The Use and Calibration of Magnetometers for Measuring Magnetic Properties

Author/Speaker: Michael Hall
National Physical Laboratory
Queens Road, Teddington, UK
Tel: +44 20 8943 7189
Fax: +44 20 8614 0493
Email: michael.hall@npl.co.uk

Abstract

A magnetic quantity frequently measured by commercial systems is the magnetic moment. From this the required material properties are determined by applying geometrical corrections. Because magnetic moment is the product of magnetization and volume, the range to be covered is considerable. The magnetometers available for measuring magnetic moment specialise on a limited part of this range. To provide comprehensive traceability a system is being established at NPL that is capable of measuring magnetic moments from 10^{-9} Am^2 to 20 Am^2. The measurement technique used provides the necessary flexibility and transparency. The details of the method will be presented and calibration issues relating to the measurement discussed. The determination of the required material properties will be presented. This includes the use of a novel magnetic material with specially engineered properties.

1. Magnetic quantities

When discussing the magnetic properties of weakly magnetic materials two parameters are used interchangeably. To avoid confusion the relationship between them is stated here. The value of the magnetic susceptibility of a material is obtained from the relative magnetic permeability by subtracting one. A material with a relative magnetic permeability of 1.003 has a volume susceptibility of 0.003. A further parameter that is frequently used is the mass susceptibility and this is obtained from the volume susceptibility by dividing by the material density. Where appropriate the parameter being used is indicated in the text.

When no yoke is used to carry the magnetic flux of a test specimen, the flux returns from one end to the other in the surrounding air. These are the familiar lines of flux observed when iron particles are sprinkled on paper placed over a permanent magnet. In addition to this non-uniform magnetic field in the space surrounding the material, the magnetisation inside can also be non-uniform. This is due to the demagnetising field that passes internally from one end of the test specimen to the other. For this open circuit arrangement the magnetic field at any position inside the test specimen will depend on the dimensions of the test specimen.

Due to this demagnetisation the magnetic polarisation of the material is different in the open and closed circuit arrangement. In the case of permanent magnets, the material exhibits its so-called ‘working point’ properties in an open circuit. One related parameter of importance is the magnetic moment and the methods that can be used to measure this quantity will be discussed.

Another magnetic measurement that is essentially performed in an open circuit configuration is the measurement of the relative magnetic permeability of feebly magnetic materials. At NPL a calibration service is offered in accordance with British Standard 5884 1999 [1]. This is technically equivalent to ASTM A 342/A 342M - 99. In these methods a test specimen with a ratio of length to lateral dimension of 10 is required so that the correction due to demagnetisation can be calculated and applied. Since the permeability is low the magnetic polarization generated in an applied magnetic field is also small. For example, material with a volume magnetic susceptibility of 0.005 in an applied magnetic field of 100 kA/m has a magnetic polarization of 0.6 mT. This compares to the magnetic field of the earth of 0.5 mT. To obtain a reasonable magnetic flux to measure with a search coil the cross sectional area of the material needs to be large. Considering the NPL system a circular cross section of diameter 40 mm can be used. The length of the test specimen therefore needs to be around 400 mm to achieve the required length to lateral dimension ratio. Clearly a large amount of material is required to measure the relative magnetic permeability using this method. In situations where a large quantity of material is not available an alternative measurement method is needed. The key requirement of any such measurement technique is that it offers sensitivity well above that of this existing method and that the technique is traceable to SI units. For the measurement system to be traceable all aspects of the measurement of magnetic susceptibility must be shown to be traceable.

A further important aspect of the standard measurement is that a magnetic field of tens of kA/m is required to produce a detectable level of magnetic flux. Low relative magnetic permeability is important in situations where the presence of the material must not introduce significant additional magnetic fields. One example is the use of materials in military situations where magnetic detection techniques are used. In these situations the magnetic susceptibility of the material is required in an applied magnetic field equivalent to that of the Earth. Since the Earth’s magnetic field is typically 80 A/m, this is 1,250 times smaller than the field given in the example above. Clearly, at this level of magnetic field the existing method for determining the susceptibility is not suitable.

For commercial magnetometers that are specified for low magnetic moment measurement, establishing traceability is difficult because of the measurement principle used. In these systems detection coils are used to determine the magnetic moment. Introduced above was the dependence of the magnetic flux in the space surrounding a test specimen on the geometry of that test specimen. The determination of the magnetic moment using a commercial magnetometer therefore requires a coupling coefficient that will depend on the geometry of the test specimen. This situation is further complicated when an electromagnet is used to magnetise the test specimen since the presence of the high permeability material distorts the distribution of the magnetic flux in a complex way.

The systems being developed at NPL will allow measurements for a range of geometries and applied magnetic field strengths that are traceable to representations of the SI units held at NPL, UK. The techniques used will also allow the calibration of test specimens that can be used as standards for calibrating commercial magnetometers. Since various geometries are possible, the calibration of a test specimen with specific dimensions is possible and this can then be used to calibrate commercial magnetometers.

2. Measurement of the magnetic moment of ferromagnetic material specimens

Three methods that can be used to measure a permanent magnetic moment are:

(i) Torsional pendulum method in which the moment is oscillated in a known magnetic field;
(ii) Magnetic flux density at a distance measured using a sensitive calibrated fluxgate magnetometers;
(iii) An electrical method in which the magnetic flux of the moment is detected and from this the magnetic moment calculated.

The last of these methods is discussed in detail since it provides the lowest measurement uncertainty. When the instrumentation used in method (iii) is calibrated individually an uncertainty in the measurement of magnetic 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.

2.1. Helmholtz coils method

Magnetic moment is an open circuit parameter. A magnetic field exists in the space surrounding the moment and it is possible to determine the magnetic moment by measuring the magnetic flux using a search coil.

A search coil could be placed directly on the surface at the geometrical centre of a permanent magnet moment and the magnetic flux linking the coil measured. However, It is difficult to avoid flux returning from the magnet ends through the space between the coil and the specimen surface. In addition, the detected flux depends crucially on the position of the coil along the magnet length. The magnetic field close to a magnetic moment depends on the moment dimensions, which can be difficult to determine for certain geometries and magnetization states. In the far field regime the magnitude of the magnetic field of a magnetic moment is given by equations (1), radial component, and (2), tangential component, and is independent of the moment dimensions. In these equations α is the angle between the magnetic moment and the field direction. A search coil placed in this field region measures a flux change when the moment is removed or reversed which depends on the magnetic moment. Positioning of the magnetic moment for this arrangement would still be significant. Using two nominally identical search coils with the magnetic moment in the middle relaxes the positioning requirement.

$$H_r = \frac{\mu_0}{4\pi}\frac{2m\cos\alpha}{x^3} \tag{1}$$

$$H_{\varphi} = \frac{\mu_0}{4\pi} \frac{m \sin\alpha}{x^3} \qquad (2)$$

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

$$H = \frac{5\sqrt{5}}{8} \frac{NI}{r} \qquad (3)$$

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 (3) 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

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

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 (4) higher order terms have been neglected.

Equation 4 is plotted in figure 1. In this figure, the y-axis is normalised to the central value and the x-axis is the distance along the coil axis normalised to the coil radius.

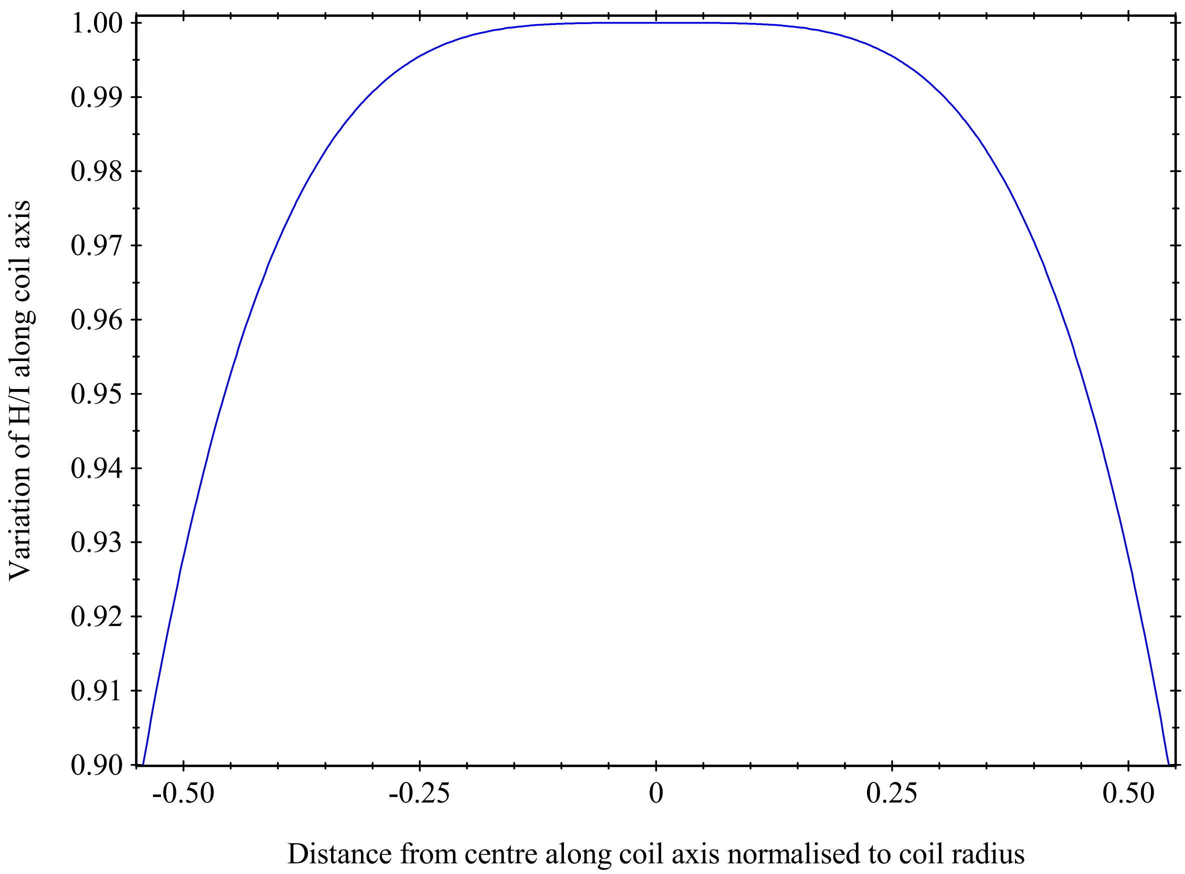

Figure 1. On axis coil constant profile for Helmholtz coils.

From the figure, it can be concluded 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 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 moment.

To calculate a magnetic 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 [2] for details. The change in flux, $\Delta\vartheta$, resulting from removing the magnetic moment is given by

$$\Delta\vartheta = m \times \frac{H}{I} \tag{5}$$

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

Rearranging equation (5)

$$m = \Delta\vartheta \times \frac{I}{H} \qquad (6)$$

Using Helmholtz coils it is therefore possible to measure a magnetic moment by measuring the change in flux when the moment is removed from the coil. When removing the moment from the coil care must to 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 moment from the measured flux change is

$$m = \frac{\Delta\vartheta}{2} \times \frac{I}{H} \qquad (7)$$

3. NPL traceable susceptometer

The Helmholtz coil method described in 2.1 is limited to ferrous materials because if no magnetising circuit is available only test specimens with permanent magnetic moments can be measured. To measure low magnetic moments generated in an external magnetic field a traceable system is being established at NPL based on the force experienced by the magnetic moment in a magnetic field gradient.

A magnetic moment m in a magnetic field gradient experiences a force given by [4,5]

$$F = m_s \times \frac{dB}{dz} \qquad (8)$$

where m_s is the magnetic moment in Am^2 and dB/dz is the magnetic field gradient in T/m. The force F in measured in Newtons.

As can be seen from equation (8) the following is required to determine the value of the magnetic moment.

1) Traceable measurement of force
2) A known magnetic field gradient

When a permanent magnetic moment does not occur, an applied magnetic field is needed to generate a magnetization and the following equation is used to obtain the magnetic moment:

$$F = m\chi_m H \frac{dB}{dz} \qquad (9)$$

where m is the mass of the test specimen in kg, χ_m the mass susceptibility in m^3/kg, H the applied magnetic field in A/m and dB/dz the magnetic field gradient in T/m.

An alternative way of expressing equation (10) is:

$$F = V\,\kappa H \frac{dB}{dz} \qquad (10)$$

where V is the volume of the test specimen in m^3 and κ is the volume susceptibility and is dimensionless.

4. Calibration of traceable low magnetic moment system

4.1 Field gradient details

Referring to equation (8), and using a microbalance to determine the force on the test specimen when the magnetic field is applied, it is clear that the range of magnetic field gradient required depends on the magnetic moment. For equation (9) the mass of the test specimen and the mass susceptibility determine the required gradient. For both cases a large range of gradient is required. To achieve these two approaches will be used.

(i) Generating the magnetic fields using a coil system of known coil constants; and

(ii) Generating the magnetic fields using an electromagnet.

To determine the magnetic field gradient a calibrated moment coil is used. The required magnetic moment will be generated using a coil of similar dimensions to that of the test specimens to be measured. The principle is that a known current is passed through the coil and the product of this current with the total turns area of the coil is the magnetic moment. The turns area required for this cannot be determined from the dimensions of the coil with sufficient accuracy. An electrical measurement based on the Helmholtz coil method discussed above will be used to determine the effective cross sectional area of the coil.

4.2 Material requirements for establishing susceptibility traceability

For the corrections applied for demagnetization [6] to have a low uncertainty, the material used should have a low ferromagnetic content. This results in a susceptibility that does not change considerably with magnetic field strength. However, to establish the traceability of the NPL system, susceptibility values of actual materials that exhibit this response are required. To achieve this NPL has developed permeability standards that have significantly improved properties over conventional materials. This is demonstrated in figure 2.

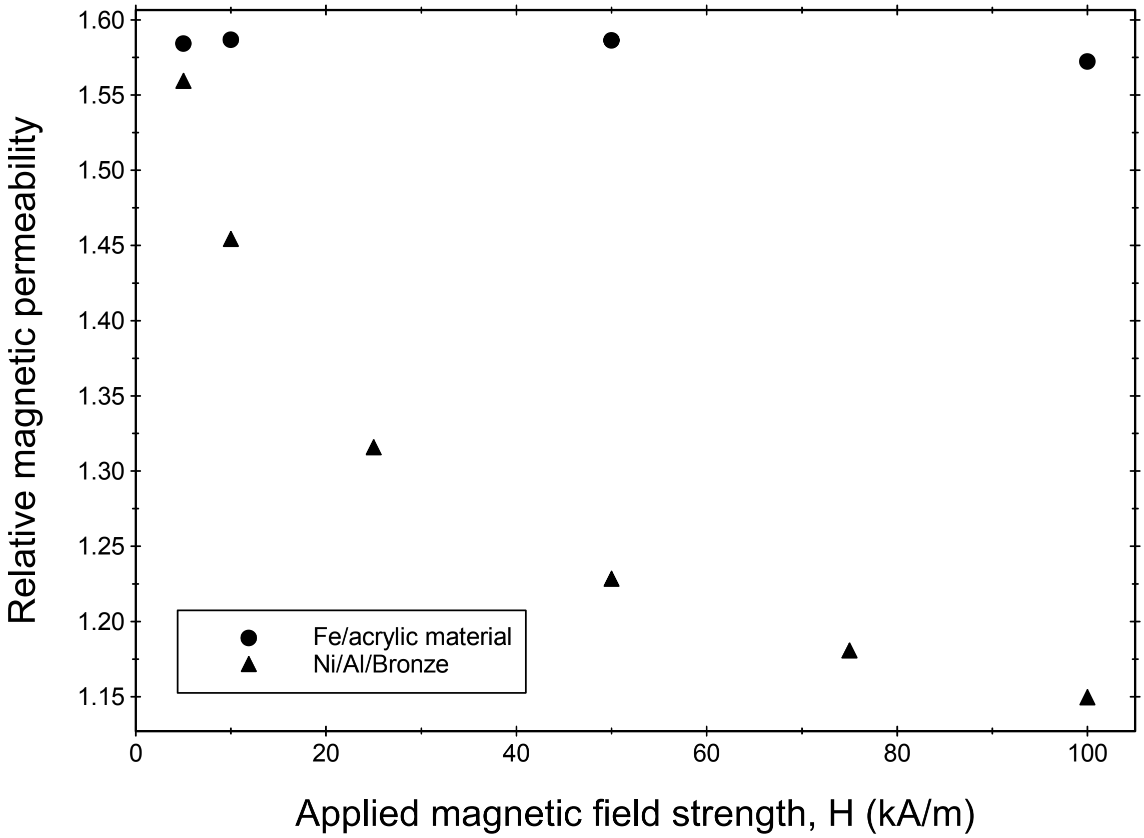

Figure 2. Improved behaviour of permeability standards for NPL low moment system calibration.

5. Conclusions

NPL is establishing a system for measuring low magnetic moment that will enable commercial systems that offer this capability the required traceability. With magnetic materials being used in many critical applications the traceable measurement of magnetic properties is crucial. With this system the scope of materials that can be measured is large since magnetic moment depends on the material volume. Because of this, artifacts from thin films to items weighing 100 g can be measured.

A method for measuring the magnetic moment of ferrous materials with an uncertainty of 0.1 % is established and uses Helmholtz coils. The measurement of this quantity will provide the traceability for the low magnetic moment system. When an applied magnetic field is required to generate the magnetic moment the measurement principle is to determine the force experienced when the test specimen is placed in a known field gradient. It is therefore necessary to know the value of the field gradient, and suitable methods have been introduced. To determine the performance of the system, materials that exhibit the ideal properties will be used.

The output of this research will be a traceable system for measuring low magnetic moment and reference materials calibrated in this system will be available for the calibration of commercial magnetometers.

Acknowledgements

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References

1. BS 5884, Methods for the determination of the relative magnetic permeability of feebly magnetic material, 1999.
2. S.R. Trout, Use of Helmholtz Coils for Magnetic Measurements, IEE Trans. Mag. Vol. 24, No. 4, July 1988.
3. M. J. Hall, A. E. Drake, S. A. C. Harmon, C. I. Ager, Low permeability reference standards with improved high magnetic field strength performance. IEE Proc. Sci. Meas. Technol., 1998, 145, (4), pp 181-183.
4. R.H. Martin and G.J. Hill, Journal of Scientific Instruments (Journal of Physics E), Series 2 Volume 1, 1257 – 1259, 1962.
5. R.S. Davis, Meas. Sci. Technol., 141 – 147 1993.
6. R. I. Joseph, Ballistic demagnetising factor in uniformly magnetized cylinders. J App Phys, 1966, Vol. 37 No. 13, pp 4639-4643.