Measuring the axial magnetic field of a thin coil

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A remarkably precise laboratory verification of the functional behavior of the magnetic field along the axis of a thin coil can be made with the apparatus described here and shown in Fig. 1.

The coil consists of 30 turns of #22 enameled copper wire, wound on a Lucite form 40 cm in diameter. The dimensions or number of turns are not critical; any thin coil of approximately these specifications would be suitable, for example, one of the coils typically used in the Helmholtz pair of an E&M experiment.

The coil is driven with a 10-V rms sine-wave generator, at a frequency $f \approx 5$ kHz, generating an ac magnetic field $B(t)$ at its center given as a function of time t by

$$B(t) = B_0 \sin(2\pi f t), \tag{1}$$

where

$$B_0 = (\mu_0 I N)/(2R), \tag{2}$$

with R being the coil radius, I the coil current, N the number of turns, and $\mu_0 = 4\pi \times 10^{-7}$ hy/m the permeability of free space.

A meter stick is attached with one end just below the center of the coil, as shown in Fig. 1. A probe containing a small 32-turn field-sensing coil of about 1.2-cm diameter is mounted on the meter stick, and is capable of sliding along its entire length. An ac voltage $V(t)$ is induced in the small coil by the time-varying magnetic field at the location of the probe coil. The amplitude of $V(t)$ is proportional to the amplitude of $B(t)$.

At this point, the probe coil could be directly connected to the vertical input of an oscilloscope, but it was found that a better signal-noise ratio could be obtained by first pre-amplifying the probe signal with a simple battery-powered 741 operational amplifier with a gain of about 100.[1] The gain of the amplifier was adjusted so that its output was about 0.5-V rms when the probe coil was at the center of the large coil.

The output of the pre-amp was now fed to an oscilloscope, and simultaneously to an ac digital voltmeter. (It is not necessary to use both instruments; the DVM was used in this study for greater precision than could be obtained with the oscilloscope alone.)

When the probe coil is moved a distance x away from the center of the large coil along the meter stick, the amplitude of the magnetic field drops from B_0 to a new value $B(x)$, given by

$$B(x) = (\mu_0 I N R^2)/2(R^2 + x^2)^{3/2} \tag{3}$$

or

$$B_0/B(x) = V_0/V(x) = (1 + x^2/R^2)^{3/2}, \tag{4}$$

where $V_0/V(x)$ is the ratio of the oscilloscope (and DVM) voltage amplitude reading at the center of the large coil to the reading at position x.

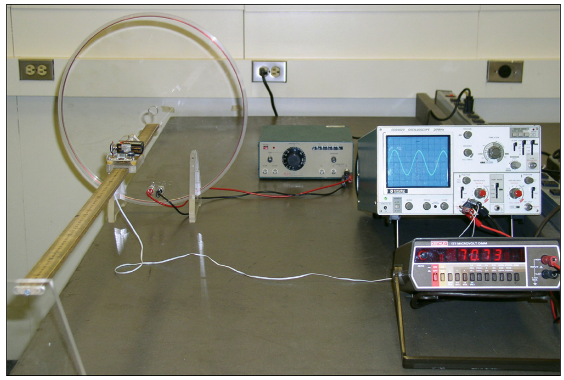

Fig. 1. Overall view of apparatus. See text for description.

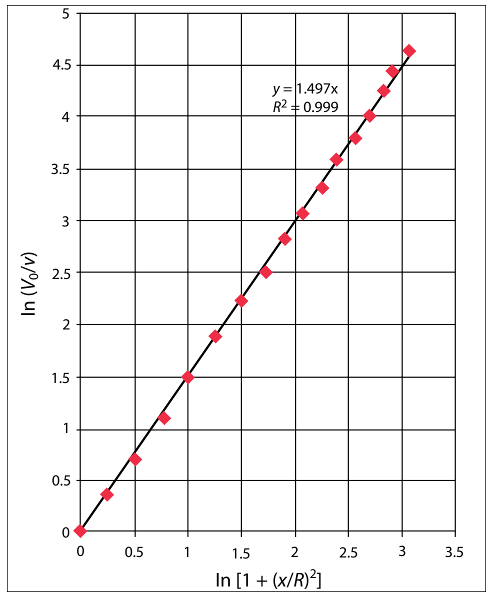

Fig. 2. Plot of the log of the sensing coil voltage ratio, ln $[V_0/V(x)]$ as a function of ln $[(1 + x^2/R^2)]$, where x is the axial distance from the center of the large coil and R is the large coil radius. The uncertainty in the slope is a fraction of a percent.

A plot of ln $[V_0/V(x)]$ versus ln $[(1 + x^2/R^2)]$ is shown in Fig. 2. If Eq. (4) is correct, the slope of this plot should be 3/2, and indeed the experimental data verify this to within a fraction of a percent. If only oscilloscope data are used, verification to within a few percent is possible with careful work.

Conclusion

The apparatus described here has been used for some years in a lab for an elementary course in electricity and magnetism. It provides students with an impressively accurate verification of a non-trivial application of the law of Biot and Savart.

Reference

1. Contact the author for a schematic of the op-amp circuit.

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