

Notes on Magnetic Measurements

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ABSTRACT

These notes have been produced as an introduction to traceable magnetic measurements of the type carried out at the National Physical Laboratory and other magnetics standards laboratories. Outlines are given of the main principles of measurement with references to publications giving more definitive procedures and methods. An attempt has been made to explain the magnetic units in common usage, to cover the bases of magnetic measurements and traceability to fundamental quantities and to set out the principle measurement techniques for the calibration of magnetic instrumentation and materials.

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1 INTRODUCTION

Magnetism and electricity are inextricably interrelated. On a macroscopic scale, a magnetic field is produced by an electric current flowing in a conductor; on a microscopic scale the motion of electrons and nuclei give an atom its characteristic magnetic properties. On the other hand, if a conductor is moved in a magnetic field, an emf is generated in the conductor. It is a sobering thought that without these electromagnetic effects alternating current could not be generated and distributed so easily.

To the uninitiated, magnetic measurements seem to be shrouded in mystery. It is apparent that confusion exists in understanding the fundamental definitions and units. This is not at all surprising since there has been a proliferation of unit systems and these have affected the field of magnetism perhaps more than any other branch of physics. Even in the two main unit systems, CGS and SI, there have been changes; the situation is summarised in the following table:-

Quantity	CGS unit		SI unit	
	1900-1932	1933-1953	1954-1959	1960-1986
magnetic field strength, H	gauss	oersted	ampere/metre	ampere/metre
magnetic flux density, B and magnetic polarization, J	gauss	gauss	weber/metre ²	tesla
magnetic constant, μ_0	1	1	henry/metre	henry/metre
magnetic flux,	maxwell	maxwell	weber	weber

Note: In geomagnetism, the unit "gamma" is used. In the CGS system 1 gamma is equivalent to 10⁻⁵ oersted, however in SI units it is deemed to be 1 nanotesla.

In the International System of Units (SI) used throughout this Report, magnetic units depend upon the fundamental units of length (metre), mass (kilogram), time (second) and upon the definition of the ampere, based upon Ampere's law for the force between two current carrying conductors:-

"If two straight parallel conductors a distance d apart carry currents I₁ and I₂ the force, F, between them per unit length in rationalised units is given by:-

$$F = \mu_0 I_1 I_2 / 2\pi d \tag{1}$$

where μ_0 is a constant called the magnetic constant (permeability of free space)".

From the definition of the ampere, the value of the magnetic constant (permeability of free space) in SI units is:-

$$\mu_0 = 4\pi \times 10^{-7} \quad (\text{henry/metre}) \tag{2}$$

The definition of magnetic flux density (magnetic induction), B, is related to the force exerted on a current carrying conductor in a magnetic field, normal to the direction of that field.

If the current is I , the force, F , per unit length is the vector product of B and I :-

$$F = B \times I \quad (\text{newton metre}) \quad (3)$$

The dimensional equation gives:-

$$N/m = [B] A \quad (4)$$

$$[B] = \frac{\text{newton}}{\text{amp.metre}} = \frac{\text{watt.second}}{\text{amp.metre}^2} = \frac{\text{volt.second}}{\text{metre}^2} = \frac{\text{weber}}{\text{metre}^2} = \text{tesla} \quad (5)$$

The magnetic field strength (magnetic field, magnetizing force), H , can be defined in free space by the expression:-

$$B = \mu_0 H \quad (6)$$

that is, H is the magnetic vector quantity at a point in a magnetic field which measures the ability of electric currents or magnetized bodies to produce a magnetic flux density at that point. The dimensional equation gives:-

$$[H] = T/Hm^{-1} \quad (7)$$

$$[H] = \frac{\text{volt.second}}{\text{metre}^2} / \frac{\text{volt.second}}{\text{ampere.metre}} = \frac{\text{ampere}}{\text{metre}} \quad (8)$$

2 FUNDAMENTAL MEASUREMENTS

Traceable measurements of magnetic field strengths and magnetic flux densities may be achieved by the use of standard search coils, solenoids, Helmholtz coils or through the use of nuclear magnetic resonance (NMR).

2.1 STANDARD SEARCH COIL

A search coil can be used in conjunction with an electronic charge integrator to measure magnetic flux densities; either the magnetic field strength is changed or the search coil moved into or out of the magnetic field so that the resulting change in the magnetic flux produces an emf in the coil. A search coil of calculable effective area can be produced by winding a single layer coil on a stable non-conducting, non-magnetic former. A set of very stable coils have been produced at the National Physical Laboratory (NPL) by winding bare copper wire under tension on fused silica formers, there being a space between turns to provide the necessary insulation. The dimensions of the former and wire were measured with an optical micrometer (to avoid crushing the wire) from which the effective area was calculated with an uncertainty of $\pm 0.02\%$. Secondary standard search coils are often fabricated using insulated wire wound on a former of resin bonded cloth, in which case it should be possible to achieve an uncertainty of $\pm 0.2\%$.

2.2 SOLENOIDS

The magnetic field strength, H , at the centre of an infinitely long solenoid uniformly wound with N turns per metre through which a current I flows is given by:-

$$H = N.I \text{ (A/m)} \quad (9)$$

In practice a useful standard solenoid can be constructed from a length of non-conducting, non-magnetic tube on which a single or multilayer winding is uniformly wound. To produce a region at the centre with reasonable uniformity of magnetic field strength, the length to diameter ratio of the solenoid should be at least 10:1. The magnetic field strength to current constant for the solenoid can either be calculated or determined using a standard search coil and the mutual inductance bridge shown in figure 1.

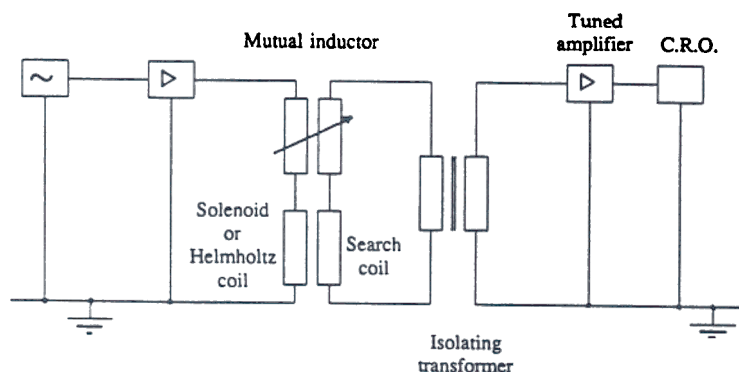


Figure 1. Mutual inductance comparison bridge

The bridge is energised with a low frequency (12 Hz) supply in order to avoid effects of the capacitance in the inductor windings. The mutual inductance, M , between the search coil (of effective area AN) and the solenoid is balanced by the variable mutual inductor and the magnetic field strength to current constant, H/I , is given by:-

$$H/I = M/NA \quad (\text{A/m/A})$$

The same bridge can be used to intercompare a standard search coil with one of unknown effective area.

2.3 HELMHOLTZ COILS

Another useful standard coil system is a pair of Helmholtz coils. These are made up from two identical circular coils each of N turns, again wound on non-conducting, non-magnetic formers, of approximately 300 mm in diameter. The winding is in a groove in the circumference and for maximum uniformity in the central region, the coils are set at a distance apart equal to the mean radius of the winding. The magnetic field strength to current ratio is then given by:-

$$H/I = 8N / 5\sqrt{5}a \quad (\text{A/m/A})$$

This type of coil system is useful for the calibration of transverse probes and search coils having a long handle since they can be accommodated in the space between the two field generating coils. The magnetic field strength to current constant can be determined using a standard search coil and mutual inductance bridge as described above. Where necessary, corrections for the variation of magnetic field strength over the volume used in a Helmholtz coil system should be applied. Calculations and formulae to facilitate the determination of these corrections have been produced by Vigoureux^{1,2}.

Another application, usually with coils of much larger dimensions, is in the cancellation of the earth's magnetic field; three pairs of coils mounted mutually at right angles to each other and having individual current control are used. Such a system forms the basis of the low magnetic field measurement facility at NPL. The precise calibration of the large (3 metre diameter) Helmholtz coils, where the uniformity of the magnetic field strength is of the order of 1 part in 10^4 over the working volume, is achieved by passing a measured current through the coils and determining the resulting magnetic field strength with a free precession proton magnetometer.

Special Helmholtz coils have been developed by Drake, Rollett and Ager³ for use at frequencies up to 120 kHz for the calibration of antenna coils and magnetic field strength measuring instruments used for electromagnetic compatibility measurements.

2.4 NUCLEAR MAGNETIC RESONANCE

Nuclear magnetic resonance (NMR), or magnetic spin resonance as it is sometimes now called to avoid the sensitive word "nuclear", depends upon the phenomenon that a proton spinning about its axis creates a magnetic field, since it carries an electric charge. This field interacts with a steady applied magnetic field causing the magnetic nucleus to precess. This is analogous to a gyroscope or toy spinning top which has been deflected from its vertical axis whilst spinning, giving rise to a secondary, lower frequency, circular motion which we call precession.

An NMR probe is placed in a uniform magnetic field and a high frequency alternating magnetic field, of low amplitude, is applied at right angles to the steady field. An absorption of power occurs in the circuit providing this field when the frequency is adjusted to be equal to that of the precession of the nuclei. This resonance occurs at a frequency known as the Larmor precession frequency, ω_0 . For a nucleus of gyromagnetic ratio γ , the value of the steady magnetic field strength, H_0 , in which it is placed, is given by:-

$$H_0 = B_0 / \mu_0 = \omega_0 / \gamma \mu_0 \quad (\text{A/m}) \quad (12)$$

The resonance is sharp requiring both a steady and uniform magnetic field. The uncertainty in the measurement of the strength of a magnetic field by NMR is governed by the measurement of the frequency, the uniformity of the magnetic field and the value of the gyromagnetic ratio of the proton. In theory the latter is the limiting factor as it is known only to about 2 parts in 10^7 . In practice it is difficult to obtain a magnetic field of uniformity better than 1 in 10^5 over the volume of the active portion of the probe.

The probe of a typical NMR magnetometer comprises a sample of aqueous lithium sulphate, contained in a small sealed sample tube on which a coil is wound. The coil is energised at a high frequency (MHz) from a source, remote from the probe to avoid interaction with the uniform field in which the probe is placed. The frequency is varied until resonance is observed and the magnetic field strength is determined from the measured value of the resonant frequency using equation 12. NMR detection circuits have been described by Robinson⁴ and Faulkner and Holman⁵.

A schematic arrangement of the system required to observe NMR is given in figure 2.

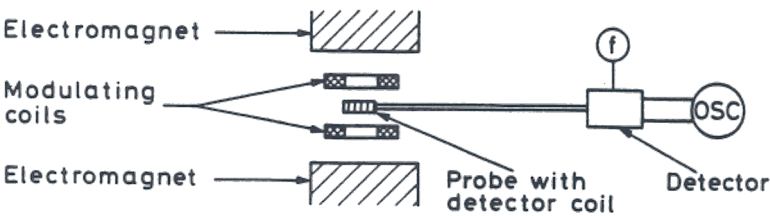


Figure 2. Schematic arrangement of an NMR magnetometer

The magnetic field to be measured is swept at a low frequency using a separate modulating coil mounted around the sample such that the axis of the modulating magnetic field is orthogonal to that of the steady magnetic field. A signal from the modulating circuit is applied to the X plates of a cathode ray oscilloscope and the trace is adjusted to be symmetrical about the centre of the screen. The output from the resonance detection circuit is connected to the Y plates. The frequency of the high frequency source is slowly varied until resonance is observed. At first two peaks may be visible; these can be caused to coincide by adjusting the phase of the modulating signal connected to the oscilloscope. The frequency of the hf source is then fine tuned to bring the resonance peak to the centre of the screen. The steady magnetic field strength is then proportional to this value of frequency.

3 MAGNETIC MEASURING INSTRUMENTS

3.1 ELECTRONIC CHARGE INTEGRATORS

A typical electronic charge integrator is shown on figure 3. It consists of a high open loop gain (10^7) or more operational amplified with capacitive feedback and resistive input. The value of the input resistor R should be high compared with that of the search coil ($10\text{ k}\Omega$ is a typical value). The value of the feedback capacitor is chosen to give a reasonable time constant; typically C is in the range $0.1\mu\text{F}$ to $1\mu\text{F}$. If the amplifier gain is large then the output voltage, e_o , is given by:-

$$e_o = -(1/RC) \int e_i dt = -(1/RC).AN/\Delta B \quad (V) \quad (13)$$

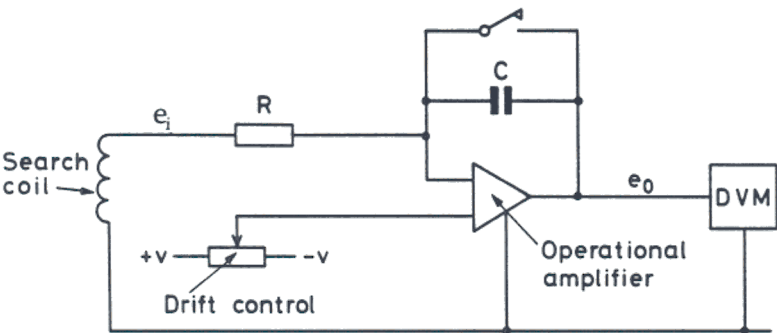


Figure 3. A typical electronic charge integrator

In practice, consideration must be given to the insulation resistance of the feedback capacitor and any parallel circuits, to thermal and stray pick-up emfs arising in the input circuit and to changes in the input offset current of the operational amplifier. A voltage can be injected into the amplifier input to counteract the latter effect.

Electronic charge integrators may be calibrated in one of several ways:-

- a) by connecting the input to the secondary of a mutual inductor of known value and making a measured change in the primary current to produce an emf. If the product of mutual inductance (in henries) and current (in amperes) is made equal to the product of the effective area, AN , of the search coil (in square metres) and the magnetic flux density, B , (in tesla) then the integrator can be made direct reading since:-

$$e_i dt \propto -\Delta B \cdot AN = -\mu_0 H \cdot AN = M \cdot I \quad (14)$$

- b) by charging a capacitor of known value up to a known voltage and then discharging into the input of the integrator, then:-

$$e_i dt \propto CV$$

- c) by connecting a linear ramp generator to the input of the integrator for a measured period of time then:-

$$e_i \propto t \cdot dv/dt$$

An uncertainty of $\pm 0.1\%$ can be achieved for magnetic flux measurements using an electronic charge integrator.

3.2 FLUXMETERS

A fluxmeter is a form of galvanometer in which the torsional control is very small and heavy damping is produced by currents induced in the coil by its motion. Fluxmeters consist of a rectangular coil of wire held between the poles of a permanent magnet either by a fine unspun silk fibre suspension or, in the case of more robust instruments, supported by jewelled bearings. Connection between the terminals and coil of the fluxmeter is made through thin spirals of strip silver, copper or gold.

Assuming that the torsional control is negligible and no air damping exists then the fluxmeter receives an impulse and the coil moves through an angle independent of the rate of change of the magnetic flux. In practice there is a very small torsional control and some air damping; these cause the pointer to drift slowly towards zero after the maximum deflection has been attained. In the case of Grassot fluxmeters the resistance of the external circuit should be kept below 10 ohms and for one type of light spot fluxmeter it is essential that the resistance of the external circuit is exactly 30 ohms to maintain the marked calibration.

Fluxmeters can be calibrated in a similar way to electronic charge integrators. The uncertainty in magnetic flux measurements is of the order of $\pm 1\%$ to $\pm 2\%$ being limited by the resolution of the scale.

3.3 HALL EFFECT GAUSSMETERS

Although these devices are called gaussmeters they are often used for measuring magnetic field strengths.

When a magnetic field is applied in a direction at right angles to the current flowing in a conductor (or semiconductor) then an emf is produced across the conductor in a direction mutually perpendicular to the current and applied magnetic field. This is called the Hall effect. It is the Lorentz force acting on the moving charges which deflect them at right angles to the direction of their motion. A typical Hall effect gaussmeter is shown in figure 4. It comprises a Hall effect probe connected by a flexible cable to a control unit housing the

current supply and Hall voltage detection unit.

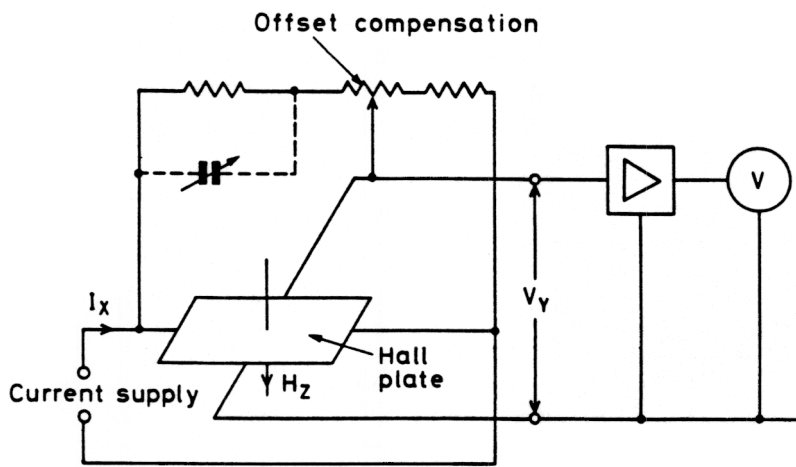


Figure 4. A Hall effect gaussmeter

For a sensitive Hall probe the material should be thin and have a large Hall coefficient. It has been found that the semiconducting materials indium arsenide and indium antimonide are particularly suitable for Hall probes. The output voltage is given by:-

$$V_y = K_H I_x \mu_o H_z / t_z \quad (V) \tag{17}$$

- where
- V_y is the Hall output voltage (V)
 - K_H is the Hall coefficient (V/TA) (about 0.75 V/TA for indium arsenide)
 - I_x is the current through Hall element (A)
 - μ_o is the magnetic constant (H/m)
 - H_z is the value of the magnetic field strength being measured (A/m)
 - t_z is the thickness of Hall element material (m)

Due to the small size of the Hall element (usually of the order of 2 mm square) it is difficult to align the voltage contacts exactly opposite each other. It is therefore necessary to employ a compensating circuit comprising a resistive divider connected as shown (with the addition of a variable capacitor if ac excitation is used). A small voltage is injected to counteract the IR drop produced by the current flowing in the region between the two voltage contacts. Hall probes are temperature dependent (about 0.05% per °C for indium arsenide) so that they are often compensated by the addition of a suitable thermistor.

Hall effect gaussmeters may be calibrated at low magnetic field strengths by mounting the probe in a long solenoid, or pair of Helmholtz coils, for which the field to current ratio has been determined. At higher magnetic field strengths the probe can be mounted in the gap of an electromagnet and the magnetic field strength determined by an NMR system. The uncertainty in magnetic field strength or magnetic flux density measurements using Hall effect gaussmeters is in the range $\pm 0.1\%$ to $\pm 2\%$ depending upon the type of instrument and method of calibration.

3.4 FLUXGATE MAGNETOMETER

These instruments are usually used for the measurement of low magnetic field strengths, of the order of the earth's magnetic field and below. They have a range of approximately 1 mT down to 100 pT.

A simple fluxgate magnetometer is shown in figure 5. It consists of a wire of high magnetic permeability material (eg mumetal or permalloy) at the centre of a solenoid. An alternating

current flowing through the solenoid produces a magnetic field which interacts with the axial component of the ambient dc magnetic field to be measured. The magnetic flux density induced in the wire varies non-symmetrically about the origin of the hysteresis loop and the resultant emf induced in a second solenoid superimposed on the first contains a second harmonic component. A direct current is passed through this second solenoid and adjusted until the magnetic field so created opposes the ambient magnetic field. This condition is detected by a phase sensitive detector connected to the second solenoid.

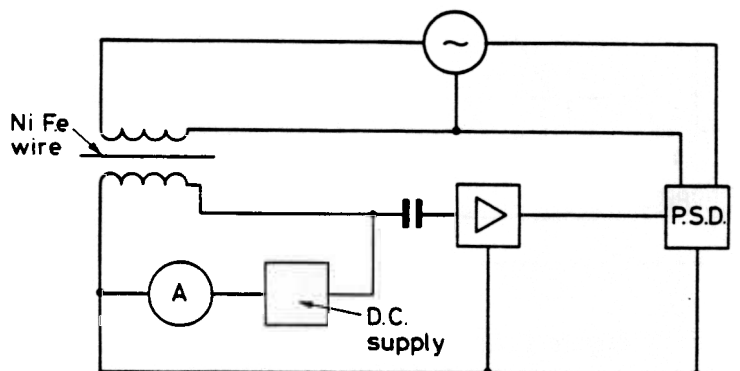


Figure 5. A fluxgate magnetometer

From the field to current ratio for the solenoid, the value of the magnetic field strength, H , can be found from the direct current flowing when the magnetic ambient field is exactly opposed. The uncertainty in the measurement of H is about $\pm 0.5\%$.

3.5 ROTATING COIL GAUSSMETER

As its name implies this device depends upon a calibrated coil rotating in a magnetic field. The output is connected via a system of slip rings to a sensitive voltmeter calibrated directly in magnetic field strength or magnetic flux density units. The system is described by Lush⁶ and has an uncertainty in the range 0.01% to 1% depending upon the calibration of the effective area of the search coil. By interchanging search coils, measurements can be made over a very wide range (1 μT to 10 T). However for low values of magnetic field strength the search coil tends to be very bulky.

3.6 SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE (SQUID)

Devised by Zimmerman et al⁷ for magnetic flux measurements, the SQUID depends upon the interaction of the magnetic flux with a 'weak link' in a superconducting loop. The weak link is in fact a Josephson junction not unlike that used as a quantum voltage standard. This link responds to flux quanta which have a magnitude of 10^{-14} weber. By means of a suitable phase control system a sensitivity of 10^{-18} weber can be achieved. To measure magnetic flux densities the effective area of the loop threaded by the magnetic flux has to be determined. Not only does the loop have small dimensions but, in use, it is normally immersed in liquid helium at a temperature of 4 K making it difficult to determine the precise dimensions. The device is therefore used to measure or detect small changes in magnetic flux, rather than make absolute measurements of magnetic flux density.

4 DC MEASUREMENTS ON FERROMAGNETIC MATERIALS

If a ferromagnetic material is demagnetized and then subjected to a steadily increasing magnetic field strength, the magnetic flux density in the material increases in the manner shown in the normal induction curve of figure 6. It can be seen that there is a non linear relationship between the magnetic flux density, B , and the magnetic field strength, H .

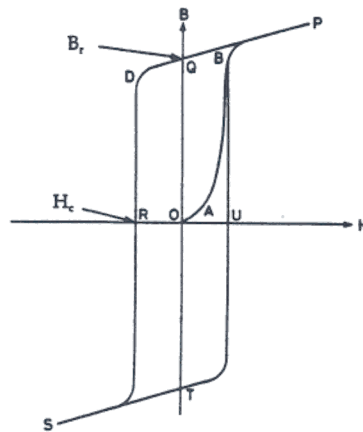


Figure 6. Normal magnetization curve and hysteresis loop

If at any point the magnetic field is reversed and steadily reduced to zero, hysteresis is observed. The flux density does not fall to zero but to a value termed the **remanent magnetic flux density**, B_r . If now the magnetic field is reversed and increased, the magnetic flux density falls to zero at a negative value of magnetic field strength termed the **coercive magnetic field strength** (coercive force), H_c . A further increase in H produces curve RS. Reduction, reversal and increase of H gives curve STUP which is symmetrical with curve PQRS.

Certain parts of these curves are of interest to the design engineer. At any point on the normal magnetization curve, OP, the ratio B/H gives the permeability:-

$$B/H = \mu = \mu_0 \mu_r \quad (18)$$

The **initial permeability** can be determined from the almost linear region OA whilst the **maximum permeability** is found on the knee of the curve near point B.

Towards point P the material reaches **saturation** when the incremental relative permeability is unity. If the maximum value of the magnetic field strength is sufficient to saturate the material then the hysteresis loop attains its maximum area; the values of the remanent flux density and coercive field reach their limiting values which are termed the **remanence** and **coercivity** respectively.

For permanent magnet materials, a point D on the demagnetization curve QR, is of interest where the product $B \times H$ is a maximum; this gives the **maximum energy product** of the magnet (J/m^3).

5 DETERMINATION OF DC PERMEABILITY, MAGNETIZATION CURVES AND HYSTERESIS LOOPS

A more complete description of the methods given in the following sections can be found in British Standard 6404 parts 4, 5 and 7⁸.

5.1 THE RING METHOD

The ring method can be used to determine the dc magnetic properties of magnetically soft materials, for example electrical sheet steels, high permeability nickel iron alloys and engineering steels. The test specimen may be in the form of a solid cast ring, a stack of

annular ring laminations or a spiral core. The diameter of the ring is chosen to accommodate the required magnetizing turns, but, to reduce the effect of the radial variation of the magnetic field, the ratio of the internal diameter to the radial width should be at least 10:1. A schematic arrangement of the equipment required for measurements by the ring method is shown in figure 7.

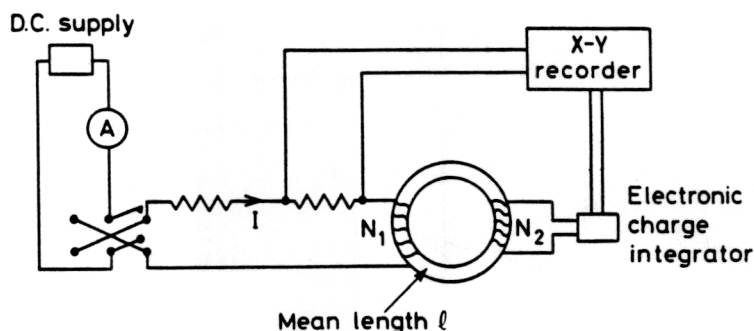


Figure 7. A typical arrangement of apparatus for the ring method

The magnetizing current is measured and the magnetic field strength, H , calculated from the relationship:-

$$H = NI/\ell \quad (\text{A/m}) \quad (19)$$

where N is the number of magnetizing turns on the ring specimen

I is the magnetizing current (A)

ℓ is the mean magnetic path length of the ring specimen (m)

The magnetic flux density is measured by a flux integrator connected to the secondary winding on the ring specimen. At high magnetic field strengths it may be necessary to apply a correction for the air flux enclosed by this secondary winding. If an electronic flux integrator is used, the output may be connected to the Y axis of an XY recorder and a signal derived from the current flowing in the magnetizing circuit connected to the X input of the recorder so that the normal magnetization curve and hysteresis loop can be plotted directly.

The method has some limitations in that test specimens are difficult to produce and wind, heating occurs when measuring at high magnetic field strengths (above 20 kA/m) and, as with all methods, difficulty is often experienced in completely demagnetizing the test specimen.

5.2 PERMEAMETER METHOD

Straight bars, rods or strips may be tested by completing the magnetic circuit with a yoke arrangement as in a permeameter described by Webb and Ford⁹ and shown in figure 8. The permeameter comprises a short magnetizing coil into which the test specimen (normally of minimum length 200 mm) is inserted and two C shaped yokes, usually of laminated grain-oriented electrical steel, which fit around the magnetizing coil and clamp the test specimen.

The magnetic flux density, B , is measured by means of a search-coil wound around the test specimen over the central region and connected to a flux integrator.

The magnetic field strength is measured either by means of a pair of search coils wound on a non-magnetic former and placed either side of the test specimen over the B coil, or by a Hall probe or, for low magnetic field strengths, by a fluxgate magnetometer.

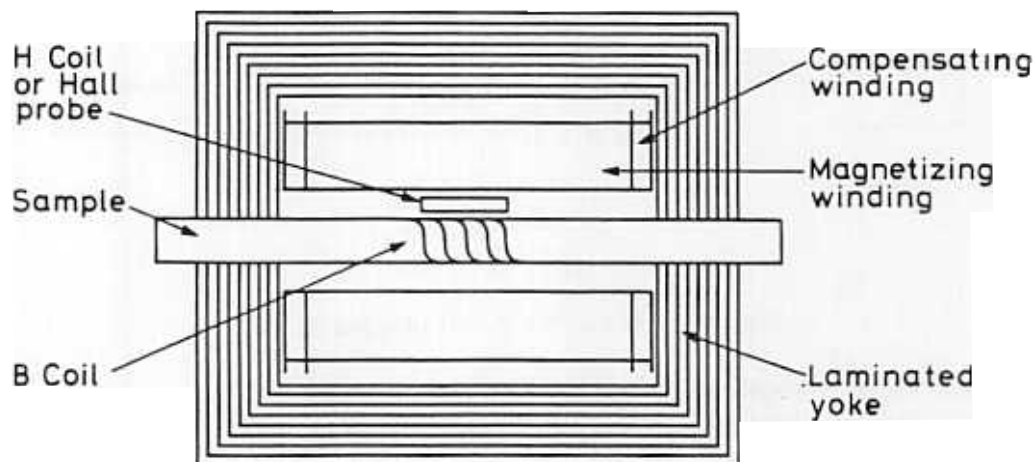


Figure 8. Diagram of the NPL compensated permeameter

Whilst measurements may be made at field strengths up to 0.2 MA/m without undue heating, problems can occur at low field strengths (below 1 kA/m) due to flux leakage at the specimen/yoke interface degrading the uniformity of the magnetic field strength over the measuring region. Half and quarter scale permeameters for bars of length down to 50 mm have been successfully devised and investigated by Rollett, Drake and Ager¹⁰.

5.3 ELECTROMAGNET METHOD

This method is particularly useful for the determination of the magnetic properties of permanent magnet material and other materials where a high magnetic field strength is required.

Short bars and rods are measured when clamped between the pole faces of an adjustable electromagnet. B and H are measured in the same way as in the permeameter method. In some cases it may be necessary to correct for the radial variation of the magnetic field strength by making two or more H measurements at measured distances from the test specimen and extrapolating back to the value at the surface of the material.

The method is not suitable for measurements on magnetically soft materials at low magnetic field strengths.

5.4 VIBRATING COIL MAGNETOMETER

This method was devised by Drake and Hartland¹¹ for the determination of the coercive force of magnetically soft materials, particularly relay steels. The test specimen may be in the form of a bar, rod or strip which is mounted at the centre of a long (about 1 m) solenoid. A small search coil, connected by a thin non-magnetic rod to a transducer, is caused to vibrate near one end of the sample as shown in figure 9.

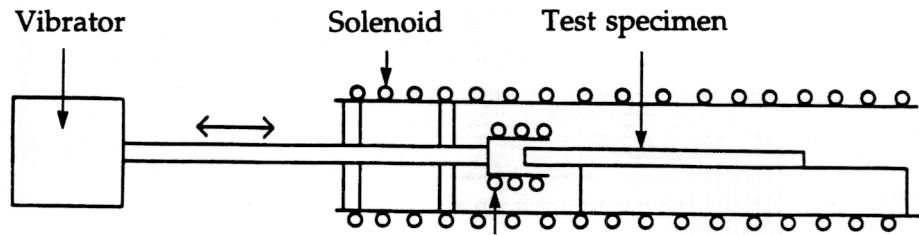


Figure 9. A vibrating coil magnetometer

The magnetic field strength produced by the solenoid is increased to saturate the test specimen and then reduced to zero, reversed and slowly increased until the output from a tuned detector connected to the search coil falls to zero. The magnetization in the test specimen is then zero. The value of magnetizing current is recorded and the magnetization coercive force, H_{cj} , of the material is found from the relationship:-

$$H_{cj} = NI/\ell \quad (\text{A/m})$$

where N is the number of turns on the solenoid

I is the magnetizing current (A)

ℓ is the length of winding on the solenoid (m).

It can be shown that the induction coercive force H_{cb} (which relates to a closed magnetic circuit) is related to the magnetization coercive force as follows:-

$$H_{cb} = H_{cj} (1 - 1/\mu')$$

where $\mu' = dB/\mu_0 dH$ in the region $B = 0$.

The uncertainty in the measurement of the magnetization coercive force by this method is of the order of $\pm 1\%$. Test specimens of less than 100 mm in length can be difficult to magnetize to saturation; extension pieces of similar material can be added during the magnetization process. For materials having a coercivity of less than 10 A/m it is necessary to provide a magnetic shield around the long solenoid. However, it is necessary to provide a means of demagnetizing this shield after saturating the test specimen. Such a system has been successfully used by Drake and Jasko (details to be published) for the determination of the magnetic coercivity of high permeability nickel iron alloys.

6 MEASUREMENT OF LOW PERMEABILITY MATERIALS

In some situations it is important to determine just how non-magnetic materials are, for instance in constructing magnetic mine sweeping equipment and devices used in close proximity to high or precise magnetic fields. Austenitic stainless steels have a relative magnetic permeability in the range 1.005 to 1.3, depending on their composition and heat treatment, and, due to their strength and corrosion resistance, find wide application where a low permeability material is required. Bronze, and its alloys with aluminium, have permeabilities down to 1.001. Two types of comparator method of measurement are commonly used to determine the magnetic permeability of these materials. Plastics, ceramics and some pure metals (copper, silver and aluminium) have much lower permeabilities and are measured using a magnetic susceptibility balance (not described here).

6.1 PERMEABILITY INDICATOR METHOD

A typical magnetic permeability indicator is shown in figure 10. It comprises a magnet mounted at one end of a pivoted balance arm with a counterweight at the other end. With the instrument mounted horizontally on a level surface, the counterweight is adjusted to balance the magnet in the absence of a test or reference specimen. A reference specimen, in the form of a disc insert, is screwed into a mounting above the magnet and the test specimen is offered up to the lower pole of the magnet. A series of pre-calibrated reference specimens are provided and these are successively screwed into the balance until the magnet changes from being attracted to the test specimen to being attracted to the reference specimen, or vice versa. The relative magnetic permeability of the test specimen is then taken as being in the range between the two reference specimens where the change of attraction takes place.

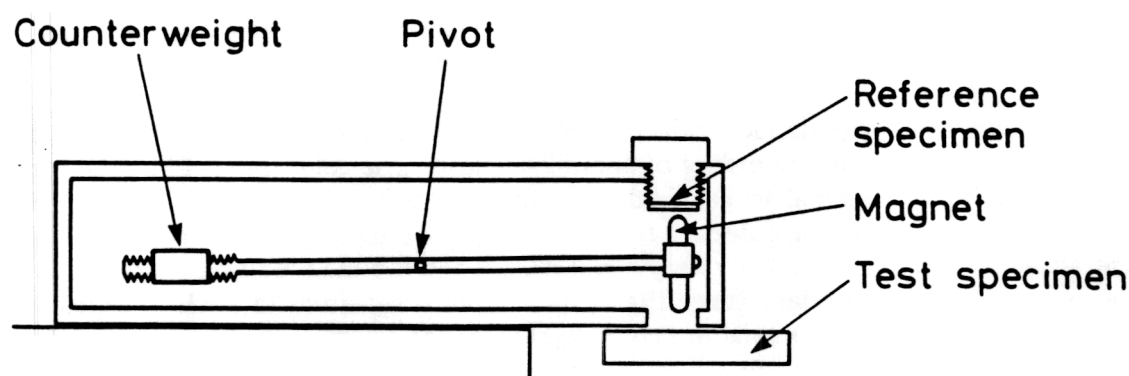


Fig 10. A typical magnetic permeability indicator

A disadvantage of this type of instrument is that it is only possible to estimate the range in which the magnetic permeability of a test specimen lies. Quite often this is perfectly satisfactory as in many cases it is only necessary to know if the magnetic permeability is below 1.05. The direct calibration of the disc inserts is not possible. Indeed they comprise of a plastic holder into which a small ferromagnetic screw is inserted and adjusted to give approximately the indicated value of relative magnetic permeability. A range of reference materials (see Drake and Ager^{12,13}) is necessary for their calibration. However, experience with instruments used for testing materials of known relative magnetic permeability has shown that, as an indicator, they are very useful especially as it is possible to carry out a total surface test on many forms of machined components.

6.2 A MAGNETIC COMPARATOR METHOD

Whilst not an absolute method, a quick and reasonably precise determination of the magnetic permeability of regular shaped bars, rods and strips can be made using the comparator shown in figure 11.

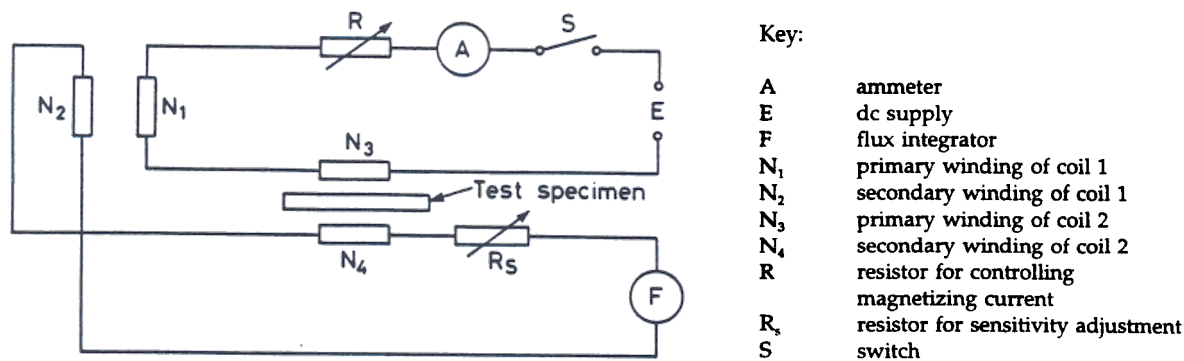


Figure 11. Arrangement of a permeability comparator

The system comprises two identical coils each wound with a secondary winding of the order of 10000 turns and a primary winding of about 200 turns. The coils are set at about 1 metre apart with their axes normal to each other so that the effect of the test specimen being inserted into one coil is not detected by the other. The object of the second coil is to counteract flux changes induced by very small changes in the magnetizing current. Due to the large number of secondary turns the system is very sensitive to such changes. The primary windings of the two coils are connected in series addition and the secondaries in series opposition. The output from the secondaries is connected to a sensitive flux integrator which need not be calibrated. However, this instrument should have good linearity over the range to be used since the system essentially compares the reading obtained by withdrawing a reference material with that obtained with the test specimen. Both test and reference materials should be demagnetized prior to the test and both should be tested by withdrawing them firstly from one side of the coil and then the other. The average of the two readings should be taken in each case. The relative magnetic permeability of the test specimen is then calculated from the following relationship:-

$$\mu_t = 1 + [(\theta_t / \theta_r - (A_r / A_t) \cdot (\mu_r - 1)] \tag{22}$$

where: μ_t, μ_r are the relative magnetic permeabilities of the test and reference specimens respectively

θ_t, θ_r are the integrator readings for the test and reference specimens

A_t, A_r are the cross sectional areas of the test and reference specimens.

The uncertainty in the measurement of the relative magnetic permeability by this method is better than $\pm 1\%$. This may seem exceptionally good since it includes the value of the reference material. However it should be realised that the method essentially determined the quantity $(\mu_r - 1)$; the uncertainty in this quantity depends upon the resolution of the comparator system as well as the value of the reference material. The uncertainty in the measurement of $(\mu_r - 1)$ is usually between $\pm 5\%$ and $\pm 20\%$.

7 AC MEASUREMENTS

When a ferromagnetic material is subjected to an alternating magnetic field, energy is absorbed by the non-reversible magnetization process of hysteresis, and also through the generation of eddy currents in the material. In materials which have a grain structure there is an additional loss due to domain wall motion. In particulate materials (ferrites) there is a so called disaccommodation factor whereby the power loss decreases with time after magnetization, due to a magnetic viscosity effect allowing the particles to gradually align in

a preferred direction.

In the design and manufacture of transformers and electrical generating machines it is necessary to evaluate the total power loss due to the combination of the contributory effects. The principal measurement methods are described in British Standard 6404 parts 2, 3, 6 and 10¹⁴ and are summarised in the following sections.

7.1 RING AND EPSTEIN SQUARE METHODS

Materials used in ac devices are usually in the form of thin sheet or strip, of thickness in the range 0.1 to 0.6 mm or of bonded ferrite cores; this minimises the effect of eddy currents which are proportional to the thickness and inversely proportional to the resistivity of the material. As with most of the dc methods of measurement it is necessary to form a closed magnetic circuit; this can be achieved using either a ring sample, in the form of a stack of laminations or a spiral core, or multiples of four strips of a standard size 280 to 305 mm in length and 30 mm in width mounted in the form of a square in an Epstein frame. In the case of the ring samples, a magnetizing and secondary winding are wound on the core. However, for strip samples the windings are on four solenoidal formers arranged on the sides of a square as in the case of the Epstein frame shown in figure 12. Ring specimens are used for soft ferrite materials and for high permeability nickel iron alloys.

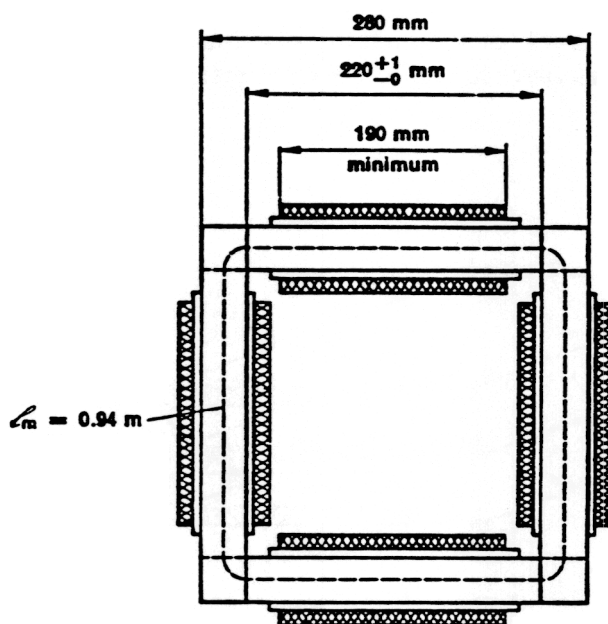


Figure 12. Epstein frame

7.2 SHEET TESTERS

Many attempts have been made to produce a whole sheet tester for non-destructively determining the total power loss of transformer type steels. The main problem is in defining the flux path and waveform in the sheet under test.

One type of sheet tester consists of a pair of flux closure yokes wound with a primary and secondary winding. This arrangement has the disadvantage that if the sheet is larger than the yoke, the flux path is undefined. A guarded yoke system similar to the local loss tester developed at NPL by Wilkins and Drake^{15,16} is more versatile. The arrangement is shown in figure 13. Although this tester was developed for the investigation of the variation of losses

over small areas, experiment has shown that, by adding a number of yokes in parallel between the two outer guard yokes, sheets of various widths can be tested.

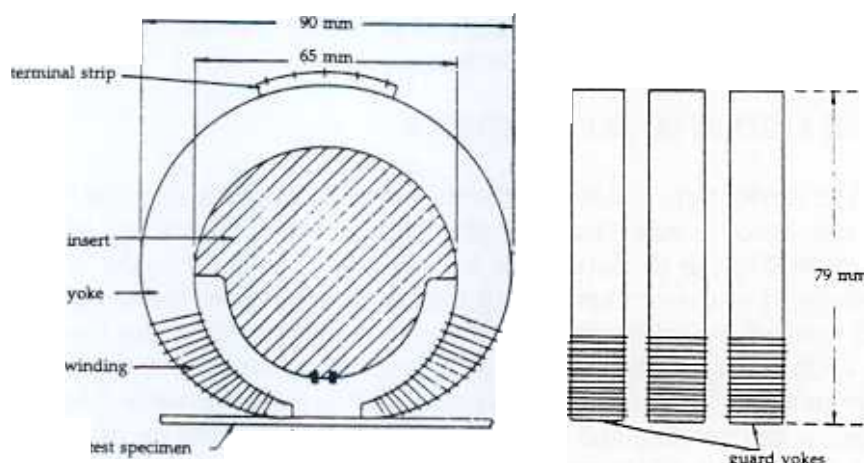


Figure 13. The NPL local power loss tester

In recent years IEC standard 404 part 3¹⁴ has been produced in which a double yoke 500 mm square sheet tester, with windings on a former around the sheet, is recommended. The yokes are made up either of a stack of laminations or from a pair of large C-cores. In practice the first type of core has been found to be the easier to construct. The system is shown in figure 14.

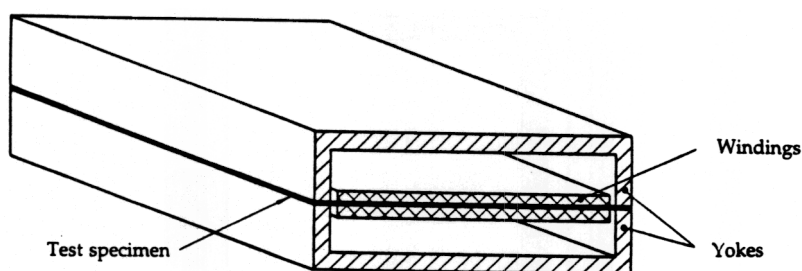


Figure 14. The IEC single sheet tester

8 METHODS OF POWER LOSS MEASUREMENT

Using any of the above methods of producing a closed magnetic circuit, the power loss can be measured either by a wattmeter or bridge method. Wattmeter methods are particularly easy to use at power frequencies and up to several hundred hertz. Bridge methods are a little more difficult to set up at first but they find wide application at audio frequencies. Perhaps by tradition wattmeter methods have been used for measurements on electrical steels and bridge methods for nickel irons and ferrites. However, provided sufficient sensitivity and reproducibility can be achieved, either method can be used.

One condition of the measurement of power loss is that the magnetic flux waveform shall be maintained sinusoidal, this the secondary induced emf is of sine wave form - a condition which prevails in the electricity supply system. This condition can be met by using a negative feedback power amplifier as the source of magnetizing current, feedback being taken from a secondary winding coupled to the test specimen.

Measurements are usually made at discrete values of frequency and magnetic flux density, B . The latter is related to the average rectified value of the secondary induced voltage, V_m , by the "transformer equation":-

$$V_m = 4 f B N A \quad (\text{volts})$$

where f is the frequency of the magnetizing current (Hz)

N is the number of turns on the secondary winding

A is the cross sectional area of the test specimen (m^2)

8.1 WATTMETER METHOD

The arrangement of the wattmeter method is shown in figure 15. Apart from meeting the sensitivity, accuracy and frequency requirements, it should be noted that the wattmeter should be capable of operating at very low power factors. For some materials magnetized almost to saturation the power factor can be as low as 0.05; power factors of 0.1 are frequently encountered.

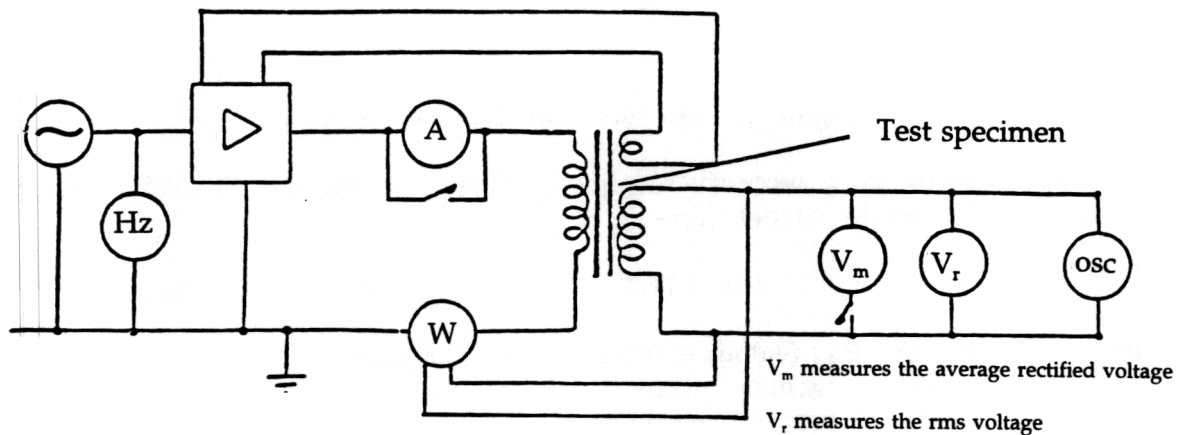


Figure 15. The wattmeter method

From the wattmeter reading the specific total power loss, P , is calculated from the relationship:-

$$P = W N_1 / (N_2 m) \quad (\text{W/kg})$$

where W is the wattmeter reading (W)

N_1, N_2 are the numbers of turns on the primary and secondary windings

m is the effective mass of the test specimen (based on an effective length of 0.94 m for the Epstein frame).

It is possible to determine the specific total power loss by the wattmeter method with an uncertainty of $\pm 2\%$ using calibrated instruments.

8.2 BRIDGE METHOD

A particularly useful bridge is a modified Heydweiller bridge (originally derived from a Hay bridge which is also sometimes used). One of the modifications allows one end of the source and one end of the detector to be earthed and this is a particularly useful feature for measurements at higher frequencies. A typical bridge arrangement is shown in figure 16.

R_3 is a low value (1 ohm) resistor capable of carrying the full magnetizing current. Convenient values for other components are: $R_1 = 100\text{k}\Omega$, R_2 a decade resistance box of total resistance approximately 10 k Ω and C is a decade capacitance box, 0 to 1 μF , with the last dial continuously variable.

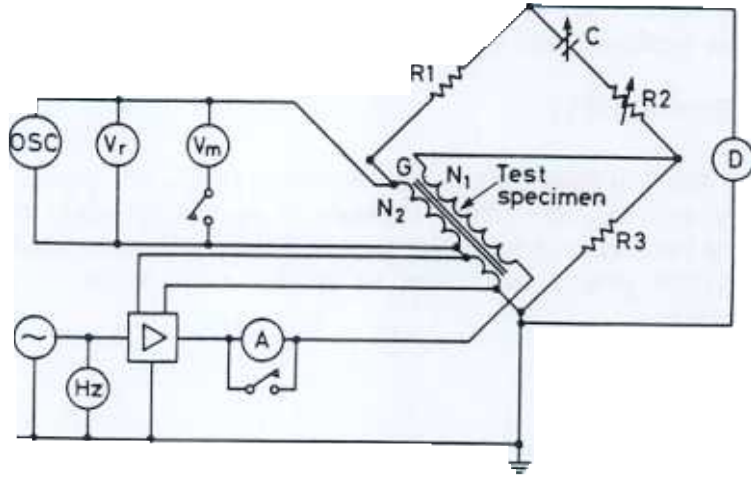


Figure 16. The modified Heydweiller bridge

The bridge is balanced by successively adjusting C and R_2 . The specific total power loss is then calculated from the relationship:-

$$P = (1.1107 V_m)^2 N_1^2 / (R_p N_2^2 m) \quad (\text{watts/kilogram})$$

where $1/R_p = R_2 / (R_1 R_3)$ (values in ohms at bridge balance)

N_1, N_2 are the numbers of primary and secondary turns

m is the effective mass of test specimen (kg)

The real (inductance) permeability is given by:-

$$\mu'_{rp} = L_p \ell_m / N_1^2 A \mu_0$$

where $L_p = C R_1 R_3$ (values at bridge balance)

ℓ_m is the magnetic path length of sample (m)

N_1 is the number of primary turns

A is the cross sectional area of test specimen (m^2).

Using calibrated bridge components and measuring instruments, it is possible to achieve an uncertainty of $\pm 2\%$ in the measurement of specific total power loss by the bridge method.

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APPENDIX 2

COMPARISON OF MEASURING DEVICES

Device	Range	Uncertainty	Traceable via
Search coil		0.1 %	Length
Fluxmeter	0.1 mT upwards	1.0 %	Current, voltage, resistance and mutual inductance
Ballistic galvanometer		0.3 %	
Electronic flux integrator		0.1 %	
NMR	0.1 t to 15 T	0.0002 %	Time
Hall effect gaussmeter	10 μ T to 3 T	0.2%	Calibration against NMR
Fluxgate magnetometer	100 pT to 1 mT	0.2 %	
Rotating coil gaussmeter	1 μ T upwards	0.01 %	Time and length
Squid	5×10^{-15} T to 0.1 mT	0.2 %	