

The Traceable Measurement of Magnetic Dipole Moment and the Calibration of Commercial Magnetometers

Michael Hall, Jon Bartholomew, Stuart Harmon and Lesley Henderson

**National Physical Laboratory, Centre for Electromagnetic and Time Metrology,
Queens Road, Teddington, Middlesex, TW11 0LW**

1 Abstract

The measurement of the magnetic properties of materials is covered by the International Electrotechnical Committee 404 series of written standards. These standards mainly deal with the measurement of properties using closed magnetic circuit. Closed refers to the use of a magnetic yoke of high permeability to carry the flux of the test specimen from one end to the other. Commercial magnetometers are available that introduce air gaps since the test specimen needs to be moved relative to detection coils. Here is an example of an open magnetic circuit. For this arrangement complex geometrical corrections are required. An important open circuit parameter is the magnetic dipole moment. In this paper the measurement of magnetic dipole moment is discussed. A method using a Helmholtz coil will be presented which provides a measurement uncertainty of $\pm 0.1\%$. Test specimens calibrated in this way can then be used to calibrate commercial magnetometers.

2 Introduction

The magnetic properties of ferromagnetic materials can be determined in accordance with written IEC standards. These standards are concerned with the determination of properties using closed magnetic circuits provided by systems such as electromagnets. Suitably calibrated instrumentation is required for the measurement of magnetic flux density, B , and applied magnetic field strength, H . While the written standards provide the measurement method, care must be taken when establishing the magnetic circuit since many unwanted contributions are possible.

The properties determined using these methods are intrinsic and are used to classify and specify material properties. The magnetic properties of a component can be estimated using intrinsic properties by applying a demagnetisation correction. Because the calculation of the required demagnetising factors is only possible within certain limits, this process is not always applicable and is always prone to large errors. A better approach is to measure a related parameter such as magnetic dipole moment.

If the magnetic materials being considered have an appreciable remanence then the magnetic dipole moment can be measured without the need for a magnetising circuit. An example is the working point of a permanent magnet. The working point magnetic polarisation is the value obtained from the intrinsic hysteresis curve when the magnetic field is equal in sign and magnitude to the demagnetising field. The magnetic dipole moment is the product of this magnetic polarization and volume. In the following sections a method that can be used to measure this magnetic dipole moment with low uncertainty is presented.

3 Methods of measurement

Three methods for the measurement of the magnetic dipole moment are:

1. Torsional pendulum method in which the dipole moment is oscillated in a known magnetic field;
2. Magnetic flux density at a distance measured using sensitive fluxgate magnetometers;
3. An electrical method in which the magnetic flux of the dipole moment is detected using a Helmholtz coil and from this the magnetic dipole moment calculated.

The last of these methods is discussed in detail since it provides the lowest measurement uncertainty. When the instrumentation used in method (3) is calibrated individually an uncertainty in the measurement of magnetic dipole moment of 0.1 % is possible. By calibrating reference standards using this traceable approach, it is possible to calibrate commercial systems to a low uncertainty.

4 Helmholtz coil method

4.1 Principles

Helmholtz coils consist of two nominally identical coils placed coaxially and separated by a distance equal to their radius. With the coils connected in series and a current flowing, a magnetic field is produced at the centre with a value of

$$H = \frac{5\sqrt{5}}{8} \frac{NI}{r} \quad (1)$$

Where H is the magnetic field strength in A/m;

N is the number of turns per coil;

I is the current in A;

r is the coil radius and coil separation in m.

A property of this coil arrangement is that the magnetic field is uniform in the central region. An important parameter for such a coil is the ratio of magnetic field strength to current, H/I , which is known as the coil constant. From equation (1) this parameter depends on the physical properties of the coil and the change in this ratio along the axis of the coils is given by the equation

$$\frac{H}{I} = \left(\frac{H}{I} \right)_0 \left(1 - \frac{144}{125} \frac{x^4}{r^4} + \dots \right) \quad (2)$$

Where the subscript 0 refers to the value at the centre,

x is the distance from the centre and

r the coil radius.

In equation (2) higher order terms have been neglected.

From a plot of the relationship shown in equation (2), it is found that the coil ratio H/I is uniform to 1% along the coil axis for a distance equal to 0.543 the coil radius. The variation of the coil constant across the central plane parallel to the coils is smaller.

Because of this good H/I uniformity, Helmholtz coils used in reverse to detect magnetic flux changes are suitable for measuring magnetic dipole moment. The open access to this uniform region further aids the measurement through ease of test specimen alignment. It is possible however to use other coil systems, such as solenoids, for measuring magnetic dipole moment.

To calculate a magnetic dipole moment from a change in flux determined using Helmholtz coils it is necessary to integrate the far field over the turns of the coils. See reference [1] for details. The change in flux, ΔJ , resulting from removing the magnetic dipole moment is given by

$$\Delta\vartheta = m \times \frac{H}{I} \quad (3)$$

Where m is the magnetic dipole moment in Wbm and H/I the coil constant in A/m/A.

Rearranging equation (3)

$$m = \Delta\vartheta \times \frac{I}{H} \quad (4)$$

Using Helmholtz coils it is therefore possible to measure a magnetic dipole moment by measuring the change in flux when the moment is removed from the coil. When removing the moment from the coil care must be taken to ensure that the moment no longer couples with the Helmholtz coils. This can be achieved by removing the moment to a suitably large distance. A more convenient approach is to rotate the moment in the coils about an axis that produces a change in signal. This also doubles the detected signal. For this rotation method the calculation of magnetic dipole moment from the measured flux change is

$$m = \frac{\Delta\vartheta}{2} \times \frac{I}{H} \quad (5)$$

4.2 Measurement uncertainty

Three methods for measuring magnetic dipole moment have been introduced. For these methods the uncertainty has been evaluated in accordance with M 3003 [2] and for the torsional pendulum measurement estimated to be $\pm 1.5\%$, for the field at a distance method $\pm 2.7\%$ and for the Helmholtz coil method $\pm 0.1\%$.

5 Calibration of commercial systems

Several manufacturers provide the instrumentation needed for the Helmholtz coil method of measuring magnetic dipole moment. Since the commercial systems are used in situations where high throughput is necessary, it is not convenient to maintain the individual instrument calibrations. In this case, the moment measurement setup is calibrated as a system. To achieve this, a reference moment is needed with the magnetic dipole moment calibrated. To obtain as low a calibration uncertainty as possible the uncertainty of the reference dipole moment must be low and the approach given above should be used. This includes using a Helmholtz coil system with suitable dimensions to limit any contribution due to non-uniform H/I to the overall measurement uncertainty.

Commercial systems such as Vibrating Sample Magnetometers (VSM) measure magnetic dipole moment using detection coils. This involves coupling the detection coils to the external magnetic field of the test specimen. A geometrical contribution to this coupling therefore exists and the calibration of the system can be performed using calibrated test specimens of the appropriate geometry. If these test specimens have a remanent magnetisation the Helmholtz coil method described above can be used. It is hoped that systems for measuring magnetic dipole moments corresponding to mass susceptibilities as low as $1 \times 10^{-8} \text{ m}^3/\text{kg}$ will be established at

NPL. With these systems, specific test specimen dimensions can be calibrated and these in turn used to calibrate magnetometers.

6 Conclusions

Magnetic dipole moment is a quantity that provides useful information about component properties. The measurement of magnetic dipole moment with a low uncertainty is therefore required. Three methods have been introduced and the uncertainty for each presented. The method using a Helmholtz coil to determine the magnetic dipole moment can provide a measurement uncertainty of $\pm 0.1\%$ at a confidence level of approximately 95%. A calibrated reference with this uncertainty provides an excellent basis for the calibration of commercial systems.

7 References

1. Trout, S.R., *Use of Helmholtz Coils for Magnetic Measurements*, IEE Trans. Mag. Vol. 24, No. 4, July 1988.
2. UKAS document M 3003, Edition 1, December 1997.