A PORTABLE DEVICE TO MEASURE LOW MAGNETIC PERMEABILITY IN SITU

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Abstract

A new and portable device for measuring low magnetic susceptibility at high field levels is described. The test material is used to close the air gap in a magnetic circuit (probe) in which the magnetizing field is given by a small permanent magnet. The change in flux is measured and the susceptibility is displayed on a digital voltmeter.

The theory is given for an ideal probe. The choice of the permanent magnet material and the design of the probe are discussed.

Two probes were made for measuring the skin permeability in situ on large mechanical components. Results of the calibration and of various measurements are given.

I. Introduction

In magnet technology, the mechanical pieces which stand inside or nearby an air gap (vacuum chamber, coils supports, etc.) have to be made of a very low permeability material. In general, the permeability of these materials, e.g. stainless steel, decreases when the magnetic induction increases and then tends to be constant above 0.2 or 0.3 Tesla. Therefore, to be valid, a measurement of permeability has to be performed for these levels of induction.

The portable device which is described here, measures directly the magnetic susceptibility $\kappa = \mu_r - 1$ (μ_r being the relative permeability) and the measuring probe can be designed to give an induction of 1 Tesla or more.

It has been developed to measure the skin susceptibility on the austenitic manganese stainless steel pillars which support the top part of the large analyzing magnet ("Split Field Magnet")[1] which is now being assembled for the Intersecting Storage Rings (ISR) at CERN.

The measuring principle and theory are given. Then the probe design is discussed and the overall apparatus for measuring the skin susceptibility on large components is described. In paragraph 4, results concerning the sensitivity and the linearity are given together with some typical measurements made with this instrument.

II. Measuring principle and theory

The main originality of this device results from the use of a small permanent magnet to produce the required field level. This magnet is inserted in a magnetic circuit (probe) with an air gap and is equiped with a flux measuring coil. When a piece of material of magnetic susceptibility $\kappa \ll 1$ is brought into the gap, the magnetic flux in the coil varies by a small amount proportional to κ. The coil is connected to an electronic integrator, the output voltage of which is measured by a digital voltmeter graduated directly in values of κ.

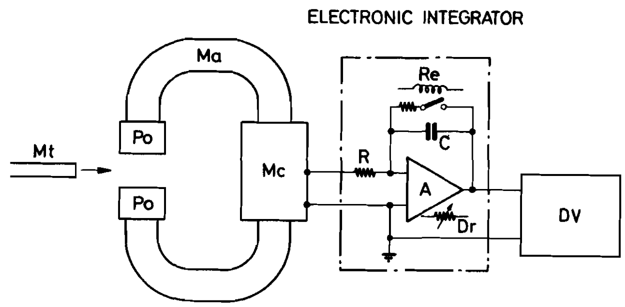

Fig. 1. Principle of the measurement. Legend: Ma = permanent magnet; Po = soft iron pole pieces; Mc = measuring coil; Mt = material to be tested; Re = relay for resetting the integrator; A = amplifier; Dr = drift adjustment; DV = digital voltmeter.

Although its design depends upon the specific task, a probe can be represented in general form by a magnet with an air gap and soft iron pieces as shown in Figure 1. For initial calculation it will be assumed that:

- there is no leakage, all flux being confined to the magnet and the gap;
- the permeability of pole pieces is infinite;
- the section of the permanent magnet is constant;
- the distribution of magnetic induction and magnetizing force in this section and in that of the gap is uniform.

Let us call:

L_m and A_m the length and the section of the permanent magnet

B_m and H_m the induction and the magnetizing force in this magnet.

L_g and A_g the height and the section of the gap

B_g and H_g the induction and the magnetizing force in the gap.

After magnetization of the completely assembled probe, the working point P of the magnet must be on the demagnetization curve B (H) of the material as shown in Figure 2. In the absence of an external magnetizing force the flux equation can be written:

$$\left(R_g + \frac{H_m}{B_m} \frac{L_m}{A_m} \right) \phi = 0 \qquad (1)$$

where R_g is the gap reluctance and $\frac{H_m}{B_m}\frac{L_m}{A_m}$ the equivalent reluctance of the magnet. ϕ is the magnetic flux in the circuit:

$$\phi = A_m B_m = A_g B_g \quad . \qquad (2)$$

From (1) B_m can be expressed by:

$$B_m = - \frac{1}{R_g} \frac{L_m}{A_m} H_m \qquad (3)$$

which is the equation of a load line of slope $-\frac{1}{R_g} \frac{L_m}{A_m}$ in Figure 2. Therefore, the working point P is at the intersection of this line with the demagnetization curve as is well known from magnet theory[2]. When a piece of thickness e made in a material of magnetic susceptibility κ is introduced into the gap, the reluctance R_g varies by:

$$\Delta R_g = - \frac{\kappa}{1+\kappa} \frac{e}{L_g} R_g \qquad (4)$$

The new working point P' can be found at the intersection of the new line of slope $-\frac{1}{R_g+\Delta R_g} \frac{L_m}{A_m}$ with the recoil curve of the magnet. For all classical magnet materials it is known that the recoil curves are practically without hysteresis effects and can be considered as straight lines. We assume this in the following and call $\mu_o\mu_{rec}$ the slope of this line in Fig. 2. The variation of induction ($\Delta B = B_m' - B_m$) when the working point moves from P to P' is given by:

$$\frac{\Delta B}{B_m'} = \frac{\mu_o\mu_{rec} H_m}{(1-\mu_o\mu_{rec} \frac{H_m}{B_m}) B_m} \frac{\Delta R_g}{R_g}$$

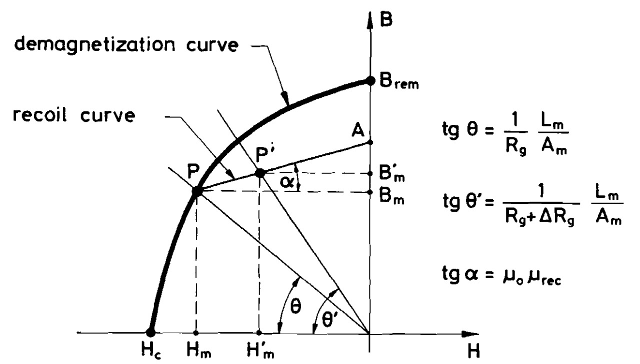

Fig. 2. Working conditions of the permanent magnet.

ΔB is not linear with the variation of gap reluctance. For small variations, one can use the first order approximation of this formula:

$$\frac{\Delta B}{B_m} = \frac{\mu_o\mu_{rec} H_m}{(1-\mu_o\mu_{rec} \frac{H_m}{B_m}) B_m} \frac{\Delta R_g}{R_g} \left[1 + \frac{\mu_o\mu_{rec} H_m}{(1-\mu_o\mu_{rec} \frac{H_m}{B_m}) B_m} \frac{\Delta R_g}{R_g} \right]$$

After replacement of $\frac{\Delta R_g}{R_g}$ by its value given by equation (4), one finds:

$$\Delta B = \frac{e}{L_g} B_m K_o \kappa \left[1 + (\frac{e}{L_g} K_o - 1) \kappa \right] \qquad (5)$$

K_o is a positive (as H_m is negative) and constant characteristic of the probe:

$$K_o = - \frac{\mu_o\mu_{rec} H_m}{(1-\mu_o\mu_{rec} \frac{H_m}{B_m}) B_m} \qquad (6)$$

The expression for flux variation $\Delta\phi$ and integrated voltage $V = \frac{n}{\tau} \Delta\phi$ follow immediately:

$$\Delta\phi = \frac{e}{L_g} B_g A_g K_o \kappa \left[1 + (\frac{e}{L_g} K_o - 1) \kappa \right]$$

$$V = \frac{n}{\tau} \frac{e}{L_g} B_g A_g K_o \kappa \left[1 + (\frac{e}{L_g} K_o - 1) \kappa \right]$$

In a first approach, the effects of flux leakage and reductions of magnetomotive force in the pole pieces can be treated by introducing, in the scheme of Figure 1, two additional reluctances R_ℓ and R_p. The flux leakage is supposed to be localised between the ends of the magnet and correspond to the reluctance R_ℓ. R_p is the reluctance of the pole pieces. The previous calculation can be repeated in the same way by replacing R_g by the external reluctance R_e:

$$R_e = \frac{(R_g + R_p)\, R_\ell}{R_g + R_p + R_\ell} \quad .$$

The equation (2) of flux conservation becomes:

$$B_m A_m = \frac{R_p + R_g + R_\ell}{R_\ell}\, B_g A_g \quad .$$

One finds finally for the integrated voltage

$$V = \frac{n}{\tau} \frac{e}{L_g} \frac{1}{k_2} B_g A_g K_o \kappa \left[1 + \left(\frac{e}{L_g} \frac{K_o}{k_1 k_2} - 1 \right) \kappa \right] \qquad (7)$$

where k_1 and k_2 are the correction factors classically used in magnet theory

$$k_1 = \frac{R_p + R_g + R_\ell}{R_\ell} = \text{magnet flux/gap flux}$$

$$k_2 = \frac{R_p + R_g}{R_g} = \text{magnet mmf / gap mmf} \quad .$$

In practice, k_1 is rarely less than 2 and can reach values of 10 or more in large magnets with long air gaps. k_2 is much smaller with typical values within the range 1.05 to 1.4. Therefore, the major effect of these corrections applies to the non-linearity term $\frac{e}{L_g} \frac{K_o}{k_1 k_2} - 1$. The sensitivity $\frac{V}{\kappa}$ expressed as a function of the air gap parameters is only slightly decreased.

For a practical probe, even with the simple geometry of Figure 1, other factors can have an influence on the sensitivity and the non-linearity, namely:

- the non-linearity of the recoil curve
- the non-uniformity of the induction and magnetizing force in the magnet and air gap
- the fact that flux leakage is distributed all along the magnet and in particular across the measuring coil.

Therefore, the equations which have been given must be considered only as guide lines for the design of the system and a calibration has to be made, at the end, by comparison with a conventional method.

III. Practical realization

A large variety of probes can be designed to solve any specific problem. Measuring inductions of 1 Tesla or more can be reached with small air gaps. For measuring sheets, the simple structure in Figure 1 would be the most appropriate.

For surface measurements on large components we have chosen a coaxial structure, the so called "pot magnet" shown in Figure 3.

As the sensitivity $\frac{V}{\kappa}$ can in general be adjusted by varying the number of turns in the measuring coil, it is preferable to design the probe for minimizing the volume of the permanent magnet (and therefore that of the probe) than for maximizing the sensitivity factor K_o. According to this criterion, the magnet material must be chosen and the probe so proportioned that the product $B_m H_m$ has a maximum value (Evershed criterion). Table I gives the value of the product $(B_m H_m)_{max}$ with the corresponding values of B_m, H_m, $\mu_o \mu_{rec}$ and the coefficient K_o for different magnet materials. Modern materials like the Alcomax and Alnico series are preferable to the chromium or cobalt steels as they have much larger values of $(B_m H_m)_{max}$ and equivalent or even larger values of K_o. In addition, they are usually used in measuring instruments for their superior time and temperature stabilities. Alcomax IV is one of the most suitable materials for the present application having both a very large product $(B_m H_m)_{max}$ and a large K_o. Another argument for designing the probe for the maximum value of $B_m H_m$ results from the following: the slope $\mu_o \mu_{rec}$ is practically a constant for all recoil curves; therefore, K_o - which in any case has a maximum of 1 - will increase only moderately when shifting P to the left in Figure 2, and it would be at the cost of a large increase in the probe dimensions.

The two probes which were made, use this material. Drawings are given in Figure 3. Probe 1, which was made according to the Evershed criterion, gives a maximum induction of 0.21 Tesla on its axis. In probe 2, the external cylindrical return yoke was modified to diminish the air gap and increase the induction up to 0.35 Tesla on the axis. Each probe is provided with a measuring coil of 12000 turns wound with 5/100 mm diameter isolated copper wire. The flux penetration into the material to be measured is of the order of the gap width (i.e. a few mm). The probe is guided by a support which allows it to retract by 20 mm from the surface of the material being measured. In order to minimize the influence of inhomogeneities of external fields (e.g. earth's field), the stroke of the probe has been reduced to a minimum which is still compatible with a measuring precision of 1 %. The probes were magnetized after the complete assembling of the magnetic circuits. For this purpose, the central magnet was extended by two external pole pieces as shown in Figure 3 and the whole assembly was put into the gap of a 1.6 Tesla electromagnet.

The electronic integrator uses a low drift chopper type amplifier (ZELTEX type 148 C). An adjustable high stability resistor is used together with a teflon capacitor of 0.1 μF for determining the time constant. The zero reset of the integrator is obtained by short circuiting the capacitor by means of a high insulation relay. The integrator with its power supply is mounted in a small box of 15 x 12 x 12 cm and the whole instrument can be easily transported as is illustrated in Figure 4.

The time constants (9.24 ms for probe 1 and 5.66 ms for probe 2) were adjusted to simplify the determination of κ from the reading; taking into account the small value of K_o and the generally large value of k_2k_1 (see section 2), the term $\frac{e}{L_g} \frac{K_o}{k_2k_1}$ of equation (7) was neglected giving the output voltage V as a function of κ:

$$V \text{ (Volt)} = 10 \kappa (1-\kappa) \quad (8)$$

For small values of κ the reading in volts is 10 times the value of κ.

TABLE I. Characteristics of magnet materials[2]

Material	B_{rem} T	H_c AT/m	$(B.H)_{max}$ T.AT/m	Working conditions at $(B.H)_{max}$ $\mu_o\mu_{rec}$ H/m x 10^{-5}	B_m T	H_m AT/m	K_o
Columax	1.35	58'900	59'700	0.226	1.170	50'930	0.089
Alcomax II	1.30	46'200	43'000	0.327	1.100	38'990	0.106
Alcomax III	1.26	51'700	43'000	0.390	1.020	42'170	0.138
Alcomax IV	1.15	59'600	35'800	0.553	0.835	42'970	0.223
Alnico normal	0.725	44'600	13'500	0.754	0.470	28'800	0.316
Alnico high remanence	0.80	39'800	13'500	0.880	0.520	26'000	0.305
Alnico high coercivity	0.65	49'300	13'500	0.653	0.425	31'800	0.490
Hynico II	0.60	71'600	14'320	0.528	0.345	41'380	0.385
35 % Cobalt steel	0.90	19'900	7'560	1.510	0.593	12'700	0.244
9 % Cobalt steel	0.78	12'700	3'980	2.070	0.500	7'960	0.248
3 % Cobalt steel	0.72	10'300	2'780	2.320	0.422	6'600	0.266
3½ % Chromium steel	0.98	5'570	2'270	4.400	0.620	3'660	0.260

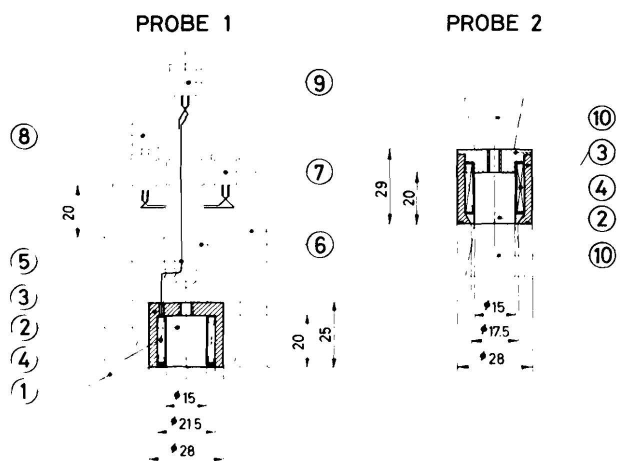

Fig. 3. Probes for measuring the skin susceptibility. Legend: 1 = material to be tested; 2 = permanent magnet; 3 = soft iron yoke; 4 = flux measuring coil; 5 = output from the coil; 6 = support; 7 = reset connector; 8 = reset push button; 9 = coil connector; 10 = soft iron pieces for magnetization of the probe.
Dimensions are in mm.

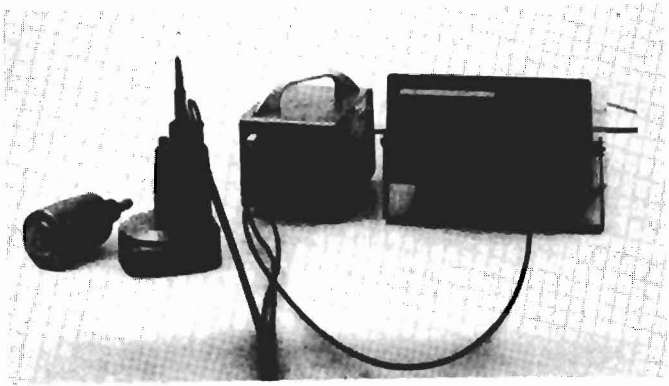

Fig. 4. Measurement of skin permeability with probe 2 (probe 1 is also shown on the left).

IV. Calibration and results of measurements

The instrument was calibrated by comparison with another method based on the measurement of the force exerted on a small sample (2 mm of diameter and 4 mm long) in an inhomogeneous field. The apparatus used was built by the ISR Vacuum Group . In this method, since the sample was small, the magnetizing field was practically constant and perpendicular to the sample axis. On the contrary, for probes 1 or 2 the field is more inhomogeneous and the result is an average of κ over the three directions. For this reason, we used materials having a susceptibility as isotropic and independent of field level as possible, namely:

- a piece of forged stainless steel 316 N
- a piece of casted stainless steel 304 L
- a piece of casted stainless steel 304 (according to the denominations of the American Iron and Steel Institute).

For the steel 316 N, κ is low (0.00335) and independent of the level and direction of the magnetizing field. The time constants were adjusted in order that the results obtained by the two methods coincided for this steel. For the two other steels, κ is larger and more dependent on the direction and level of the field. The results of the comparison between the two methods are given in Table II. After making the measurement with probe 1, three samples (along the three orthogonal axes) were cut in the first 8 mm below the surface and measured. The dispersion between the three samples is quite large (16 % for the steel 304) but within this limit the agreement between the two methods is good.

The sensitivity of the method is limited by the erratic drift of the integrator. This was measured by the dispersion of 25 measurements on steel 316 N. The value obtained with probe 1:

$$\Delta\kappa = \pm 0.00003 \quad \text{(peak values)}$$

corresponds quite well to the drifts calculated by using:

- a typical low frequency input noise in the µV range for the amplifier;
- a duration of a few seconds for a single measurment.

At this level of sensitivity, external stray fields may have an influence. For instance, when probe 1 is rotated by 180° in the earth's magnetic field, it gives a reading equivalent to a κ value of 0.003. Therefore, the earth field must vary by less than 1 % over the 20 mm probe displacement to keep the error below the sensitivity figure. This is easily achieved by keeping the probe a few tens of centimeter away from any magnetic pieces.

The influence of a possible hysteresis of the recoil curve was found to be negligible. For this purpose, κ was measured in two extreme con-

TABLE II. Comparison of measurements made with the instrument and with a magnetic balance

The three samples were cut along three orthogonal axes in the first 8 mm below the surface, the axis of sample 1 being perpendicular to the surface.

Designation of the stainless steel	Measurement with probe 1 (0.21 T)	measured with a magnetic balance at 0.21 T		
	κ =	sample 1 κ =	sample 2 κ =	sample 3 κ =
AISI 316 N	0.00335	---	0.00335	---
AISI 304 L	0.00925	0.0088	0.0090	0.0085
AISI 304	0.125	0.108	0.115	0.126

ditions:

a) after a cycle of 10 identical measurements;

b) immediately after having closed and opened the gap by a magnetic shunt.

In the latter case, the working point P recoils to A in Figure 2 and comes back to its original position. After such a perturbation, a few minutes are necessary for the probe to become stable. After this time, the first measurement of κ gave the same results as in case a) to within the measuring sensitivity.

The surface machining of the tested material is not critical as the irregularities affect the measurement only in proportion to the air gap. For a measuring precision of a few %, tool marks of 2 or 3 tenths of a mm were found tolerable, even for probe 2 which has the smallest air gap.

At the factory, this instrument was used to measure the magnetic susceptibility at various stages of the fabrication of the SFM pillars and especially to check that no magnetic skin was produced by machining. Also specific problems like the influence of mechanical stresses were studied. For this test, the κ measurement was simply performed on one side of a block of steel placed in a press under different loads. For the particular austenitic manganese steel which was used (IMPHY NMF3 produced by Creusot-Loire) the κ value at 0.21 Tesla (κ = 0.00220) and at 0.35 Tesla (κ = 0.00197) remained unchanged to within $\pm$ 1 % for stresses up to 19 kg/mm^2.

V. Conclusion

The instrument described provides an easy and precise method for measuring the magnetic susceptibility. A large variety of probes can be designed for any specific problem. The probe is designed as a permanent magnet and in the case of a small gap, measuring inductions of 1 Tesla or more are achievable.

The calibration has to be made by comparison with another method. For small values of susceptibility κ, the non-linear factor $(1-\kappa)$ can be neglected and the instrument provides a direct reading of κ.

For the two probes which were built for measurements of the skin susceptibility on large mechanical components, the induction level is relatively modest, 0.21 Tesla and 0.35 Tesla, respectively. However, despite their small effective volume (a few cm^3), a sensitivity of $\Delta\kappa$ = 0.00003 was achieved and no effects of hysteresis were noticed.

No special treatment or machining is needed for the test material so allowing the measurement to be performed in situ on any roughly machined mechanical pieces.

Acknowledgements

Many of the related measurements were made by V. Sergo. P. Bacher kindly made the measurements by the conventional method for us. Finally, I would like to acknowledge the help of M.Chassard who made a large contribution to the practical realization of the instrument.

References

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