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AUTOMATED SET-UP TO MEASURE RELATIVE MAGNETIC PERMEABILITY OF MAGNETICALLY SOFT STEELS

1996

Automated set-up to measure relative magnetic permeability (μ) of magnetically soft steels (hereinafter called a set-up) is discussed in general in Ref.1. In the present paper we discuss the particular design implemented at the Joint Institute for Nuclear Research. A simplified block diagram of the set-up is given in Fig. 1. Its basic units are 1) a controlled bipolar DC stabilizer, 2) a commutator of measuring coils, 3) an electronic integrator of the measurement channel for magnetic induction B (channel B), 4) an electronic integrator of the measurement channel for magnetic field strength H (channel H), 5) the first measuring coil, 6) the second measuring coil, 7) a computer, 8) a CAMAC controller, 9) a CAMAC commutator, 10) a digital voltmeter interface, 11) a digital voltmeter, 12) a magnetizing device. The device 12 incorporates 13) an electromagnetic yoke, 14) pads, 15) poles, and 16) electromagnet excitation coil. A steel sample 17 to be tested is inserted in holes in the poles and held down with special clamps. Elements 13-15 are made of ST-08 steel.

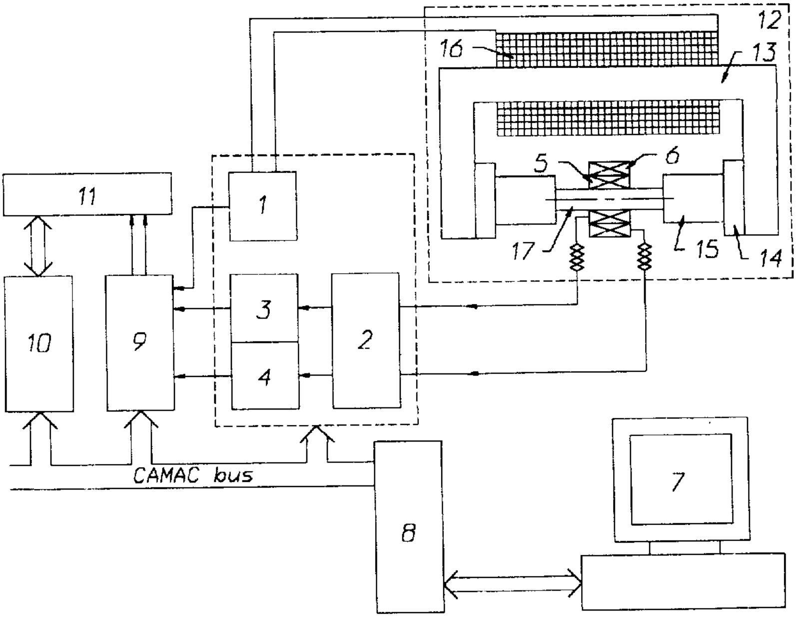

Fig.1. Simplified block diagram of the automated set-up tomeasure relative magnetic permeability of magnetically soft stell

Units 1-6, 11, 12 form a permeameter, others ensure automatic measurement and processing of measurement results. Operation of a permeameter like the one used in the set-up is discussed in Refs.1-6. That is why we confine ourselves to considering the operation of the set-up as a whole and describing its individual units. Also, measurement of the magnetic field strength in a sample will be discussed (this subject was also discussed in [6] published in Russian).

All electronic units of the set-up are of CAMAC standard. There is software to form time diagrams and organize operation algorithms. This design allows

- the measurement process to be fully automated,
- the operation algorithm to be optimised during comprehensive adjustment,
- the batch-produced type KA004 analog commutator [7], digital voltmeter interface [8], type KK009 CAMAC crate controller [9] to be used. Structurally units 1-4 are a CAMAC block 3M wide with a common bus interface.

Unit 2 is a set of relays K1-K4 controlled through the CAMAC bus by entering a binary code into the controlling register. Connection of unit 2 with measuring coils 5, 6 is shown in Fig. 2. Receiving an instruction from the CAMAC bus the commutator of the measuring coils connects them to inputs of integrators 3 and 4. Contacts of relays K2.1, K4.1 connect integrator inputs to the common bus reducing noise at the inputs in the storage mode. The integrators have similar circuitry and design, differing only in nominal values of time-setting circuits. An integrator circuit diagram is shown in Fig. 3. The integrator consists of a precise operational amplifier (DA1) with a balancing circuit (R1,R2), a time-setting RC-circuit and a reset circuit (K5, R1). Used in this integrator, a type AD707CQ precise operational amplifier and a capacitor with low leakage current and low absorption coefficient allowed higher integration accuracy owing to reduction of the output voltage drift to 0.5 mV/min.

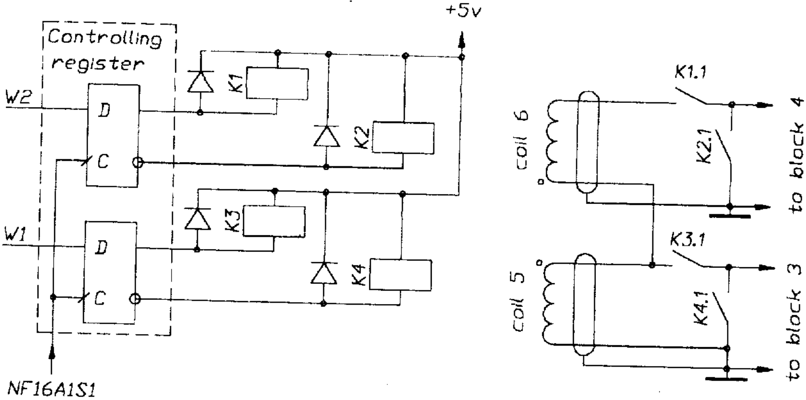

Fig. 2. Connection of the commutator to the measuring coils

Structurally integrators are separate circuit boards enclosed in screening housings. To reset the integrators, an instruction is sent from the CAMAC bus by entering a binary code into the controlling register.

The controlled bipolar DC stabilizer is of compensation type and incorporates a voltage amplifier in the feedback circuit. Its simplified circuit diagram is shown in Fig. 4. The reference voltage Uref is formed by a 12-bit digital-to-analog converter DAC with a reversal circuit (DA1, DA2, K). The reversal circuit and the digital-to-analog converter are controlled from the CAMAC bus by means of register RG.

The output cascade is of two-arm type and consists of a complementary pair of powerful composite transistors (VT1, VT2) and controlling transistor optopairs (VU1, VU2). This design allows resistive isolation of the high-current (±24 V) and the low-current (±15 V) power supply and an output voltage amplitude as high as ±22 V. The output cascade load is the electromagnet coil 16, a measuring bridge Rs and a reference resistor Rref connected in series. Running through Rref, output current is converted into voltage, which is amplified by a voltage amplifier and applied to the noninverting input of OA DA3. The voltage amplifier is a classic instrumental amplifier of 3 type AD707CQ OAs. The reference resistance is chosen to be 0.1 Ω to provide minimum heat energy release in the reference resistor.

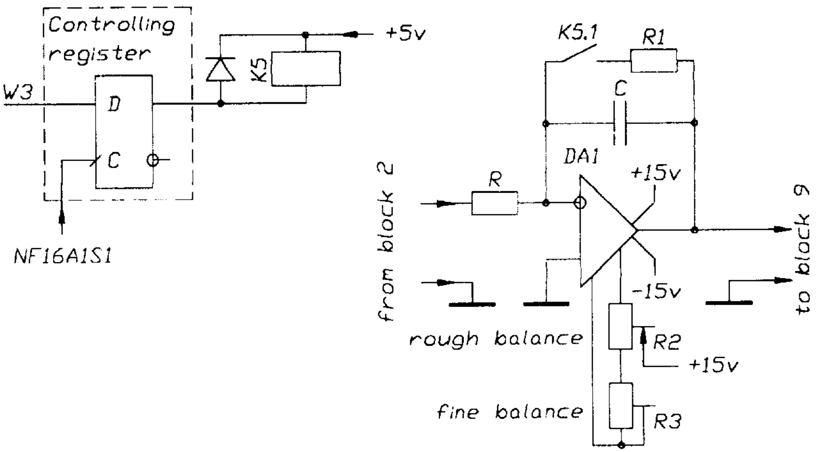

Fig.3. Circuit diagram of the integrator

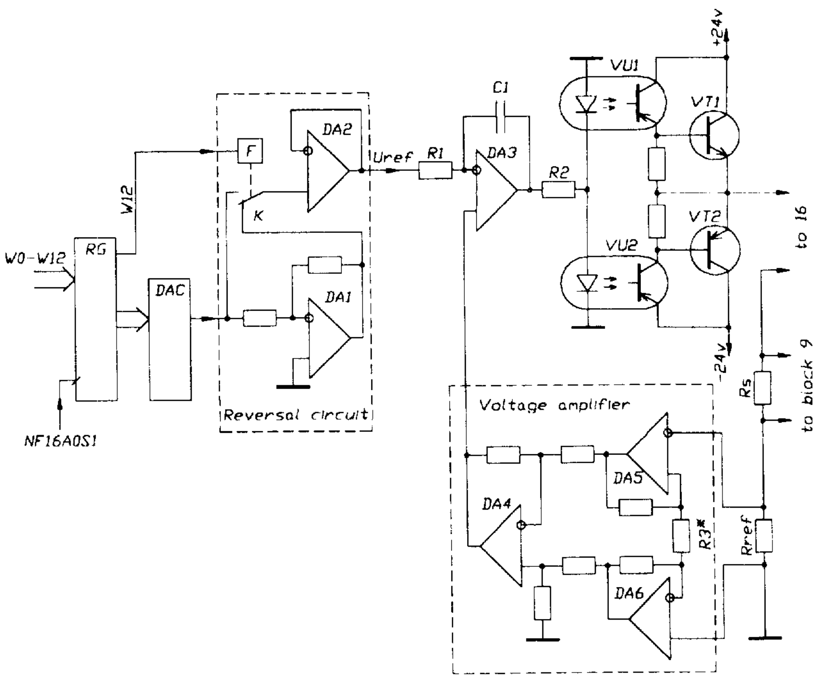

Fig. 4. Simplified circuit diagram of the controlled bipolar DC stabilizer

The voltage released at the standard resistor Rs comes to unit 9, which allows the current in the load to be measured by a digital voltmeter.

The stabilizer is adjusted by balancing operational amplifiers and setting the voltage-to-current conversion coefficient with a properly chosen resistor R3.

It should be recalled that determination of relative magnetic permeability μ by means of a permeameter implies measurement of the longitudinal component of magnetic induction B in a sample and the longitudinal component of magnetic field strength H on the surface (or near the surface) of a sample. The measured values of B and H must agree with the basic induction curve, which is achieved by using the commutation method to measure B and H. The set-up in question ensures measurement of B and H (channels B and H, respectively) in the commutation mode effected by the controlled bipolar DC stabilizer. Practically all methods for determination of induction in samples are based on the electromagnetic induction law. Induction is calculated as a ratio of the magnetic flux induced in a sample (and running through the cross section of the measuring coil) to the cross section of the sample, i.e., an average induction value is defined.

Magnetic field strength in a sample is determined by means of measuring coils, transducers (e.g., Hall probes) and potentiometers. Determination is based on the fact that the tangential component of the field strength does not change at the boundary between two media [10]. Thus, the magnetic field strength in a sample can be found by measuring the field strength on its surface.

Distribution of the magnetic field near the surface of cylindrical sample was studied at LNP JINR [6]. A special measuring mount with a Hall probe was made. The cylindrical sample was placed in the magnetizing device of the permeameter described in [5] (a diagram of this device is shown in Fig. 1 of Ref. 3). The quantity H was measured as follows. The Hall probe was moved in the median plane (XZ plane at Y = 0) around the cylindrical sample (along its circumference) from 0 to 360 ($0 < \alpha < 360$). The diameter of the sample was 23 mm, its effective length (the distance between the poles of the magnetizing device) was 50 mm, the distance between the Hall probe centre and the sample surface was about 1.15 mm, the working zone of the Hall probe was 0.45 mm by 0.15 mm. The Hall probe was oriented in such a way as to measure the longitudinal component (i.e., the Y-component) of the field strength in the place of the probe near the sample surface. As the working zone of the Hall probe is of small size, measurements of $H(\alpha)$ were practically point-like.

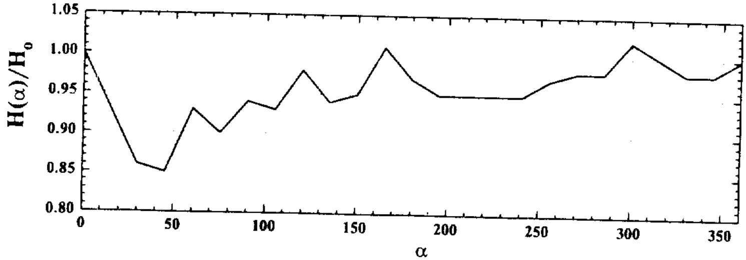

Fig. 5. Relation $H(\alpha)/H_0 = f(\alpha)$

Figure 5 shows the relation $H(\alpha)/H_0$ as a function of angle α at induction B = 1.8 T in the sample. Here H is the value of $H(\alpha)$ at $\alpha = 0$. The magnetic field strength near the sample surface was measured from point to point. That is why in the general case the measured mean induction in the sample does not agree with the magnetic field strength measured on or near the sample surface, which leads to a substantial error in determination of μ. To reduce the error, the method used in a permeameter to measure the magnetic field strength H on or near the sample surface must ensure determination of a mean strength value rather than its value at a point. The mean values of B and H must be measured in the same part of the sample.

The above factors taken into account, it seems advisable to use samples of magnetic materials in the form of round rods (cylinders) for testing in a permeameter and to employ a probe with two cylindrical coils for measuring H in samples. The coils are fixed coaxially to each other on a rigid frame in which a sample is inserted (coaxially to the coils). The turns of the first coil must be as close to the sample surface as possible. The length of the second coil must be the same as the length of the first one. Both coils must have the same number of turns. Their windings must be as thin as possible. If these conditions are fulfilled, the second coil of the probe can be considered to surround the first one.

Overall, it can be shown that the series-inverse connection of the coils (by means of integrators and other necessary units) ensures measurement of the magnetic field strength in the volume between the two coils, i.e.,this probe allows the magnetic field strength to be measured near the sample surface and it is the mean strength H in the part of the sample adjacent to the probe (surrounded by the probe) that is measured. If only the first coil is measured (the second is switched off), the probe measures the magnetic field induction (its mean values) in the same part of the sample.

Induction B is measured in the following way. Switches K1.1 and K4.1 are off while switches K2.1 and K3.1 are on (see Figs.1, 2). Coil 6 is disconnected from the input of integrator 4 and coil 5 is connected to the input of integrator 3, i.e.,channel B is put into operation.

From the electromagnetic induction law $e=-Wd\Phi_1/dt$ the change $\Delta\Phi_1$ in the magnetic flux Φ_1 running through the cross section of the first coil is defined as

$$\Delta\Phi_1=-\frac{1}{W}\int_{t_1}^{t_2} e_1 dt, \qquad (1)$$

where W is the number of turns of the first measuring coil 5, e_1 is the emf induced in the first measuring coil, t_1 and t_2 are the initial and final time limits of integration, respectively.

The output voltage U_B of integrator 3, to input of which the emf e_1 is applied, is

$$U_B=-\frac{1}{\tau_B}\int e_1 dt, \qquad (2)$$

where τ_B is the time constant of integrator 3. From relations (1) and (2) we get

$$\Delta\Phi_1=\tau_B U_B/W. \qquad (3)$$

If one takes the difference in cross section areas S_S of the sample and S_1 of the first coil to be negligible ($S_S \cong S_1$) and keeps in mind that $\Delta\Phi_1 = 2\Phi_1$ within the commutation method, we find from relation (3) that

$$B=\tau_B U_B/2WS_1 \qquad (4)$$

or

$$B=0.5C_B U_B,$$

where C_B is the constant of the induction measurement channel, $C_B=\tau_B/WS_S$. Relation (4) proves that the first coil 5 ensures measurement of induction B in a sample.

Let us consider measurement of the magnetic field strength H. Coils 5 and 6 are connected to each other in series and in opposition and then connected to the input of integrator 4 while the input of integrator 3 is disconnected from coil 5 (switches K1.1 and K4.1 are on, switches K2.1 and K3.1 are off). Magnetic fluxes Φ_1 and Φ_2 pass through the cross sections S_1 of coil 5 and S_2 of coil 6 respectively, the number of turns in each coil being equal to W. A change in Φ_1 and Φ_2 induces emf e_1 and e_2 in the coils. Since the coils are connected in opposition, at the input of integrator 4 one has the difference e_1-e_2. The output voltage U_H of integrator 4 is

$$U_H=-\frac{1}{\tau_H}\int (e_2-e_1)dt, \qquad (5)$$

where τ_H is the time constant of integrator 4.

Variations $\Delta\Phi_1$ and $\Delta\Phi_2$ of the magnetic fluxes Φ_1 and Φ_2 are defined as

$$\Delta\Phi_1 = -\frac{1}{W}\int_{t_1}^{t_2} e_1 dt$$

and

$$\Delta\Phi_2 = -\frac{1}{W}\int_{t_1}^{t_2} e_2 dt ,$$

whence

$$\Delta\Phi_2 - \Delta\Phi_1 = -\frac{1}{W}\int_{t_1}^{t_2} (e_2 - e_1) dt . \qquad (6)$$

If, as above, the difference in cross section areas S_S of the sample and S_1 of the first coil is taken to be negligible, $\Delta\Phi_1$ and $\Delta\Phi_2$ can be represented as

$$\Delta\Phi_1 = \mu\mu_0 \Delta H S_1$$

and

$$\Delta\Phi_2 = \mu\mu_0 \Delta H S_1 + \mu_0 \Delta H (S_2 - S_1), \qquad (7)$$

where ΔH is the change in the magnetic field strength, μ_0 is the magnetic constant ($\mu_0 = 4\pi\times10^{-7}$ H/m), μ is the relative magnetic permeability of the sample material. The term $\mu_0 \Delta H (S_2 - S_1)$ is variation of the magnetic flux in the air gap between the coils of probe 1. Keeping in mind that $\Delta H = 2H$ within the commutation method, we find from relations (5)-(7) that

$$H = \tau_H U_H / 2W(S_2 - S_1)\mu_0$$

or

$$H = 0,5 C_H U_H, \qquad (8)$$

where C_H is the constant of the channel for measurement of magnetic field strength, $C_H = \tau_H / \mu_0 W (S_2 - S_1)$. Relation (8) proves that a probe with two coils ensures measurement of the mean magnetic field strength near the sample surface.

It should be recalled that precise determination of the magnetic field strength in a sample requires strength measurement directly on its surface. Determination of μ with strength values obtained near the sample surface results in an additional error. To reduce the error one must find the corresponding values of strength on the surface from the values of strength measured near the surface. The correction coefficients to relate surface values to near-surface values can be derived by numeric calculation of field distribution in elements of the magnetizing device and in the sample [2, 3].

Now we give some technical parameters for one of the two-coil probe versions. Each coil has 460 turns of wire ПЭВ-2 ∅ 0.1 mm wound in four layers, the winding being 15 mm long and 0.6 mm thick. The average diameters of the first and second coil are 24.8 mm and 27 mm,respectively (calculated values). The leads-out o the first coil are twisted (the beginning and the end) and connected to the relevant inputs of commutator 2. The second coil is connected in a similar way.

The constant C_B of the channel for measurement of induction B (see relation (4)) is determined through a standard procedure with a standard mutual induction coil [10]. In LNP JINR these tests are carried out with type P5009 mutual induction standard ($M = 10\times10^{-3}$ H). The integrator output voltage is measured with a type B7-34 digital voltmeter.

The constant C_H of the channel for measurement of magnetic field strength H (see relation (8)) can be determined through a standard procedure [10] in a solenoid with the known constant. In LNP JINR there are other possibilities of measuring C_H with a high accuracy. For example, a two-coil probe can be placed in the electromagnet gap (a zone of highly uniform field). Varying the direct excitation current of the electromagnet one varies induction in the gap from B_1 to B_2 (a change in induction is $\Delta B = B_1 - B_2$). At the same time one measures the voltage U_{HC} at the output of the channel H integrator by means of a digital voltmeter. Using the data obtained, one determines the channel H constant

$$C_H = \Delta H / U_{HC},$$

where $\Delta H = \Delta B/\mu_0$. The B_1 and B_2 induction values are found by means of the NMR magnetometer [11, 12]. A magnetometer with a Hall probe is also used in calibration [13].

Finally we consider the μ measurement algorithm. The μ measurement macroalgorithm is as follows.

1. Demagnetization of a sample.
2. N_1 cycles of magnetic preparation of the sample with the chosen current.
3. N_2 cycles of U_H measurement.
4. N_3 cycles of U_H measurement.
5. Calculation of μ by the formulae:

$$\mu = B/\mu_0 H, \text{ where } B = 0.5C_B(23/d)^2\,\overline{U}_B,\ H = 0.5C_H K \overline{U}_H,\ K = f(B),$$

$$C_B = 0.5189\ \mathrm{T/V},\ C_B = 0.8630 \times 10^6\ \mathrm{(A/M)/B},$$

d is the sample diameter in mm.

6. Increase in current and repetition of the procedure from item 2 until the result with final current are obtained.
7. Demagnetization of the sample.

The values of N_1, N_2, N_3, d, the initial and final current values and a step in current are set by the operator at the beginning of the procedure. After measurements the μ-B relation is plotted for the sample material by the data obtained.

Magnetic preparation cycles, U_B and U_H measurements involve the following sequence of operations:

1. Choice of a measurement channel (B or H).
2. Opening of the integrator input.
3. Switch of the integrator modes from "Reset" to "Integration".
4. Measurement of U_{B1} (or U_{H1}) for the initial state of the integrator.
5. Current reversal.
6. Integration for 1.2 s.
7. Switch of the integrator modes from "Integration" to "Storage".
8. Measurement of U_{B2} (or U_{H2}) at the beginning of the "Storage" mode.
9. Determination of $U_B = U_{B2} - U_{B1}$ (or $U_H = U_{H2} - U_{H1}$).
10. Switch of the integrator modes from "Storage" to "Reset".

The total cycle time is about 2.2 s.

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Беляев А.Л. и др. D13-96-388

Автоматизированная установка для измерения относительной
магнитной проницаемости магнитомягких сталей

Описана автоматизированная установка для измерения относительной магнитной проницаемости (μ) магнитомягких сталей. Диапазон рабочих значений индукции в испытуемом образце составляет от 1,6 до 1,95 Тл, рабочий зазор — 50 мм, диаметр образца — 23 мм, длина образца — 230 мм. Погрешность измерения относительной магнитной проницаемости μ составляет ± 1,5 %. Приведены блок-схема установки, принципиальные электрические схемы основных узлов, краткое описание схем. Все электронные узлы выполнены в стандарте КАМАК.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 1996

Belyaev A.L. et al. D13-96-388

Automated Set-Up to Measure Relative Magnetic Permeability
of Magnetically Soft Steels

Automated set-up to measure relative magnetic permeability (μ) of magnetically soft steels is described. The range of working induction values in the sample under investigation is from 1.6 to 1.95 T; working gap, 50 mm; sample diameter, 23 mm; sample length, 230 mm. The measurement error of the relative magnetic permeability, μ, is ± 1.5 %. The block diagram of the set-up, the schematic diagrams of main units and their brief description are presented. All the electronic units are produced within the CAMAC.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 1996

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