c amplifier, with input in series with the search coil and meter sensing coil, was used to energize the torque coil with sufficient power to drive the meter movement and a potentiometer directly coupled to it. The Weston inductronic fluxmeter [14] (1950-1955) also used a d-c amplifier along with mutual inductance feedback in its integrating channel. The Japanese d-c loop tracer [15] (Yokogawa Electric Works, 1963) uses an integrator which includes a galvanometer nulling system employing a d-c to a-c converter and a balancing motor.

Leaving hysteresigraphs which include galvanometers as part of their integrating channels, we come to the "all-electronic" category. Most popular in this category are: (*a*) the Miller integrator type and (*b*) the voltage to frequency converter/digital counter/digital to analog converter type.

Elarde [16] (1965) described the R-C Miller integrator type and indicated an overall accuracy of ± 0.6 percent for his all-electronic hysteresigraph. Earlier Brownell and Barker [17] (1961) described the use of a Miller integrator in a specially built hysteresigraph, which included means to trace loops at a constant rate of change of flux. Fietz [*18*] (1965) reported the use of Miller type integrators for measuring magnetization of superconductors, with an absolute accuracy of 5 percent. Steingroever [*19*] (1966) described an electronic fluxmeter used in his Permagraph magnet tester. Utilizing a Miller integrator followed by additional amplification, the overall accuracy for B measurements is listed at ± 3 percent.

The "magnemetrics hysteresigraphs" are described in the current paper by Fredrick [*20*]. They utilize Miller integrator with low-drift input circuitry and a solid-state chopper amplifier. Drift is given at less than 100 maxwell turns per minute with overall accuracy better than 1 percent on all ranges. Other Miller type integrator fluxmeters or hysteresigraphs have been described by Copeland et al [*21*] (1965), Mazzetti and Soardo [*22*] (1966), Kubach [*23*] (1966), Hermann [*24*] (1967), and Scholes [*25, 35*] (1968-1970). Kubach's paper is particularly instructive, since it includes a systematic discussion of magnetic measurement concepts, electronic integration, as well as hysteresigraph design.

In the categroy of fluxmeters which integrate through the technique of voltage to frequency (V-F) conversion followed by pulse counting and then digital to analog (D-A) conversion for driving the recorder, is the instrument of DeMott [*26, 36*] (1966, 1970), who estimates maximum error as 0.35 percent and resolution as 5 maxwell turns. Other fluxmeters utilizing the V-F conversion techniques in the integration process have been described by Capptuller [*27, 37*] (1962, 1970), Mouton [*28*] (1964), Argyle and Kwap [*29*] (1966), deSa [*30*] (1966), and McGuire [*31*] (1967).

In brief, the d-c hysteresigraphs developed to date utilize voltage integrators of three general types: (*a*) electromechanical: galvanometers and motors, (*b*) operational amplifier: resistance capacitance, Miller type, and (*c*) voltage to frequency converter.

Detailed descriptions of these types are given in the following papers and a more extensive bibliography is presented at the end of this introduction. The Appendix lists present manufacturers of d-c hysteresigraphs and the instruments they offer.

Definitions

The terms defined are used in this monograph. The definitions concur with those given in ASTM Definitions A340, Terms, Symbols, and Conversion Factors Relating to Magnetic Testing.

Fluxmeter—A device or system used to measure changes in the flux-linkages with a B-coil or a search coil. All fluxmeters contain some form of integrator.

Note—For measuring slowly changing flux linkages, the ballistic galvanometer, if used, must have essentially zero restoring torque and some means of setting the scale reading at zero after the test.

Galvanometer, Ballistic—A sensitive D'Arsonval galvanometer having the appropriate electromechanical constants such that its coil rotation begins only after a current impulse in the galvanometer coil is essentially completed. It gives an ultimate momentary deflection which is proportional to the integrated value $\int e\,dt$ of the volt-seconds of a sudden impulse of voltage induced in a B-coil or a search coil and applied to the galvanometer coil. (See Galvanometer, D'Arsonval.)

Galvanometer, D'Arsonval–A sensitive current-measuring instrument comprised of a rotatable coil suspended in a uniform, radial magnetic field between the poles of a permanent magnet, and provided with an indicator which shows the angular rotation of the coil from its initial (nonenergized) position.

Gaussmeter–Equipment designed to measure the intensity of a magnetic field or the resulting induction, B, in free space. A prefix indicates the type of sensor employed, for example: *rotating coil gaussmeter, Hall effect gaussmeter*, etc.

Hysteresigraph (Magnetic Curve Tracer)–A device or system for plotting graphically, in a continuous sweep, magnetization curves or hysteresis loops, usually on an X-Y recorder. Derivation of the X and Y coordinate values may be by several means. Often the ordinate displacement is driven by the output of a fluxmeter, and the abscissa displacement is driven by a signal proportional to the corresponding H-value.

Integrator, Magnetic–A device or system which determines the time integral of a voltage or current, such as the value of $\int e\, dt$ derived from a change of flux in a B-coil or a search coil.

Magnetometer–A generic term applicable to any equipment used to measure static amounts of induction and magnetic moment in an ambient region by using a suitable form of gaussmeter, a torsion device, or a direct measurement of mechanical force, etc. This term is used specifically for equipment designed to evaluate the magnetic moment of the earth's field at any point.

Permeameter–A term originally used to designate a complete system for determining the d-c magnetic properties of materials, usually in bar or rod form, and now generally limited to the magnetizing means associated with such systems.

Sensor, Magnetic Field–A flux-sensitive element responsible to the magnetostatic induction, B, within a limited region of free space. Examples: *rotating coil sensor, Hall effect sensor, nuclear resonance sensor, second harmonic sensor,* etc.

References

[*1*] Haworth, F.E., "A Magnetic Curve Tracer," *Bell System Technical Journal,* Vol. 10, pp. 20-32.

[2] Edgar, R.F. "A New Photoelectric Hysteresigraph," *Electrical Engineering,* Vol. 56, July 1937, pp. 805-809.

[*3*] Dicke, R.H., "An Electronic Fluxmeter," *Review of Scientific Instruments,* Vol. 19, Aug. 1948, pp. 533-534.

[*4*] Cioffi, P.P., "A Recording Fluxmeter of High Accuracy and Sensitivity," *Review of Scientific Instruments,* Vol. 21, 1950, pp. 624-628; also *Physical Review,* Vol. 67, 1945, p. 200.

[*5*] Paine, T.O. and Becker, J.J., "A Hysteresigraph for D-C Magnetic Measurements," Report RL-517, General Electric Research Laboratory, June 1951.

[*6*] Bockemuehl, R.R. and Sargeant, W.E., "A Practical Hysteresigraph," *Journal of Applied Physics,* Supplement to Vol. 31, May 1960, pp. 180s-182s.

[7] Callarotti, R.C., "Analysis and Design of an Improved Cioffi Integrator," Technical Report 2, Contract NONR 3963-16, Metals Processing Laboratory, Metallurgy Department, Massachusetts Institute of Technology, Cambridge, June 1966.

[*8*] Cohen, P., "A Cioffi Fluxmeter," paper given at conference at Marquette University, Milwaukee, Wis., 1968.

[*9*] Bockman, F.G. and Steneck, W.G., "A New Automatic Hysteresis Curve Recorder," *Philips Technical Review,* Vol. 16, Sept. 1954, pp. 79-87.

[*10*] Tompkins, R.E. and Young, J.D., "New D-C Recording Hysteresigraph," Publication T-91, American Institute of Electrical Engineers, Conference on Magnetism and Magnetic Materials, Boston, Feb. 1957.

[*11*] Mygren, B., "An Integrator with Photocell Amplifier and Its Use for Measurements of Permanent Magnets," in German, *Zeitschrift für Angewandte Physik,* Vol. 17, 1964, p. 255.

[*12*] Gall, D. and Watson, J.D., "Instrument for Automatic Recording of Hysteresis

Loops," *Journal of Scientific Instruments,* Vol. 33, 1956, p. 265.
[13] Steingroever, E., "Fluxmeter with Electronic Amplification (electromechanical)," *Bulletin of ELEKTRO-PHYSIK,* Cologne, West Germany, 1962.
[14] "Inductronic Fluxmeter," Weston Instrument Notes and Catalog, Weston Instrument Co., March 1953.
[15] "D-C Magnetic Hysteresis Loop Tracer," advertisement in *Journal of Applied Physics,* Yokogawa Electric Works, Nov. 1963.
[16] Elarde, P.F., "All Electronic Magnetic Hysteresigraph," *Western Electric Engineer,* Vol. 9, Jan. 1965, pp. 8-14.
[17] Brownell, R.M. and Barker, R.C., "Detailed Measurements of Slow Magnetization of Hysteretic Superconducting Materials," *Communication and Electronics,* No. 56, Sept. 1961, pp. 402-412.
[18] Fietz, W.A., "Electronic Integration Technique for Measuring Magnetization of Hysteretic Superconducting Materials," *Review of Scientific Instruments,* Vol. 36, Nov. 1965, pp. 1621-1626.
[19] Steingroever, E., "Permagraph Magnet Tester with Electronic Fluxmeter," *Bulletin of ELEKTRO-PHYSIK KG,* Cologne, West Germany, 1966.
[20] Fredrick, A.H. in *Direct-Current Magnetic Hysteresigraphs, ASTM STP 526,* American Society for Testing and Materials, 1973, pp. 31-42.
[21] Copeland, J.A., Kuo, C.K., and Schiebner, E.J., "Hysteresis Loop Tracer for Thin Films in Ultrahigh Vacuum," *Review of Scientific Instruments,* Vol. 36, March 1965, pp. 291-294.
[22] Mazzetti, P. and Soardo, P., "Electronic Hysteresigraph Holds dB/dt Constant," *Review of Scientific Instruments,* Vol. 37, May 1966, p. 548.
[23] Kubach, R.W., "A Hysteresigraph for Plotting Magnetization Curves," Technical Report AFML-TR-67-216, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, Dec. 1966.
[24] Hermann, K., "Small Toroid Hysteresigraph," *Instrument and Control Systems,* Vol. 40, Oct. 1967, p. 110.
[25] Scholes, R., "Hysteresigraph for Permanent Magnet Materials," *Journal of Scientific Instruments (Journal of Physical Engineering)* Series 2, Vol. 1, June 1968, pp. 1016-1018.
[26] DeMott, E.G., "Integrating Type of Electronic Hysteresigraph," *Journal of Applied Physics,* Vol. 37, March 1966, pp. 1118-1119.
[27] Capptuller, H. *Zeitschrift* für *Instrumentenkunde,* Vol. 70, 1962, p. 279, in German.
[28] Mouton, G.L. "Magnetic Properties of Rare Earth-Iron Alloys, Chapter III (The Apparatus)," M.S. thesis, Air Force Institute of Technology, Air University, Wright-Patterson Air Force Base, Ohio, GNE-Phys-64-12, Ad 603612, Department of Commerce, Office of Technical Services, Aug. 1964.
[29] Argyle, B.E. and Kwap, T., "Automatic Digital Integrating Magnetometer," IBM Research Note, NC-677, 1967.
[30] deSa, A., "Digital Integration and Recording of Low Frequency Signals," *Journal of Scientific Instruments,* Vol. 43, May 1966.
[31] McGuire, T.R., "Automated Induction Magnetometer, *Journal of Applied Physics,* Vol. 38, March 1967, p. 1299.
[32] Baldwin, J.A., Jr., "A Controlled-Flux Hysteresis Loop Tracer," *Review of Scientific Instruments,* Vol. 41, 1970, p. 468.
[33] Zijlstra, H., *Experimental Methods in Magnetism,* Part 2, (Measurement of Magnetic Quantities), Wiley, New York, 1967, pp. 30-36.
[34] Tebble, R.S., "A Recording Fluxmeter," *Journal of Scientific Instruments,* Vol. 30, 1953, p. 369.
[35] Scholes, R., "Application of Operational Amplifiers to Magnetic Measurements," *Transactions on Magnetics,* Institute of Electrical and Electronics Engineers, Vol. MAG-6, June 1970, pp. 289-291.
[36] DeMott, E.G., "Integrating Fluxmeter with Digital Readout," *Transactions on Magnetics,* Institute of Electrical and Electronics Engineers, Vol. MAG-6, June 1970, pp. 269-271.

[37] Capptuller, H., "Numeric and Graphic Recording of Magnetization Curves by Means of Analog-Digital Techniques," *Transactions on Magnetics*, Institute of Electrical and Electronics Engineers, Vol. MAG-6, June 1970, pp. 263-265.