

Enhancing electromagnetism experiments with clamp-on ammeters

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Experiments designed to illustrate the principles embodied in Ampere's Law and Faraday's Law often depend on the knowledge of the number of turns of wire on various types of laboratory coils. The lack of direct measurement of this parameter can be overcome with the use of inexpensive (<\$85) digital clamp-on ammeters. The meters themselves illustrate the connection between the current enclosed by a closed path and the line integral of the magnetic intensity \mathbf{H} around that contour. In this paper we present laboratory exercises that make essential use of clamp-on ammeters.

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I. INTRODUCTION

One of the weekly experiments that grew out of our department's redevelopment¹ of its third-semester course in electromagnetism centers on quantitative verification of Faraday's law and the Biot-Savart law.² This particular experiment modifies and extends a laboratory experiment developed by Christopher C. Jones.³ We report here some useful enhancements employing clamp-on ammeters.⁴

In the course of the experiment, ac magnetic fields are produced by both Helmholtz-type and planar coils driven by transformers or audio-frequency generators. In these applications the coils generate sinusoidal magnetic fields that pass through small planar pickup or search coils placed at various nearby points. A quantitative analysis to compare the predicted and measured induced EMFs in the search coil requires, among other measurable quantities, a knowledge of the number of turns of wire on both the field and search coils. Since it is usually impractical to count the turns on the coils, students have traditionally relied on values supplied with the apparatus. However, quite good measurements of the number of coil turns can be achieved using a tool familiar to electricians, but not often found in physics labs, the clamp-on ammeter.⁵ Inexpensive (<\$85) digital versions of these meters are available from several sources.⁶ Accuracies of 2%–3% are typical. The fundamentals of these instruments have been nicely explained in papers by Heller, Julian, and Murgatroyd.^{7,8} In the context of the kinds of introductory laboratory experiments and demonstrations described in this paper, the instructor can point out that the instrument's reading is proportional to the line integral of the magnetic intensity $\mathbf{H} = \mathbf{B}/\mu$ around the iron magnetic circuit, which equals the linked current.⁹ We begin with a basic introduction to these meters.

II. OPERATION OF CLAMP-ON AMMETERS

The closed clamp forms a magnetic circuit that comprises the core of an ac current transformer (Fig. 1). The primary current is the net current enclosed by the jaws. The magnetic field lines surrounding the current-carrying conductor(s) are concentrated in the highly permeable ferromagnetic circuit core. The secondary winding lies inside the meter housing, wrapped around the core. The primary current and the secondary voltage are related by the *transfer impedance*,¹⁰ which is a design parameter of the meter, included in its

calibration. If the jaws enclose multiple turns N of a coil carrying a current I , the clamp-on ammeter reading is NI (Fig. 2).

The particular meter used in our labs is the Heathkit Model SM-2374, which is no longer available.¹¹ It was chosen over models from other vendors because of its small cross-section jaws and 200.0-ampere and 1000-ampere (rms) ranges. It also offers standard DMM functions, but these are not used in this experiment. Since these meters are designed to be used at the commercial 50–60 Hz power frequencies, the inherent frequency dependence is not obvious, but should be kept in mind for more general applications.¹² Some clamp-on ammeters are susceptible to interference from non-uniform ac and dc magnetic fields from strong sources, such as the very electromagnets whose current is being measured. It can be important to position the instrument away from such sources, as experience will verify.

III. EXAMPLES OF APPLICATIONS AND LIMITATIONS

We introduce the clamp-on ammeter in the course of several classroom demonstrations of electromagnetism, a few days before the lab experiment involving multiple-turn coils. These demonstrations have been reported in some detail in a previous article,¹³ but one is briefly described here.

The current through the heating element of a transformer-type soldering gun, such as the Weller models, can be directly measured with a clamp-on ammeter. This current is surprisingly high, on the order of half a kiloampere, about a factor of 10 more than most technically trained people guess. The heating tip of the gun may be spread a bit to avoid contact with the jaws of the clamp-on meter, but it is wise to use some insulating rubber tape over them, such as Scotch®

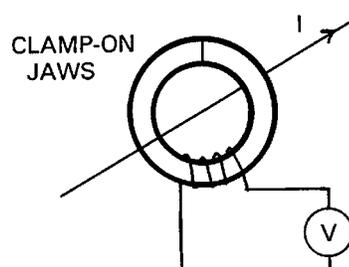


Fig. 1. Clamp-on ammeter as transformer.

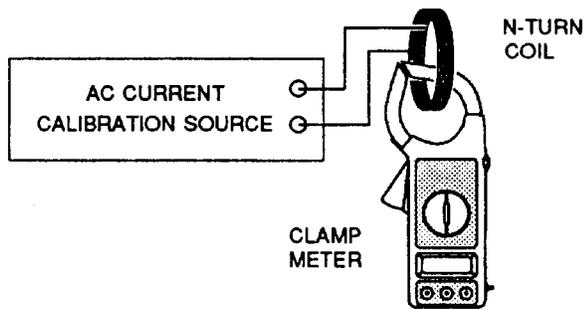


Fig. 2. Application for measuring N for simple coil. (Drawing reproduced by permission of Heathkit® Educational Systems.)

70, to prevent melting. This demonstration gives an opportunity for discussion of transformer basics, as discussed in the *TPT* article.

We will now describe the general experimental tasks involved in the laboratory exercise, with emphasis on the procedures that benefit from the use of the clamp-on ammeter.

The Helmholtz coils from the familiar Sargent-Welch Bainbridge tube e/m experiment [No. 0623] are used as a source of uniform ac magnetic field to calibrate the sensitivity of the small search coils. Students may already have shown through a standard (albeit algebraically involved) textbook problem that both the first and second derivatives of B with respect to axial position are zero at the center of the Helmholtz pair, for which the separation distance equals the coil radius R .¹⁴ The experimental setup is shown in Fig. 3.

The Helmholtz coils are supplied with a current of, say, 1.00 ampere, and the search coil voltage measured for optimal orientation in the center. This is repeated for several more currents, up to about 5 amperes, each time also measuring the ampere-turns value NI recorded by the clamp-on ammeter applied to either coil. The magnetic induction B at the center of the Helmholtz coils may be calculated from Eq. (1)

$$B = \frac{8\mu_0 NI}{\sqrt{125}a}, \quad (1)$$

where N is the number of turns in either coil and a is the mean radius of the coil. The ratio of the two ammeter readings gives a value for N of about 69.5 turns (for models with the structural coil form made from bare aluminum channel). This is some 2.5 turns below the manufacturer's specified (and verifiable) 72 turns. The discrepancy here arises from the induced counter circulating (i.e., eddy) current in the aluminum rings, as expected from Lenz's law.¹⁵ Thus at 60 Hz, the induced circulating currents in the aluminum ring "cancel" about 2.5 of the 72 turns in each coil. This effect increases nearly linearly with frequency and reaches about

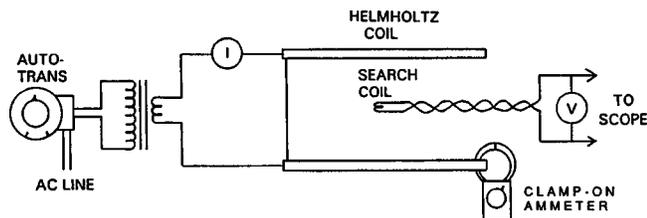


Fig. 3. Experimental setup for calibrating search coil and measuring effective N for Helmholtz coils.

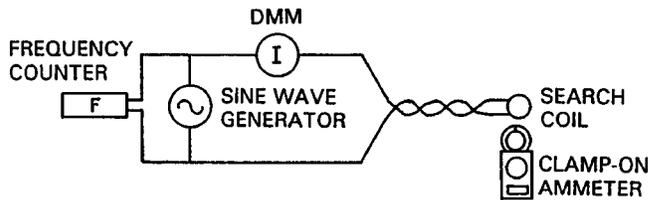


Fig. 4. Circuit for measuring N for search coil.

80% cancellation at 1 kHz, as we reported in a previous paper.¹⁶

It would be possible, in principle, to eliminate the series ammeter to measure the current through the coil system, and use the clamp-on meter for that current, too. This would eliminate a possible source of systematic error due to meter differences. However, the lack of sensitivity and resolution of commercial clamp-on ammeters for sub-ampere currents leads to significant loss of precision by this method.¹⁷

It remains to determine the number of turns in the search coil¹⁸ and the planar field coil. Each lab station is also provided with a sine wave generator, frequency meter, DMM and clamp-on ammeter. The circuit is shown in Fig. 4. Students then supply the search coil with a measured small 60-Hz current (<50 mA) and determine the number of turns in their search coil. A sine wave generator, rather than a combination of autotransformer and step-down transformer is used here to assure that the currents used are well below the burnout value of the fine wire in the search coil. This has the disadvantages of slightly increasing complexity of the circuit, and also introducing a slight "loading effect" when the clamp-on ammeter is applied to the search coil. This latter effect appears as a decrease in the DMM (ammeter) current, but the simultaneous values are still valid. The lower the output impedance of the generator or transformer, the smaller this effect will be.

The planar field coils are local "legacy models," consisting of several hundred turns of 22–28 AWG magnet wire wound as a circular "donut," with mean diameters of 15–18 cm. Their turn numbers are also measured using the arrangement shown in Fig. 4, except that as much current as the generator can supply (without distortion) may be safely used.

Before proceeding, the students use the measured number of turns and search coil dimensions to predict the sensitivity of the search coil from Faraday's Law.

The students next take various measurements of the magnitude and direction of \mathbf{B} at the center and points around the field coil, using the arrangement shown in Fig. 5.

The combination of field coil and search coil suggests itself as a transformer, and the students are asked to explain why the measured voltage ratio is so much lower than the turns ratio (poor flux linking).

The experiment concludes with a rough measurement of the magnetic susceptibility of steel, and aluminum or copper rods. The search and field coils are made co-planar and rods of ferromagnetic and nonferromagnetic metals are inserted

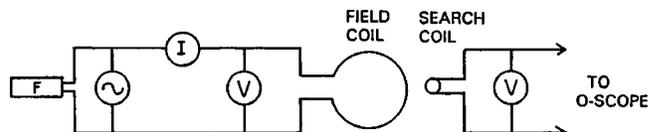


Fig. 5. Circuit for measuring \mathbf{B} from field coil.

inside the inner coil and the induced emfs measured with and without the rods. Rod diameters are measured and students carry out an analysis based on Faraday's Law to determine the magnetic susceptibility of each rod under these conditions. (We mention but do not compensate for some systematic problems with this method, such as the variable mutual inductance between the coils, and possible eddy currents in the rods.)

IV. CONCLUSION

This lab brings a lot of electromagnetism together in situations that are the standard cases developed in the lecture course. Ampere's law, the Biot-Savart results for coils, and Faraday's law (as applied to sinusoidal fields) all receive roughly equal attention. The addition of the clamp-on ammeter technique for measuring the number of turns in the various coils removes the last experimental quantity from the category of "given by the instructor." Phenomena such as flux multiplication, eddy currents, Lenz's law, and inductive loading can be quantitatively explored or observed in context. Students become familiar with the clamp-on ammeter as a measuring tool, as well as other test equipment, and the Helmholtz coils that will be used for e/m measurements in a following lab course.

¹"Microcomputer Interfaced Experiments in Introductory Physics Laboratories," NSF-ILI Grant No. USE-9050491. 1990-92. Co-PIs S. H. Mellema and C. F. Niederriter.

²Copy available by request to dchenry@gustavus.edu.

³C. C. Jones, "Faraday's Law apparatus for the freshman laboratory," *Am. J. Phys.* **55**, 1148-1150 (1987).

⁴D. C. Henry and C. F. Niederriter, "Enhancing Electromagnetism Experiments with Clamp-On Ammeters," Summer AAPT Meeting, Boise State University, July 27, 1993.

⁵For examples of the clamp-on ammeter used for measuring electrical appliance energy consumption in a high school physics course see "Encouraging energy saving with a clamp-on ammeter," by Lawrence Ruby, *Phys. Teach.* **32**, 510-511 (1994).

⁶Manufacturers include Fluke Instruments, Radio Shack, Tektronix, B&K Instruments, and others.

⁷P. Heller, "Analog demonstrations of Ampere's law and magnetic flux,"

Am. J. Phys. **60**, 17-25 (1992); Erratum *ibid.* **60**, 274 (1992).

⁸1995 AAPT Summer Meeting [AAPT Announcer, July 1995, 69, abstract CE6].

⁹The theory of these instruments can profitably be recalled during a following course in electromagnetic theory, as an example of the Reciprocity Theorem. The theory and application of "pure" (i.e., no iron) air-core solenoids ("Rogowski coils") have been presented by Heller *et al.* in the previous reference. See also A. G. Klein, "On demonstrations of Ampere's law," *Am. J. Phys.* **61**, 1045 (1993).

¹⁰The transfer impedance is operationally defined as the ratio of the induced voltage to the enclosed current.

¹¹An identical meter is available under other labels from the following suppliers: Tenma No. 72-645 from MCM Electronics, 650 Congress Park Drive, Centerville, OH 45459-6959 (800-543-4330); CE Model DM-260T from Alfa Electronics, P. O. Box 8089, Princeton, NJ 08543-8089 (800-526-2532).

¹²Clamp-on ammeters for dc currents are also available, but they use Hall-effect sensors, and are both more expensive and less directly applicable in the experiments cited here. It is, however, nice to have one around for dc current situations.

¹³D. C. Henry and S. A. Danielson, "Experiments and demonstrations with soldering guns," *Phys. Teach.* **31**, 42-46 (1993).

¹⁴R. A. Serway, *Physics for Scientists and Engineers*, 4th ed. (Saunders, Philadelphia, 1996), Chap. 30, Problem 71, p. 900.

¹⁵Useful insight into the phase relationships among the applied field, induced emf, eddy current, and consequent magnetic field comes through analogy to the familiar levitating ring demonstration, as analyzed by Mak and Young [*Am. J. Phys.* **54**, 808-811 (1986)]. We have experimentally verified that the eddy currents in the Helmholtz ring are primarily limited by these self-induction effects, and not the ring's resistance. We are grateful to one reviewer for calling our attention to this paper, which clarifies the physics of both pieces of equipment.

¹⁶D. C. Henry and J. Kavanaugh, "Audio frequency characteristics of the Sargent-Welch Helmholtz coil," Summer AAPT Meeting, University of British Columbia, June 29, 1991. We again acknowledge the insightful suggestions of Professor Duane Olson during our study.

¹⁷Clamp-on probe attachments for connection to a DMM are available from some manufacturers (e.g., Fluke), and these offer sufficient sensitivity and resolution for both applications.

¹⁸The search coils are in the form of a bobbin made from a 1-cm length of plastic water pipe [hardware store 1 in. type], around which a collar has been cut on a lathe. Between 350 and 550 turns of No. 32 copper magnet wire are wound around this collar, and then the wire ends soldered to twisted-pair hook-up wire terminated in banana plugs. The bobbin and wire connections are epoxied at the end of a wooden dowel rod.

NOETHER'S THEOREM

It is not difficult to teach Noether's theorem, for there are some beautiful and intuitive ideas behind it. I have explained it every time I have taught introductory physics, but no textbook at this level mentions it. Without it, one does not really understand why riding a bicycle is safe.

Lee Smolin, *Physics World*, October, 1999, p. 13.