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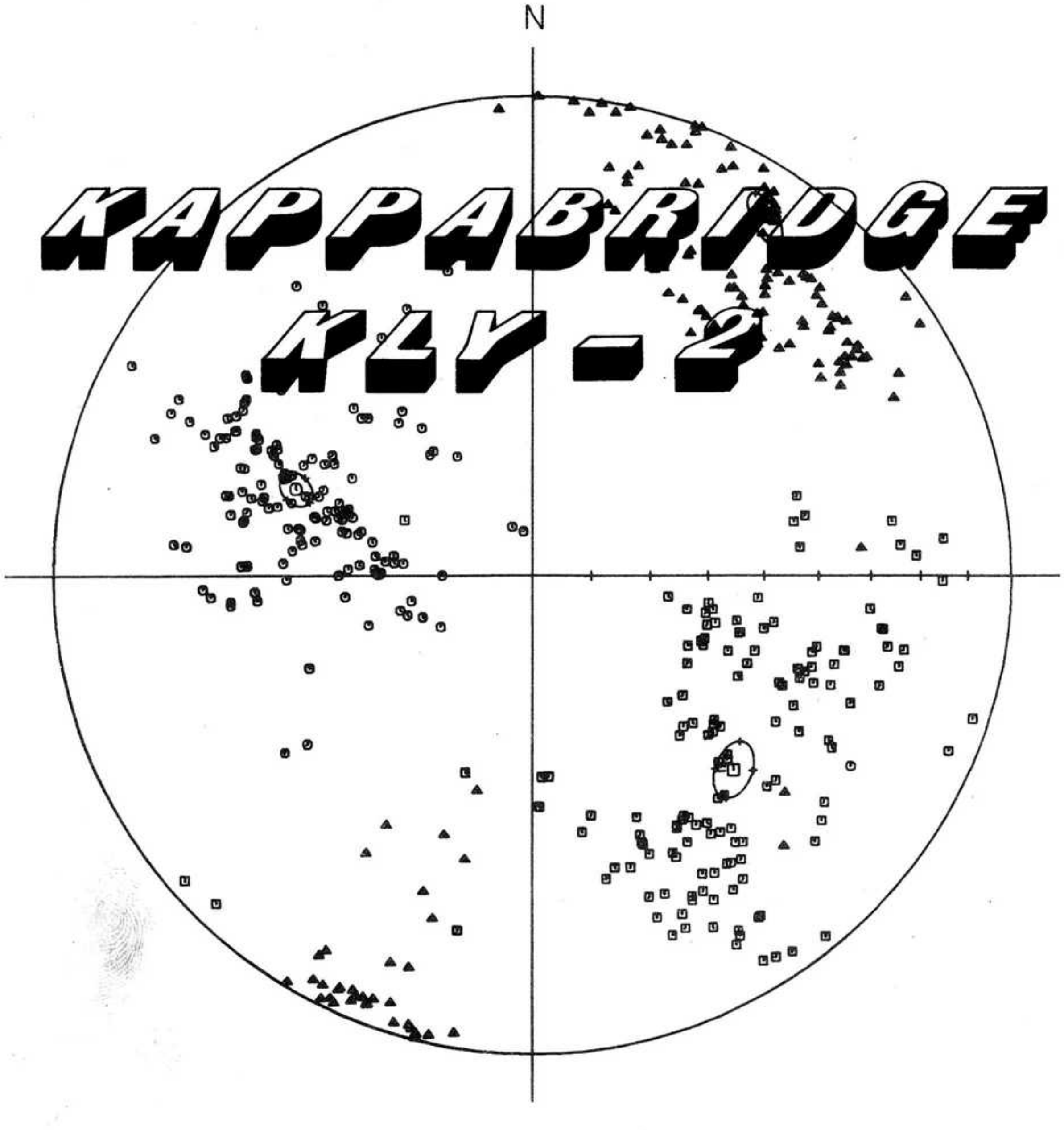
INSTRUCTION MANUAL
FOR
MAGNETIC SUSCEPTIBILITY BRIDGE



KAPPABRIDGE
KLY-2

Geofyzika n. p. Brno
Czechoslovakia

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FOR

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CONTENTS

1. GENERAL INFORMATION

1.1 BASIC FEATURES

The **Kappabridge KLY-2** is designed for measuring the magnetic susceptibility of rocks and its anisotropy. Its operation is based on measurements of inductivity changes in a coil due to a rock specimen.

In principle the instrument represents a precision semi-automatic autobalance inductivity bridge. It is equipped with automatic zeroing and automatic compensation of the thermal drift of the bridge unbalance. The data measured is shown in the digital display and besides it is put out on the connector in the parallel BCD code.

The standard pick-up unit is designed for measuring regularly shaped rock specimens of a volume of 10 cm^3 or of fragments in a measuring vessel of a volume of 40 cm^3. As an option, a pick-up unit for measuring regularly shaped rock specimens of a volume of 65 cm^3 or of fragments in a measuring vessel of a volume of 240 cm^3 can be delivered. The measuring coils of both the units are designed as 6th-order compensated solenoids, with a remarkably high field homogeneity.

The KLY-2 bridge has high accuracy, fast measuring rate and an outstanding sensitivity that makes it possible to measure even rocks with very weak magnetic properties. Owing to these features the instrument can be widely utilized in research into the magnetic properties of rocks, as well as for routine measurements in geophysical survey.

The output of the bridge can be connected to a data recording or to a data processing device via an appropriate interface.

The manufacturer can supply the KIM-20 Asynchronous Interface Module for interfacing the KLY-2 to a teletype (full duplex, 20 mA current loop). The teletype prints a listing of the data measured and simultaneously punches the data on a punch tape for further processing.

By means of the KIM-20 Interface Module the KLY-2 can also be connected to a computer or a terminal with an IEC RS 232 C standard input interface.

1.2 SPECIFICATIONS

Kappabridge KLY-2 comprises

measuring unit	KLY-2.0
standard pick-up unit	KLY-2.1
pick-up unit for large specimens (optional)	KLY-2.2

	Pick-up unit	
	KLY-2.1	**KLY-2.2**
Inner diameter of the pick-up coil	43 mm	76 mm
Nominal specimen volume	10 cm^3	65 cm^3
Cubic specimen *)	20 x 20 x 20 mm	38 x 38 x 38 mm
Cylindrical specimen *)	ϕ 25.4 x 22 mm	ϕ 46 x 40 mm
Spherical specimen		ϕ 50 mm
Measuring vessel for fragment specimens	40 cm^3	240 cm^3
Magnetic field intensity (r.m.s. value)	300 A/m	
Field homogenity **)	0,2 %	
Operating frequency	920 Hz	
Measuring ranges	100, 200, 400, 1 000, ... 200 000 x 10^{-6} (SI) 11 ranges	

Digital display	0 - 1 999 units
Output	parallel BCD
Sensitivity for specimen of nominal volume 10 cm^3 (65 cm^3)	4×10^{-8}
Accuracy within one range	± 0.1 % ± 1 count
Accuracy of the range divider	± 0.3 %
Accuracy of absolute calibration	± 3 %
Power requirements	220 V ***) 50/60 Hz
Power consumption (with the KIM-20 Interface)	60 VA
Operating conditions	
Ambient temperature	10°C - 35°C
Relative humidity	up to 80 %
Dimensions, weight	
Measuring unit KLY-2.0	554 x 170 x 389 mm 20.5 kg
Standard pick-up unit KLY-2.1	208 x 260 x 223 mm 7.5 kg
Large specimen pick-up unit KLY-2.2	380 x 428 x 374 mm 26.5 kg

Notes:

*) Holders of specimens of slightly different size can be supplied on request.

**) Within the cylindrical space 43 mm in diam. (76 mm) and 41 mm in height (72 mm).

***) Standard instrument. **Kappabridge** adapted for another mains voltage can be supplied on request.

1.3 SAFETY REQUIREMENTS

The metal surface of the instrument, the panel, the handles and the covers are separated by double reinforced insulation from the inner live parts with dangerous voltage. In this way, protection against dangerous touch voltage is ensured in accordance with electrotechnical safety regulations. Therefore, there is no terminal on the instrument for connecting protective earthing.

The zero point of the bridge connected with the chassis of the instrument is earthed through the operational earthing terminal. This operational earthing does not function as a protective earthing and can even be eliminated provided that the function of the bridge does not deteriorate under the given conditions.

The mains voltage is in the power-input part of the instrument up to the main insulating transformer. The voltage in the other parts of the instument is not dangerous.

The floor in the room in which measurements are made must be covered with dry insulating material, e.g., rubber.

When working with the instrument the operator must not touch electric instruments with conductive (metal) surfaces and earthed objects, e.g. water piping, conductive building constructions, etc.

The instrument can be moved or carried only when disconnected from the mains.

The operator must be properly trained for operation with the instrument. He must follow Instruction Manual and observe safety regulations.

The instrument can be operated only if it is in good condition. In case of unexpected malfunction or damage the instrument must immediately be disconnected and must not be operated before it has been repaired.

If the instrument has not been in use for a longer time, it must be cleaned and checked for damage or malfunction with respect to safety. This should also be performed at regular intervals. Damaged or worn parts should be exchanged to prevent malfunction.

A slow fuse (type T, 250 mA for 220 V, 400 mA for 120 V) serves for protection against short-circuit and overload.

Fuses from the manufacturer should be used only. If a fuse with a different characteristic is used, the protection is not effective.

Other devices e.g. a desk-calculator, a computer, a teletype, a voltmeter or an oscilloscope can be connected to the instrument via the appropriate interface, if needed.

The zero point of an additional device which is connected via an appropriate connector with the zero point of the bridge, must either be floating or must have zero potential.

The construction, testing and quality control of the instrument are in accordance with the Czechoslovak State Standard ČSN 356501 - ELECTRONIC MEASURING INSTRUMENTS - Safety Requirements.

2. PRINCIPLE OF OPERATION

2.1 BRIDGE NUCLEUS

The bridge nucleus, i.e. the bridge circuit proper, is illustrated in a simplified form in Fig. 1. The primary of the differential transformer **Tr** is supplied with an **AC** voltage of 920 Hz frequency from the generator **G.**

On the secondary it produces two voltages of the same amplitude and opposite phase.

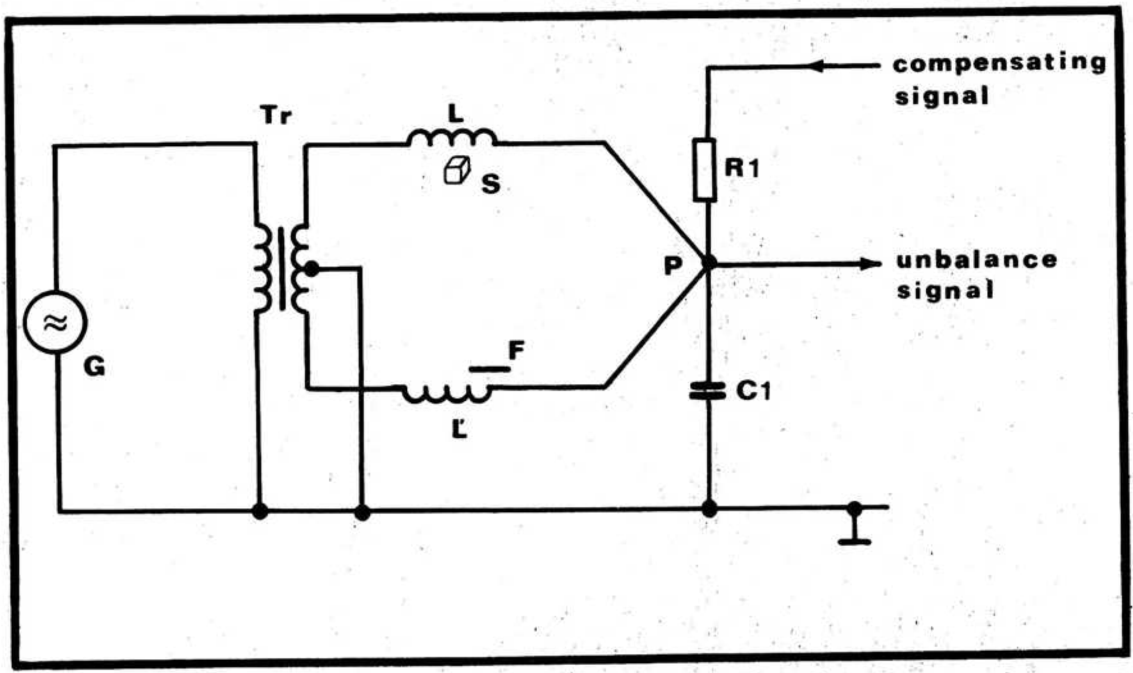


Fig. 1 Simplified circuit diagram of the KLY-2 bridge nucleus

Two measuring coils are connected to the secondary winding of the transformer: the pick-up coil **L** into which the specimen is inserted during the measurement, and identically designed balancing coil **L´** equipped with a small ferrite slug **F** for manual zeroing of the bridge.

The terminals **L, L´** that are not connected to the transformer **Tr** are connected to the bridge network output point **P** from which the signal of unbalance is taken for furher processing. The output of the bridge is tuned by means of the capacitor **C 1** connected between the point **P** and the zero point of the bridge. (The required selectivity and real output impedance of the bridge network are thus obtained).

To the point **P** the compensating signal, maintaining the balance of the bridge circuit during the measurement, is also fed via the resistor **R 1**.

2.2 THE DIRECT AND THE FEEDBACK BRANCHES

The block diagram of the bridge is shown in Fig. 2. The voltage generated by the generator **1** is fed to the bridge nucleus **2.** (We shall assign the zero phase to this voltage). Besides, the generator **1** supplies two rectangular voltages with the phase +90° and -90°, and an auxiliary sine-wave voltage with the phase of 90° to an oscilloscope.

The unbalance voltage from the bridge nucleus **2** is amplified by the pre-amplifier **3** and passed to the attenuator **4.** It is then fed to the amplifier **5,** the synchronous demodulator **6,** controlled by the rectangular voltage from the generator **1,** and to the integrator with the low-pass filter **7.**

The digital voltmeter **(DVM) 8** operating on the double-slope integration principle is connected to the output of the low-pass filter. A rather long integration time has been chosen (2 s) in order to achieve effective noise suppression.

So far we have been describing the direct branch of the bridge. As the bridge operates on the autobalance principle, it also comprises a feedback branch. The signal from the integrator with the low-pass filter **7** is passed to the input of the demodulator **18,** controlled by the rectangular voltage from the generator **1.** (We have not paid attention to block **19** yet). The signal is then passed to the amplifier **17** and further to the attenuator **16,** and from its output to the bridge nucleus via the amplifier **10,** see Fig. 1.

Both the attenuators **4** and **16** are switched simultaneously in such a way that the attenuation is constant. The switching is accomplished by the range selector **11** that supplies **DC** signals, controlling the attenuators electronically.

The described feedback loop maintains the zero value of the real unbalance component of the bridge nucleus **2,** which is the principle of the autobalance function. The real unbalance component corresponds to the sus-

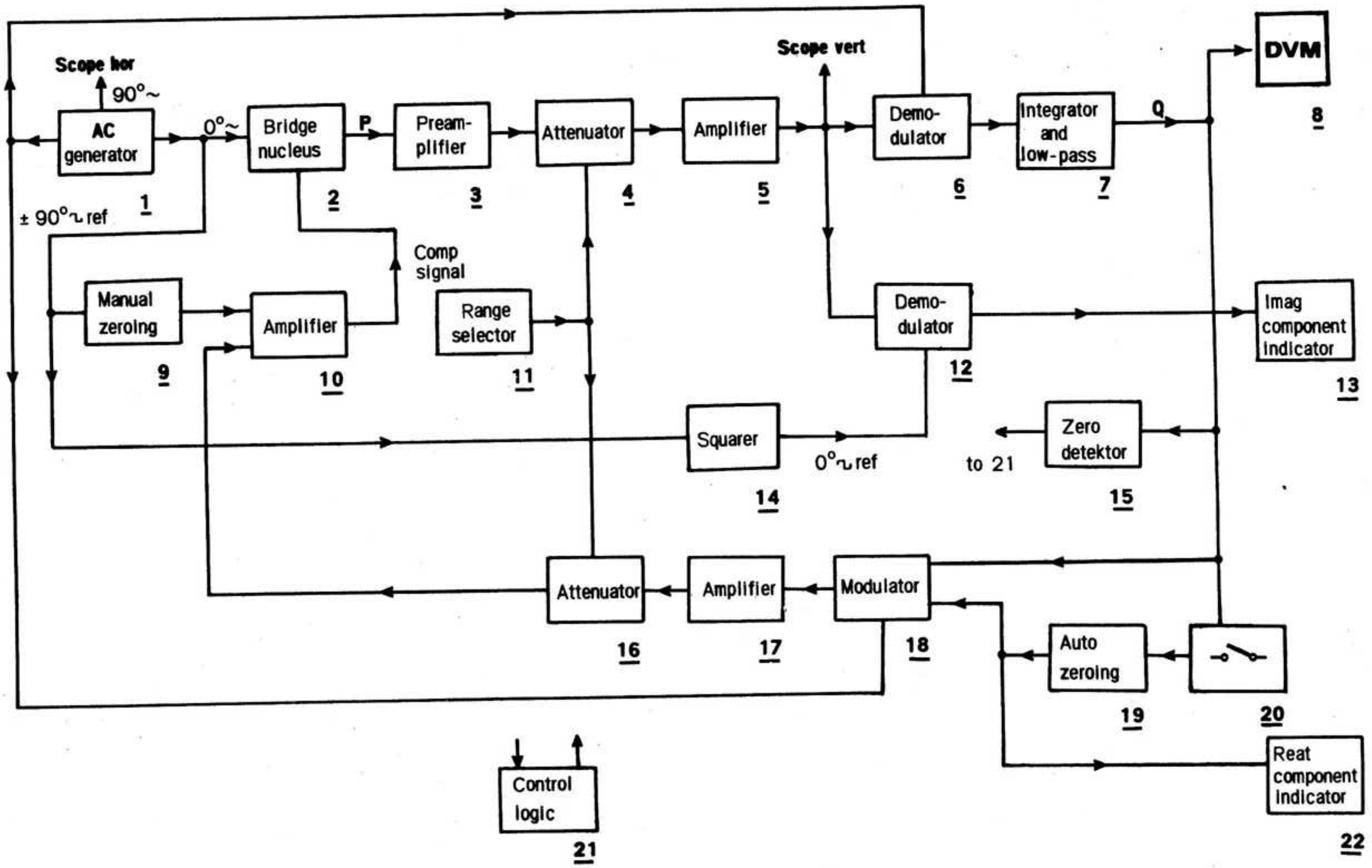


Fig. 2 Schematic block diagram **Kappabridge KLY-2**

ceptibility of the specimen, i.e. to the change of the pick-up coil inductivity.

The principle of measurement is as follows:
Let us assume that the bridge has been zeroed, i.e. there is zero voltage on the input of **DVM 8**, and that the switch **20** is off. (The zeroing will be explained later on). By inserting the specimen into the measuring coil its inductivity will be increased. The induced signal of unbalance will be compensated immediately by the effect of the feedback loop. A voltage proportional to the inductivity change and thus to the susceptibility measured will appear on the input of **DVM 8**.

2.3 ZEROING

To a certain extent the zeroing is automatic and is combined with the automatic compensation of the drift due to changes in the parameters of the measuring coils. By manual zeroing the bridge is brought to the region of automatic zeroing.

The circuit **19** (Fig. 2) for transmission with double integration, i.e. its transfer function F (p) has a double pole at the point p = 0, serves for automatic zeroing and compensation of the drift.

Let us assume that the bridge has roughly been zeroed manually. The switch **20** is off, and let us suppose that also the output of the circuit **19** is disconnected. The voltage on the input of **DVM 8** differs from zero and it changes gradually due to the measuring coils drift. Let us assume that these changes are linear, time-dependent.

Now activate the circuit **19** by connecting its output to the input of the modulator **18** and by turning on the switch **20**. In this way the input voltage of **DVM 8** will be fully zeroed after a certain period.

If we now turn off the switch **20**, neither the immediate value, nor the rate of change of the output voltage of the circuit **19** change because they are stored in its analog memory. Thus the zeroing is preserved for some time.

The assumed disconnection of the output of the circuit **19**, mentioned above, is relevant for the description of its function only. Actually, the output of the circuit **19** is permanently connected to the input of the demodulator **18**.

In the higher ranges, beginning from the 7th, the transfer of the circuit **19** changes so that only one integration is performed. This means that its transfer function has a single pole at the point $p = 0$. The circuit thus performs the zeroing only and not the drift compensation. In this way steady state is reached sooner.

The automatic zeroing concerns only the real component of unbalance that corresponds to the changes of the inductivity of the pick-up coil. In manual zeroing the switch **20** is always turned on.

The zeroing in the real component is performed by means of a ferrite slug inserted into the balancing coil **L´** by means of a screw (Fif. 1). The screw is set to a position in which the indicator of the real component **22** shows zero.

The indicator **22** is connected to the output of the circuit **19**. This indicator does not indicate the real component of unbalance directly, but the magnitude of voltage that must be supplied by the circuit **19** to achieve balance. However, this is not important for the operator.

The zeroing in the imaginary component is performed by means of a potentiometer in the circuit **9**. From this circuit the necessary zeroing signal is passed via the amplifier **10** into the nucleus of the bridge. The potentiometer is set so that the imaginary component indicator **13** shows zero.

The indicator **13** is connected to the output of the demodulator **12.** The input of the demodulator is connected to the output of the amplifier **5** and is controlled by the reference rectangular voltage generated by the squarer **14** of the voltage of the generator **1.**

The manual zeroing need not be accurate. In the course of measurement it should be repeated only if the deflection of any of the indicators **22, 13** exceeds about 50 % of the scale range to either side.

2.4 CONTROL LOGIC

The measuring process is controlled by the logic **21** gathering information from individual circuits and giving the necessary commands. The logic is operated by the push-button **PB1 START/RESET**, see Fig. 7.

The bridge operates in four statuses. Each of them is indicated by a luminiscence diode:

Status	**Diode**
WAIT	1. red
READY	green
MEASURE	yellow
HALT	2. red

WAIT. The switch **20** is on, the automatic zeroing is on. The signal VTS for the voltmeter start (see the connectors on the rear panel of the measuring unit, Fig. 8) is at the logic level 1. **DVM** measures the residual unbalance repeatedly. The push-button **PB1** is disabled. When the zeroing has been completed, the signal transmitted by the zero detector **15** to the control logic changes from the level 0 to the level 1, after approx. 2 s the bridge enters the status READY.

READY. This status does not differ from the previous one substantially. The push-button **PB1** is enabled. When it is pressed, the bridge passes to the status MEASURE. If the balance is disturbed in the status READY, the bridge returns to the status WAIT.

MEASURE. After reaching this status, the switch **20** is turned off and thus the automatic zeroing is eliminated. **DVM** is blocked and internally cleared when the signal VTS (Fig. 8) drops to 0, and a short pulse of the level 1 appears in the signal VLC. Immediately after enterning the status MEASURE the specimen is inserted for measurement.

After approx. 4 s, the voltmeter is started for a single measurement by a pulse of the level 1 in VST. After the integration has been completed (2 s) a pulse of the level 1 in the EOI signal is sent; an accoustic signal is generated in the control logic indicating that the specimen should be pulled out.

Approx. 3 s after the integration has been completed, the circuit converts to the status HALT.

HALT. The automatic zeroing is resumed since the switch **20** is turned on. The reading on the voltmeter does not change as the signal VST remains at the level 0. In this status, the reading can be read off and recorded (also automatically). The push-button **PB1** is enabled. If it is pressed, the bridge enters WAIT or READY according to the zeroing state.

2.5 OSCILLOSCOPE AND EXTERNAL VOLTMETER

An oscilloscope and an external voltmeter may be used to check some of the instrument functions.

For this purpose a special measuring cord is delivered, with a connector on one end and six banana plugs on the other. The connector is plugged into the connector AB on the rear panel of the measuring unit, see Fig. 8. The banana plugs are connected as follows:

Outlet	**Colour**	**Connection**
short	green	zero terminal of the scope
short	blue	horizontal input of the scope
short	red	vertical input of the scope
long	green	zero terminal of the voltmeter
long	blue	"low" terminal of the voltmeter
long	red	"high" terminal of the voltmeter

In this way the horizontal and the vertical inputs of the scope are connected to the points marked in Fig. 2; the external voltmeter is connected in parallel to the digital voltmeter of the bridge.

The measurement by the scope is performed in the status WAIT or READY. The basic pattern is a horizontal ellipse. The narrower the ellipse, the better the zeroing of the imaginary component. If the ellipse is inclined, the feedback is not working. This may be due, in particular, to serious detuning in the real component.

On the screen of the scope we can observe noise and disturbing signals that are induced in the measuring coils. In this way we can estimate whether the operation can be performed in the environment given.

The external digital voltmeter can be used for checking the function of the internal voltmeter. A count on the digital display DATA represents approx. 5 mV.

Sometimes it is useful to utilize an external analog voltmeter with zero in the middle of the scale. Noise and spurious signals, in particular the pulse ones, can be observed in the status READY.

3. INSTRUMENT LAYOUT

The instrument consists of two independent units - the pick-up unit KLY-2.1 (or KLY-2.2), and the measuring unit KLY-2.0. A general view of the instrument with the pick-up unit KLY-2.1 is in Fig. 3.

3.1 PICK-UP UNITS KLY-2.1 and KLY-2.2

The pick-up unit comprises the nucleus of the bridge **2** - Fig. 2 (the transformer, the pick-up coil, the balance coil and other passive components), and the pre-amplifier **3** located on the printed-circuit card denoted PAM1 and PAM2 in the pick-up unit KLY-2.1 and KLY-2.2, respectively. The pre-amplifiers differ in the value of one resistor only.

The KLY-2.1 with the cover removed is illustrated in Fig. 4. The design of the KLY-2.2 is almost identical.

A cross-section view of the pick-up unit KLY-2.1 is in Fig. 5 a:

1 - ceramic former
2 - winding
3 - tubular inset
4 - base plate

The tubular inset defines the position of the specimen during the measurement, prevents mechanical contact of the specimen with the coil, and acts as thermal insulation.

Fig. 5 b shows the field homogenity along the axis of the pick-up coil of the unit KLY-2.1.

A cross-section through the KLY-2.2 pick-up coil is illustrated in Fig. 6 a. The individual items are identical with those of the KLY-2.1 pick-

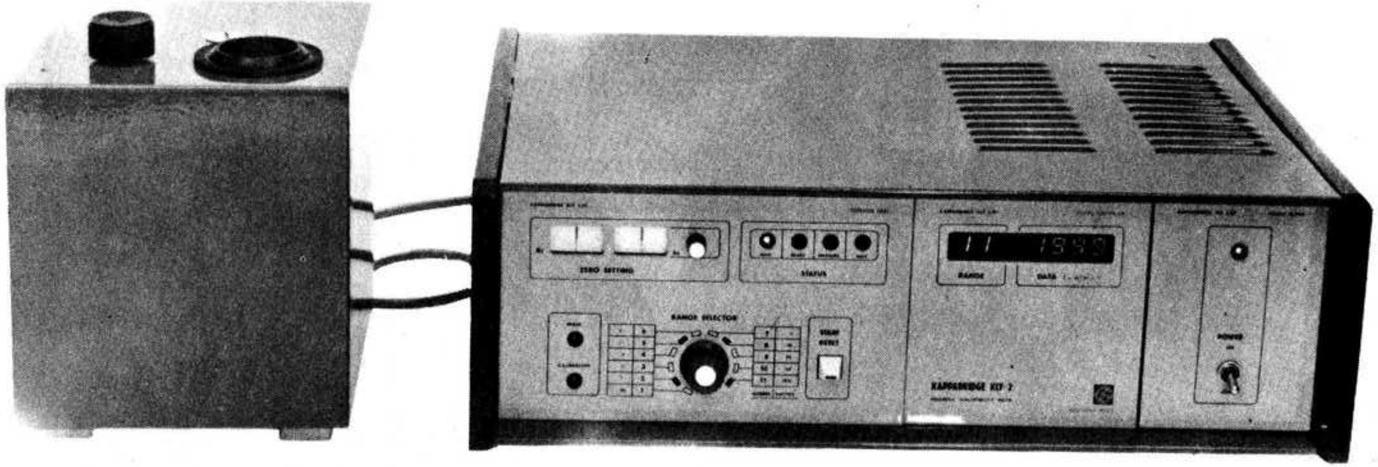


Fig. 3. General view of the **Kappabridge** measuring unit KLY-2.0 with the standard pick-up unit KLY-2.1

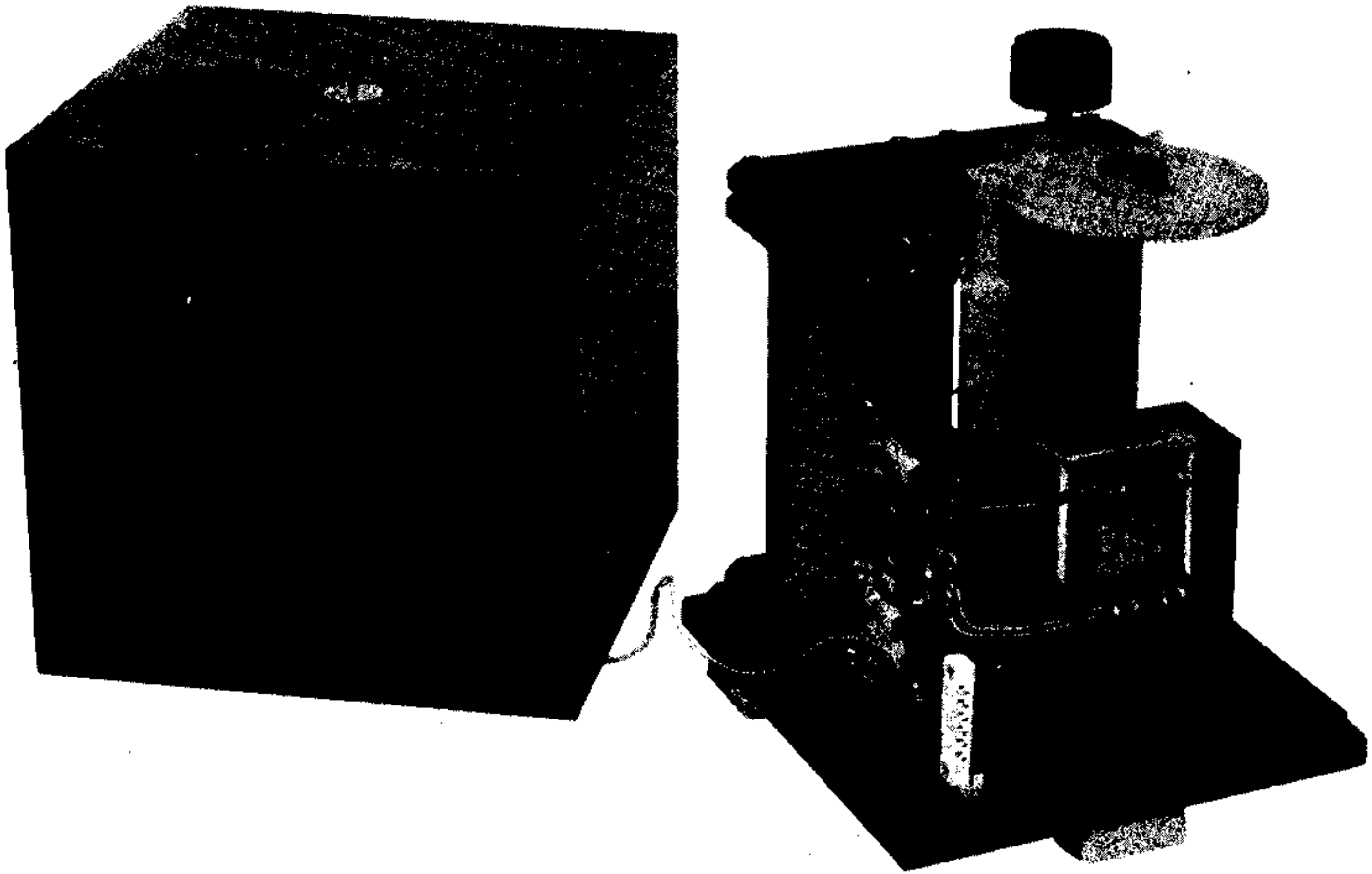


Fig. 4. Standard pick-up unit KLY-2 with cover removed

-up coil. The tubular inset is designed in a rather different way. It is not mounted on the base plate, but suspended from the case of the unit. Thus a deformation of the pick-up system by the weight of the specimen is almost avoided.

Fig. 6 b shows the field homogeneity along the axsis of the pick-up of the unit KLY-2.2.

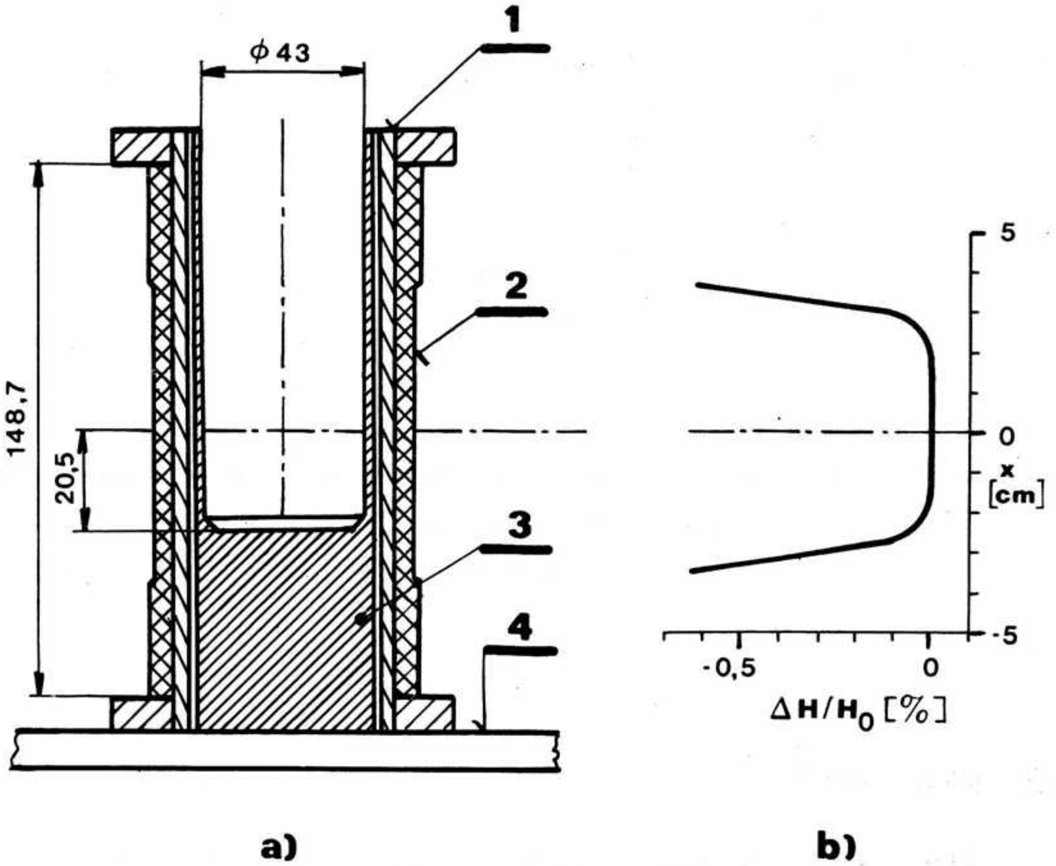


Fig. 5. Pick-up coil of the KLY-2.1 unit
a) cross-section view
b) field homogeneity diagram

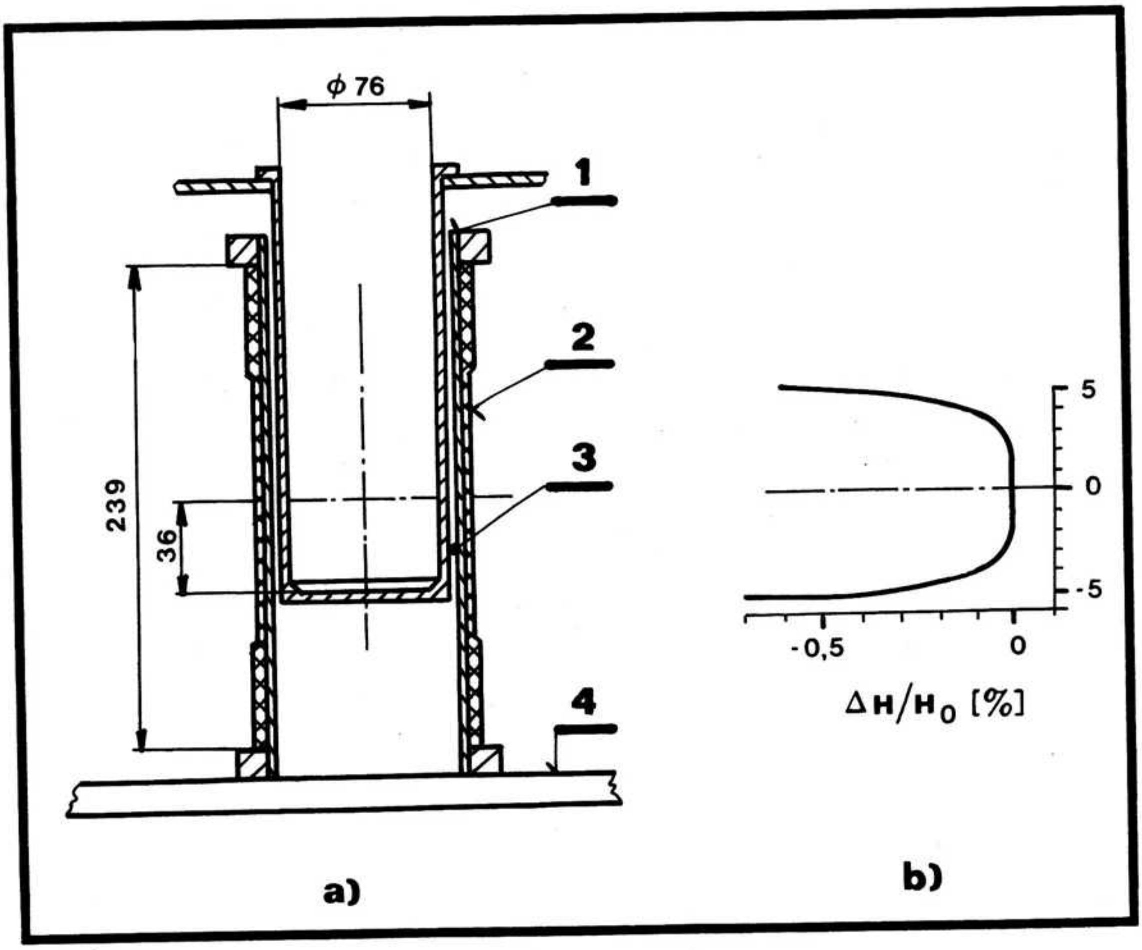


Fig. 6. Pick-up coil of the KLY-2.2 unit
a) cross-section view b) field homogeneity diagram

3.2 MEASURING UNIT KLY-2.0

The measuring unit panel with control elements is illustrated in Fig. 7.

The measuring units of three sub-units:

a) control unit
b) digital voltmeter
c) power supply

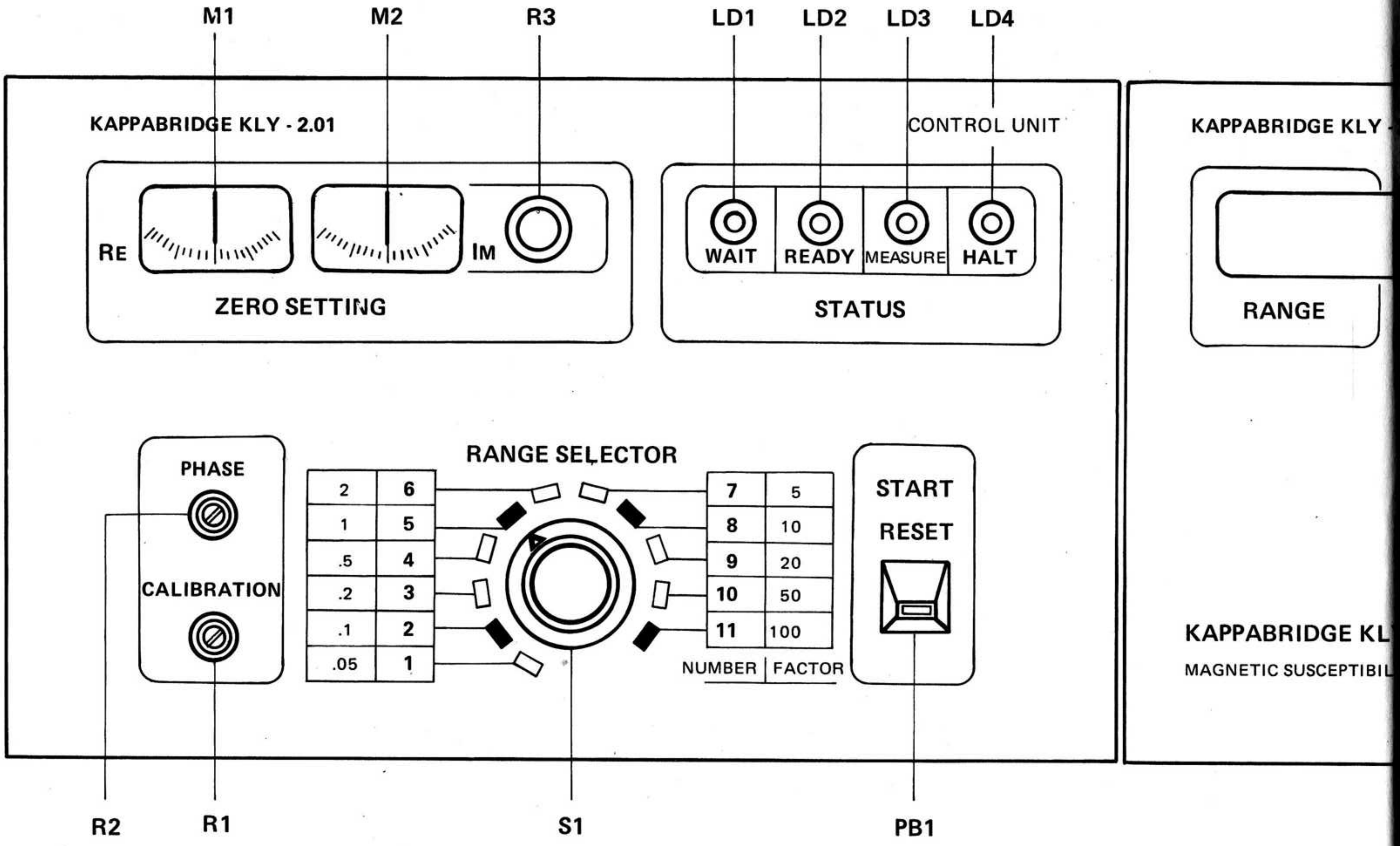
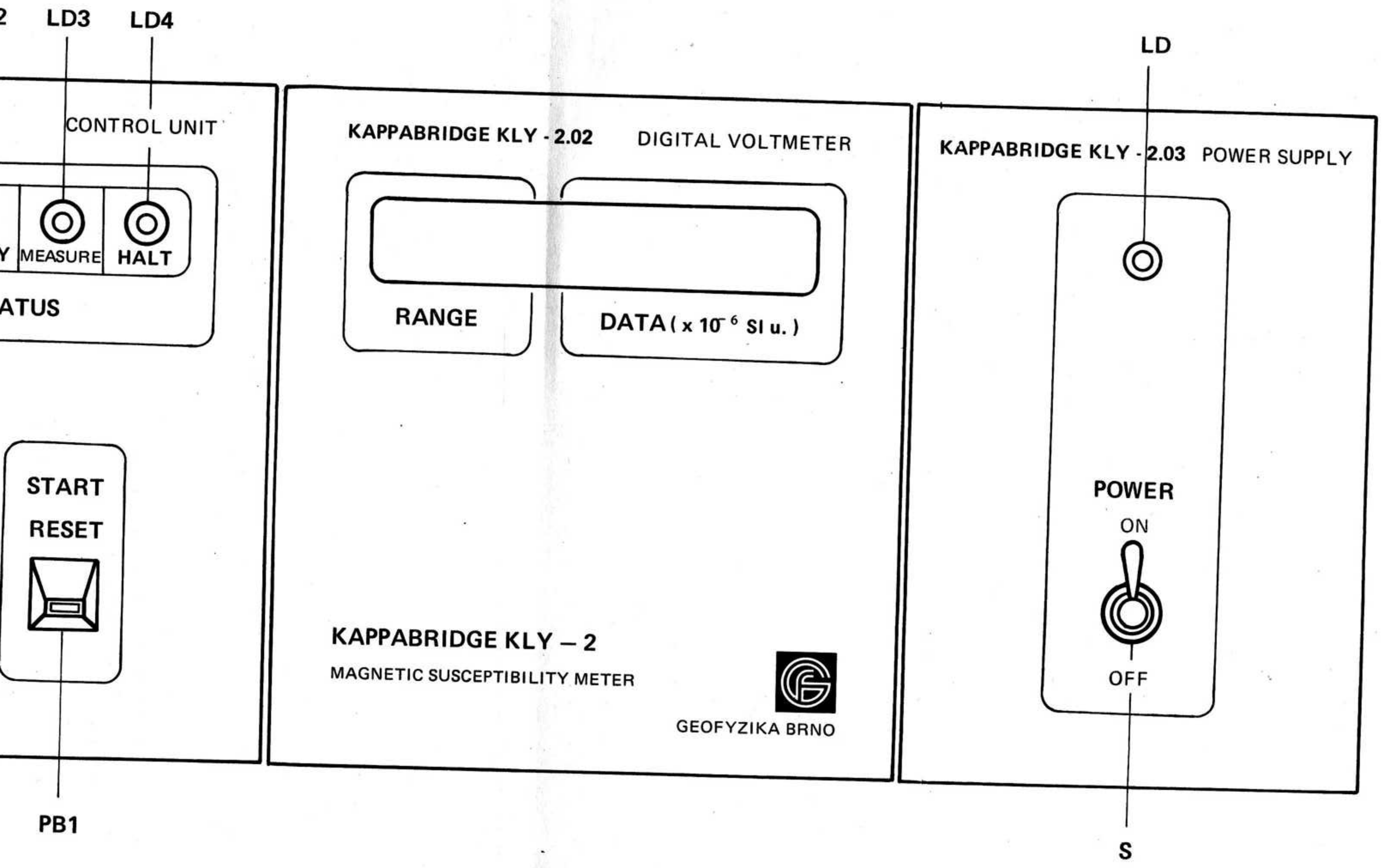


Fig. 7 Front panel of the measuring unit KLY - 2.0


2
LD3
LD4
LD
CONTROL UNIT
Y
MEASURE
HALT
ATUS
START
RESET
PB1
KAPPABRIDGE KLY - 2.02
DIGITAL VOLTMETER
RANGE
DATA (x 10⁻⁶ SI u.)
KAPPABRIDGE KLY – 2
MAGNETIC SUSCEPTIBILITY METER
GEOFYZIKA BRNO
KAPPABRIDGE KLY - 2.03
POWER SUPPLY
POWER
ON
OFF
S

3.2.1 Control unit

The control unit comprises all electronic circuitry of the bridge proper with the exception of the pre-amplifier PAM1 (PAM2), housed in the pick-up unit.

Control elements and indicators:

Designation		Function
M1	R_E	Real component indicator **22** *).
M2	I_M	Imaginary component indicator **13**.
LD1 ÷ **LD4**	WAIT, READY MEASURE, HALT	LED diodes indicating the status of the instrument.
R1	CALIBRATION	Calibration potentiometer linked with modulator **18**.
R2	PHASE	Potentiometer for setting the phase shift of the direct branch. It is linked with the pre-amplifier **5**.
R3	I_M	Potentiometer for manual zeroing in the imaginary component. It is linked with the manual zeroing circuits **9**.
S1	RANGE SELECTOR	Range selector linked with the CCV card, see below.
PB1	START/RESET	Push-button for control of the measuring process.

All these elements are mounted on the ASP sub-panel.

There are 11 cards at 10 planes inside the control unit. Viewed from front they are numbered from left to right.

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*) The underlined numbers refer to the respective blocks in Fig. 2.

Position	Designation	Function (contents)
1	**ADB**	Attenuator **4**, amplifier **5**, demodulator **6**, integrator and low-pass filter **7** (part).
2	**AZI**	Aut. zeroing circuit **19** (part), zero detector **15**, squarer **14**, demodulator **12**.
3 a (front)	**TZ P64**	Commercial operational amplifier, this belongs to the integrator and low-pass filter **7**.
3 b (rear)	**TZ P64**	Commercial operational amplifier within the aut. zeroing circuit **19**.
4	**AFB**	Modulator **18**, amplifier **17**, attenuator **16**, amplifier **10**, manual zeroing circuit **9**.
5	**GNA**	Generator **1** (part).
6	**GNB**	Generator **1** (part).
7	**APS**	Stabilizer 2 x 15 V.
8	**LGA**	Control logic (part).
9	**LGB**	Control logic (part), stabilizer 5 V.
10	**CCV**	Coding matrices processing the signal from the range selector **11**.

The control unit is enclosed with a couple of so-called printed-circuit side-boards interconnecting the grate at the bottom of the sub-unit. The left--hand printed-circuit side-board is designated LSB, the right-hand RSB.

3.2.2 Digital voltmeter

There is a double display on the panel mounted on the sub-panel DVP. The left half of the display des. RANGE shows the sequential number of the measuring range, the right half des. DATA, shows the measured value. On the panel, there are also decoders and other auxiliary circuits of the display.

Inside the sub-unit there are 7 cards at 6 planes, numbered from the left to the right when viewed from the front.

Position	Designation	Function (contents)
1 a (front)	**TZP64**	Commercial operational amplifier. A part of the integrator.
1 b (rear)	**INTB**	Integrator capacitor, integrating relay, 2 discharging relays, zeroing relay.
2	**CMPB**	Comparator, logic circuits controlling the switching of the respective discharging relay.
3	**LPSB**	Two 5 V stabilizers - one for supplying the voltmeter; the output of the second one is fed to the connector **VC** for supplying the interface.
4	**MST**	Master circuit controlling the individual working statuses of the voltmeter.
5	**OSCB**	Crystal-controlled 100 kHz oscillator, frequency dividers, multivibrator for display blinking.
6	**CNTB**	Counter and buffer memory.

Similarly to the control unit, the sub-unit of the digital voltmeter is enclosed with a couple of printed-circuit side-boards. The left-hand one is designated VSSB, the right-hand VLSB. Besides there is an auxiliary inset printed-circuit board VLIB with a connector on the rear side.

3.2.3 Connectors and terminals on the rear side of the measuring unit and the pick-up unit

A diagram of the connectors and terminals is in Fig. 8. The connectors **PA, AA, AB, VB, VC,** the terminal **ST1** and the mains power supply **SB** are directly accessible. Other terminals and connectors are accessible after the cover has been removed, which can be performed by a qualified person only.

AA **PA**	Connectors for interconnection of the pick-up unit and measuring unit via a cable.	
AB	Testing connector, see section 2.5.	
	DC output	Analog output of the bridge, also input signal for the digital voltmeter. The external voltmeter can be connected across these terminals and $\mathrm{GND}_{\mathbf{ref}}$.
	Scope vert. Scope hor.	Terminals corresponding to the synonymous points in the block diagram in Fig. 2. The terminals and $\mathrm{GND}_{\mathbf{ref}}$ can be connected to the scope.
	$\mathbf{GND}_{\mathbf{ref}}$	The zero point of the bridge, reference terminal.
	SR	Start and reset. Connecting this terminal with $\mathrm{GND}_{\mathbf{ref}}$ has the same effect as pressing **PB1**. This can be used for external control.
AC **VA**	Interconnection between the control unit and the digital voltmeter. Also the output of the power supply is connected to this point.	
	EXR	External reset. The pulse EXR = 1 is transmitted by the interface after reception of data. The bridge reverts from HALT to WAIT or READY.
	OVL	OVL = 1 indicates voltmeter overload.
	VCL	The pulse VCL = 1 starts the digital voltmeter zeroing.
	VST	Start of the voltmeter. The pulse VST = 1 initiates single measurement. If VST = 1 continues, the voltmeter measures repeatedly.

	EOI	End of integration. The voltmeter transmits the pulse EOI = 1 . In the MEASURE status the control unit converts the pulse into an accoustic signal.
	DC output	As with the connector **AB.**
	MSD	Most significant digit.
	LSD	Least significant digit.
	DRY	Data ready. DRY = 1 when the bridge is in the HALT status and OVL = 0.
VB		An auxiliary connector for setting up and servicing only. Here a special aid can be inserted to expand the display DATA by another least significant digit. Another aid for indicating the status of the voltmeter - zeroing, integration, discharging.
VC		A connector for data output. An interface for teletype, calculator, mini-computer.
	+ 5 V	Interface supplying.
	+ 15 V	Interface supplying.
	- 15 V	Interface supplying.
	RANGE	Data on the display RANGE.
	DRY EXR	As with connectors **AC, VA.**
SA		Connector of the power supply. The outputs lead to connectors **AC, VA.**
SB		Mains socket.
ST1		Operational earthing terminal on the rear panel of the supply source. Connected with the zero point of the bridge via a capacitor.

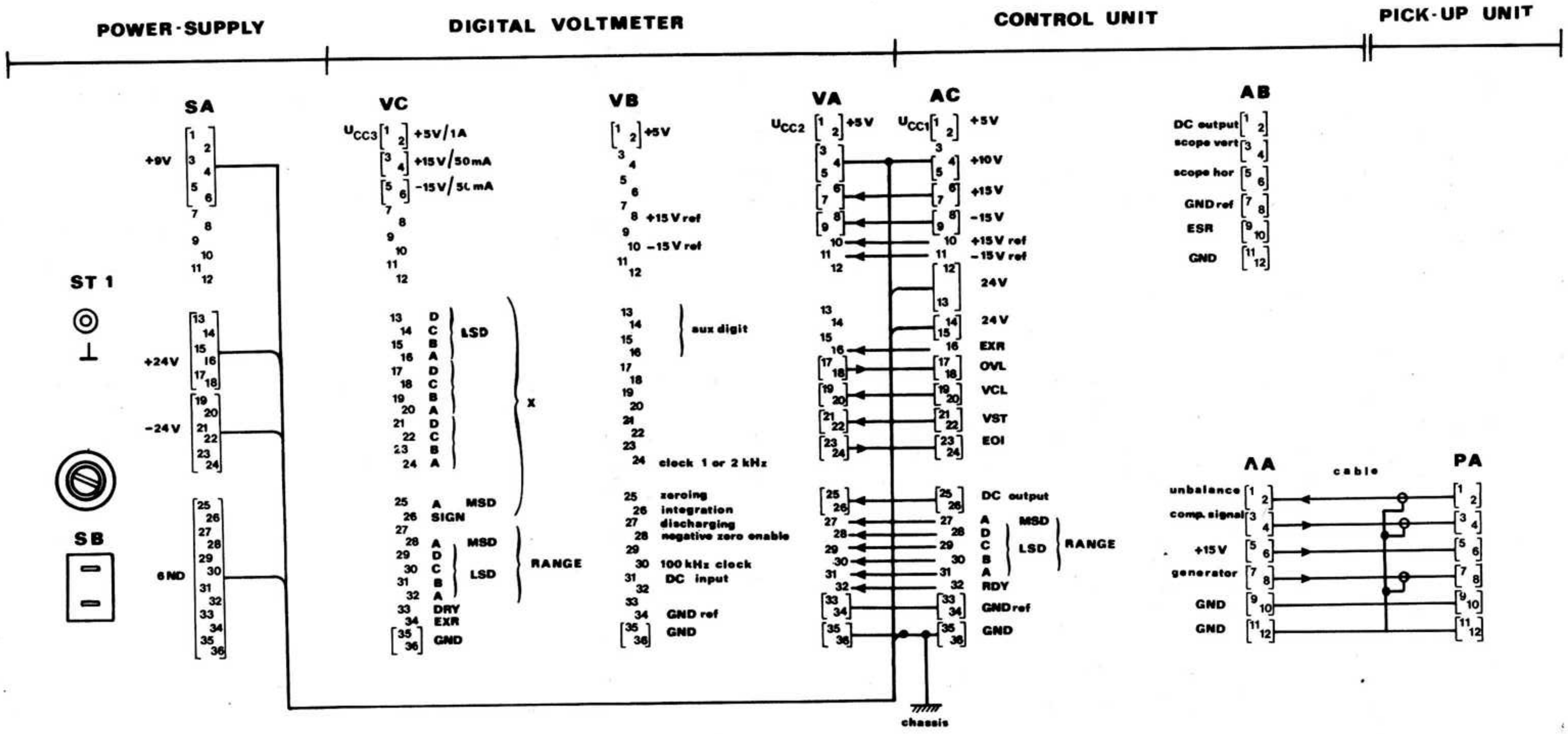


Fig. 8. Connectors and terminals on the rear panel of the measuring unit and the rear side of the pick-up unit

4. THEORETICAL PRINCIPLES OF MEASUREMENT OF THE MAGNETIC SUSCEPTIBILITY OF ROCKS

By the magnetic susceptibility of rocks we understand the magnetic susceptibility in a weak field where, within a certain approximation, the rock behaves as a magnetically linear, generally anisotropic medium. For the sake of being brief, in the following text we shall leave out the word "magnetic", and use **SB** for "susceptibility" and **TSB** for "total suceptibility".

The theory of **SB** measurements, in particular the **SB** of anisotropic materials, is somewhat complicated. Therefore, we shall mention the most important terms and equations only. The subject is discussed in greater detail in the monograph (1).

4.1 THE SUSCEPTIBILITY TENSOR

Let us consider a magnetically linear medium. $\underline{\mathbf{H}}$ is the vector of the magnetic field intensity with the components $\mathbf{H_1}$, $\mathbf{H_2}$, $\mathbf{H_3}$. $\underline{\mathbf{J}}$ is the vector of induced magnetic polarization with the components $\mathbf{J_1}$, $\mathbf{J_2}$, $\mathbf{J_3}$; the components are related to a certain fixed Cartesian coordinate system.

The linear relations between the components of both vectors can be expressed by a matrix equation,

$$(1) \qquad \begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} = \mu_0 \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix} \times \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix},$$

where μ_0 is the permeability of vacuum ($4\pi \times 10^{-7}$ H/m) and $\mathbf{k}_{ij}$ are dimensionless constants. They can be interpreted as components of the 2nd order tensor called the susceptibility tensor and denoted $\underline{\underline{\mathbf{k}}}$.

Let us denote the matrices expressing the vectors $\underline{\mathbf{H}}$, $\underline{\mathbf{J}}$ and the tensor $\underline{\underline{\mathbf{k}}}$ in the chosen coordinate system also with the symbols $\underline{\mathbf{H}}$, $\underline{\mathbf{J}}$ and $\underline{\underline{\mathbf{k}}}$. Equation (1) can be written more briefly,

$$\underline{J} = \mu_0 \, \underline{\underline{k}} \, \underline{H}. \tag{2}$$

Since the suceptibility tensor is symmetric,

$$k_{ij} = k_{ji} \qquad (i, j = 1, 2, 3), \tag{3}$$

and it has only 6 independet components.

4.2 DIRECTIONAL SUSCEPTIBILITY

Let us choose a certain direction defined by the unit vector $\underline{\mathbf{d}}$. The matrix expressing the vector is also denoted $\underline{\mathbf{d}}$,

$$\underline{d} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix}. \tag{4}$$

Assume the vector of the magnetic field intensity $\underline{\mathbf{H}}$ to be parallel to this direction, so that

$$\underline{H} = \underline{d} \, H, \tag{5}$$

where $\underline{\mathbf{H}}$ is not-negative number expressing the magnitude of the magnetic field intensity.

The magnetic polarization vector $\underline{\mathbf{J}}$ generally deviates from the direction of the vector $\underline{\mathbf{H}}$. Its perpendicular projection into the direction $\underline{\mathbf{d}}$ is denoted $\mathbf{J_D}$. Then

(6) $$J_{\mathbf{D}} = \underline{d}' \, \underline{J},$$

where $\underline{\mathbf{d}}'$ is the matrix transposed to $\underline{\mathbf{d}}$.

From equations (2, 5, 6) it follows that

(7) $$J_{\mathbf{D}} = \mu_0 \, \underline{d}' \, \underline{\underline{k}} \, \underline{d} \, H.$$

If we introduce the notation

(8) $$\varkappa_{\mathbf{D}} = \mu_0 \, \underline{d}' \, \underline{\underline{k}} \, \underline{d},$$

equation (7) can be re-written in a simpler form:

(9) $$J_{\mathbf{D}} = \mu_0 \, \varkappa_{\mathbf{D}} \, H.$$

The quantity $\varkappa_{\mathbf{D}}$ defined by equation (8) is called the directional **SB** of the medium respective to the direction $\underline{\mathbf{d}}$. The quantity, as we shall see, is of basic importance for theory of the bridge.

4.3 DETERMINATION OF THE SUSCEPTIBILITY TENSOR FROM DIRECTIONAL SUSCEPTIBILITIES

The **SB** tensor can be determined in terms of the directional **SB**´s. As the **SB** tensor has 6 independent components, measurement of 6 directional **SB**´s in 6 suitably chosen directions is sufficient. However, the measurement is made in a greater number of directions, and thus the influence of measuring errors can be decreased. Further it is possible to estimate the accuracy of results statistically and to exclude erroneous measurements.

The least-squares method is employed for the calculation. The resulting relation for a system of **n** directions can be written in the form

(10) $$\underline{k} = \underline{\underline{B}}\, \underline{\varkappa}_D ,$$

where $$\underline{k} = [k_{11} \;\; k_{22} \;\; k_{33} \;\; k_{12} \;\; k_{23} \;\; k_{31}] ,$$

$$\underline{\varkappa}_D = [\varkappa_{D1} \;\; \varkappa_{D2} \;\; . \;\; . \;\; . \;\; \varkappa_{Dn}] ,$$

$\underline{\underline{B}}$ is a 6 by **n** matrix. The matrix $\underline{\underline{B}}$ is constant for the given system and can easily be determined.

There are certain especially suitable patterns of directions called rotatable. For measurements on the bridge we choose a rotatable pattern of 15 directions, which will be described in detail section 5.3.

The form of the matrix $\underline{\underline{B}}$ for this pattern is as follows

$$\frac{1}{20}\begin{bmatrix} 3 & 3 & 8 & 3 & 3 & -2 & -2 & -2 & -2 & -2 & 3 & 3 & -2 & 3 & 3 \\ 3 & 3 & -2 & 3 & 3 & 3 & 3 & 8 & 3 & 3 & -2 & -2 & -2 & -2 & -2 \\ -2 & -2 & -2 & -2 & -2 & 3 & 3 & -2 & 3 & 3 & 3 & 3 & 8 & 3 & 3 \\ -5 & 5 & 0 & -5 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -5 & 5 & 0 & -5 & 5 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5 & 5 & 0 & -5 & 5 \end{bmatrix}.$$

4.4 PRINCIPAL SUSCEPTIBILITIES AND PRINCIPAL DIRECTIONS

Let us denote the eigenvalues of the matrix $\underline{\underline{k}}$ with $\varkappa_1, \varkappa_2, \varkappa_3$ and the respective unit eigenvectors with $\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3$. These quantities, as we know, satisfy equation

(11) $$\underline{\underline{k}}\, \underline{p}_i = \varkappa_i\, \underline{p}_i .$$

The numbers $\varkappa_1$, $\varkappa_2$, $\varkappa_3$ are called the principal susceptibilities, the vectors $\underline{\mathbf{p}}_1$, $\underline{\mathbf{p}}_2$, $\underline{\mathbf{p}}_3$ are called the vectors of principal directions.

For formal reasons, we choose such a numbering of the eigenvalues so that

$$\varkappa_1 \geqq \varkappa_2 \geqq \varkappa_3 . \tag{12}$$

The quantity $\varkappa_1$ ($\varkappa_2$, $\varkappa_3$) is called the maximum (intermediate, minimum) **SB**. The maximum (minimum) **SB** is equal to the maximum (minimum) value of all directional **SB**´s.

The vectors $\underline{\mathbf{p}}_1$, $\underline{\mathbf{p}}_2$, $\underline{\mathbf{p}}_3$, always from an orthogonal system.

4.5 MEAN SUSCEPTIBILITY

The mean **SB** $\varkappa$ is defined as the mean value of directional **SB** of all directions while the same weight is assigned to each direction. From the transformation properties of the **SB** tensor it follows that the mean **SB** is equal to the arithmetic mean of the three directional **SB** s measured in three arbitrary mutually perpendicular directions. Therefore, the mean **SB** is also the mean of the three principal **SB**´s.

$$\varkappa = (\varkappa_1 + \varkappa_2 + \varkappa_3) / 3 . \tag{13}$$

4.6 ISOTROPIC MEDIUM SUSCEPTIBILITY

An isotropic medium can be undersood as a special case of the anisotropic medium. The matrix expressing here the **SB** tensor is in the form

$$\underline{\underline{k}} = \varkappa \, \underline{\underline{1}} , \tag{14}$$

where $\underline{\underline{1}}$ is the unit matrix. The **SB** $\varkappa$ is also the mean **SB**.

4.7 DIRECTIONAL TOTAL SUSCEPTIBILITY

In principle the bridge gives the directional **SB** of the axis of the pick-up coil; however, the reading also depends on the volume of the bridge and in more strongly magnetic materials it may also be influenced by the demagnetization effect. It is, therefore, useful to introduce an auxiliary quantity - the directional total susceptibility (directional **TSB**) in which the bridge can be calibrated. Meantime, for the sake of simplicity, we shall not take into account the influence of the holder. Let us assume that we measure a specimen with such a low susceptibility that the influence of demagnetization can be neglected. This means that the inner field of the specimen $\underline{\mathbf{H}}$ does not actually differ from the outer field that would be measured if the specimen were removed from the space in which it was placed.

A specimen of the volume **V** causes a relative change of inductivity,

$$\Delta L/L = C\ V \varkappa_{\mathbf{D}}\ , \tag{15}$$

where **C** is a constant characterizing the pick-up coil and $\varkappa_{\mathbf{D}}$ is the directional **SB** of the specimen in the direction of the axis of the coil. The volumes of specimens vary within the tolerance given by the construction of the instrument.

However, let us introduce a certain constant nominal volume $\mathbf{V_0}$ that will be characteristic for the given pick-up unit. Equation (15) will then read

$$\Delta L/L = C\ V_0\ \vartheta_{\mathbf{D}}\ , \tag{16}$$

we shall call the quantity $\vartheta_{\mathbf{D}}$ the directional total **SB.** Further we shall introduce the constant

$$\eta = C\ V_0\ , \tag{17}$$

that is called the factor of filling the coil with the specimen, so that

(18) $$\Delta L/L = \eta \, \vartheta_{D} \, .$$

If the shape of the coil is that of a long thin solenoid, the filling factor is approximately equal to the ratio of the nominal volume V_0 and of the volume of the interior of the solenoid.

The directional **SB** is calculated from the directional **TSB** according to the simple equation.

(19) $$\varkappa_{D} = \frac{V_0}{V} \, \vartheta_{D} \, ,$$

directly following from (15, 16).

For the pick-up unit KLY-2.1 (KLY-2.2) the nominal volume $V_0 = 10 \text{ cm}^3$ (65 cm^3) and the filling factor is 2.3 % (2.9 %).

4.8 INFLUENCE OF THE DEMAGNETIZATION EFFECT

We have so far assumed that the demagnetization effect can be neglected. This is true for $\varkappa < 0.02$ (ranges 1 - 8), say.

If the demagnetization effect cannot be neglected, the situation becomes complicated. The specimen manifests itself not by the **SB** tensor $\underline{\underline{\mathbf{k}}}$, but by the so-called apparent **SB** tensor $\underline{\underline{\mathbf{k}}}^*$ influenced by the demagnetization effect.

The directional **TBS** maintains its meaning given by the equation (18). From the directional **TBS** we can calculate, using the analogous equation (19), the apparent directional **SB** $\varkappa^*$

(20) $$\varkappa_{\mathbf{D}}^{*} = \frac{V_0}{V} \vartheta_{\mathbf{D}} .$$

The apparent directional **SB**´s $\varkappa^*_{\mathbf{D}}$ are related to the tensor $\underline{\underline{\mathbf{k}}}^*$ similarly as the directional **SB**´s $\varkappa_{\mathbf{D}}$ to the tensor $\underline{\underline{\mathbf{k}}}$.

It is possible to find a simple relationship for calculating the tensor $\underline{\underline{\mathbf{k}}}^*$ from the tensor $\underline{\underline{\mathbf{k}}}$ for spherical specimens only. In this case

(21) $$\underline{\underline{k}} = \underline{\underline{k}}^* \left(1 - \frac{1}{3} \underline{\underline{k}}^*\right)^{-1} .$$

If the spherical specimen is isotropic, we use an equation following from (21) for its **SB**

(22) $$\varkappa = \varkappa^* / \left(1 - \frac{1}{3} \varkappa^*\right) .$$

This relationship holds approximately also for calculating the mean **SB** from the apparent mean **SB** of a weakly anisotropic specimen.

The given correction relationship hold roughly for specimens similar to sphere (cube, cylinder with an approx. square cross-section). In spite of this, they may only be used if the introduced corrections are not too large, i.e. if the mean **SB** does not exceed several units of the order 10^{-1}, which is satisfied even in the highest ranges of the bridge.

The corrections cannot be made for fragment specimens.

4.9 INFLUENCE OF THE SPECIMEN HOLDER

When specimens with very low **SB** are measured we have to consider the influence of the holder. The holder is made of diamagnetic material (perspex, polyamide). The holder as a whole shows a certain negative **TSB** ϑ_D.

An immediate result of the measurement is the directional **TSB** of the specimen with the holder. The directional **TSB** of the specimen itself is then calculated from the equation

$$\vartheta_D = \vartheta'_D - \vartheta_H \quad . \tag{23}$$

5. METHODOLOGY OF MEASUREMENT

5.1 GENERAL INFORMATION

5.1.1 Installation of the bridge, arrangemet of the working place

The bridge must be installed in a magnetically undisturbed environment with a constant temperature. There must be no sources of **AC** or pulse magnetic fields, e.g. large transformers, eletric motors, contactors, etc., in the laboratory and its vicinity. The room must be closed and the heating (or air conditioning) such that the changes of temperature are minimmal and as slow as possible.

The arrangement of the working place is illustrated in Fig. 9. The measuring unit is placed on the table top desk. The pick-up unit is located on a special stand close to the left-hand edge of the table or rather shifted somewhat forward. The top surface of the pick-up unit should be with the surface of the top desk. With his left hand the operator inserts and pulls out the specimen from the pick-up unit and controls the measuring unit with his right hand. The distance between the operator and the pick-up unit should be as large as possible.

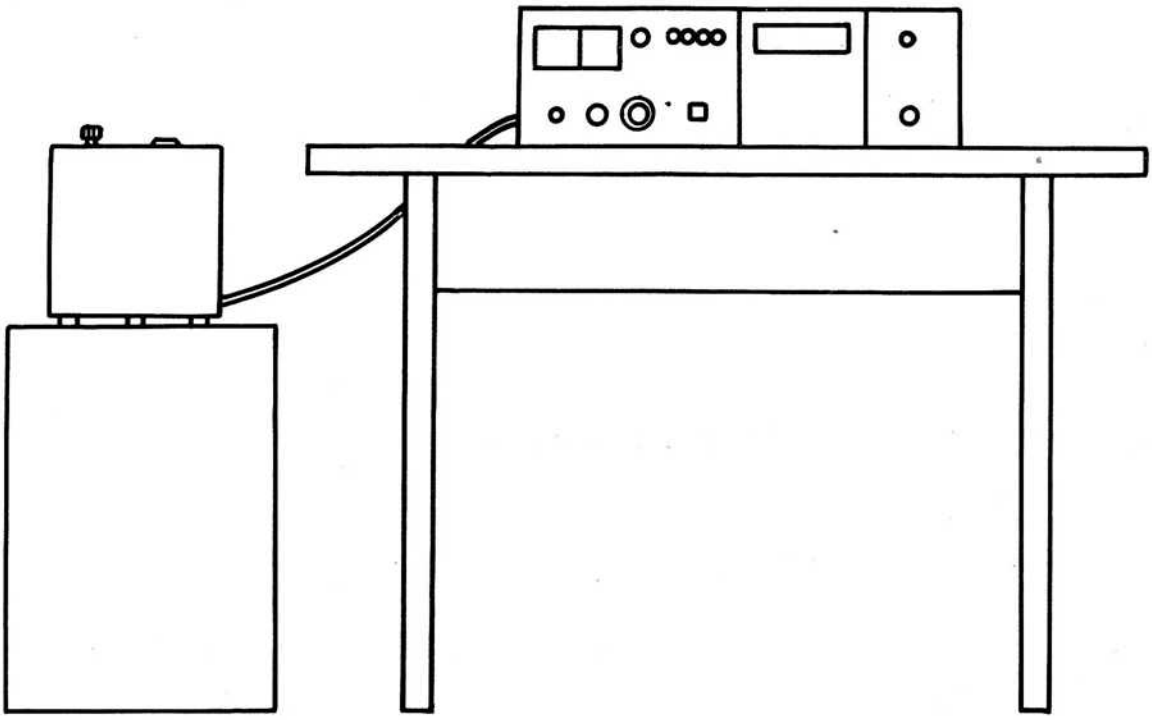


Fig. 9. **Kappabridge KLY-2** working place arangement

The working top desk, the stand of the pick-up unit and the chair of the operator must not be made of metal to avoid disturbing the pick-up unit. The operator should work without wrist-watch, rings, etc.

The pick-up unit and the measuring unit are connected by a cable, in the measuring unit, the cable should be connected to the lower twelve-pin connector designated **AA** in Fig. 8.

It is recommended to connect the terminal **ST1** to an operational earthing. However, it does not have protective function.

5.1.2 Shapes of specimen, holders

In the KLY-2.1 pick-up unit cubic specimens with an edge of 20 mm (8 cm^3), cylindrical specimens ⌀ 25.4 x 22 mm (11.15 cm^3) or crushed specimens in the 40 cm^3 measuring vessel can be measured.

The holder of cubic specimens is illustrated in Fig. 10a. The holder of cylindrical specimens with a cylindrical capsule is in Fig. 10b. This holder consists of two parts; the specimen is inserted in a capsule that is put in the holder. The holder of cylindrical specimens with a spherical capsule is similar, see Fig. 10c.

The holder of cylindrical specimens with a cylindrical capsule as shown in Fig. 10b, is universal. It can be used for measurement of specimens with very low to very high **SB**´s. The shape and size of the specimen need not be too accurate. However, it is a disadvantage if the individual measuring positions are not defined precisely. With the holder of spherical specimens (Fig. 10c) all positions are precisely defined; due to its high intrinsic **TBS** the holder is suitable for specimens with high **SB** (starting from the 3rd range, say). The dimensions of the specimen must be accurate, in particular the length.

The KLY-2.2 pick-up unit is designated for measurement of cubic specimens with an edge of 38 mm (54.87 cm^3), cylindrical specimens ⌀ 46 x 40 mm (66.48 cm^3) and specimens in the measuring vessel with the capacity of 240 cm^3.

The holders, the measuring vessel and the calibration standard are quite similar to those of the KLY-2.1. As an addition, a holder of spherical specimens 50 mm in diam. (65.45 cm^3) has been designed.

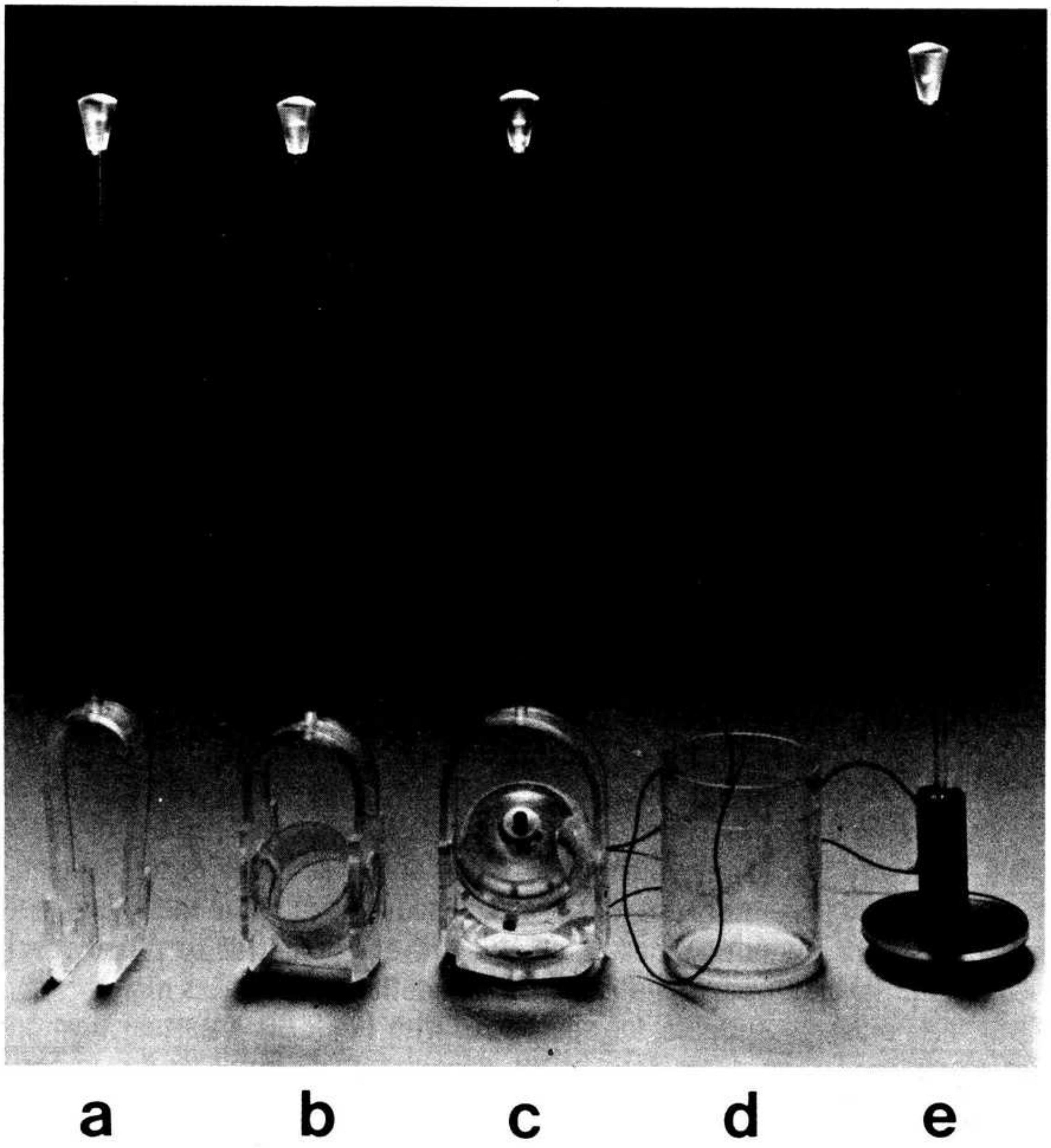


Fig. 10. Accessories of the pick-up unit KLY-2

a) cubic specimen holder
b) cylindrical specimen holder with cylindrical capsule
c) cylindrical specimen holder with spherical capsule
d) measuring vessel
e) calibration standard

According to the customer's specification, holders of cubic and cylindrical specimens of slightly different dimensions can be delivered. This mainly concerns the KLY-2.2 unit.

5.1.3 Calibration standards

A standard of susceptibility is delivered with each pick-up unit.

The standard for the KLY-2.1 pick-up unit is in Fig. 10e; the standard for the KLY-2.2 differs in dimensions only. In the bottom cylindrical part of the standard, there is a small ferromagnetic particle.

On each standard there are written:

a) the registration number
b) the nominal volume V_0
c) the number of the range for which the standard is designed
d) the nominal reading of the display **DATA**.

The reading **DATA** is determined by the reference bridge, previously calibrated with the primary standard. A coil of precisely defined dimensions that is inserted into the measuring coil of the bridge and is loaded with a suitable two-pole of mainly inductive character, is used as the primary standard.

5.1.4 Measuring ranges

The measuring ranges are given in the following table:

Range No	Range factor 10^{-6} (SI)	Full range 10^{-6} (SI)
1	0.05	100
2	0.1	200
3	0.2	400
4	0.5	1 000
5	1	2 000
6	2	4 000
7	5	10 000
8	10	20 000
9	20	40 000
10	50	100 000
11	100	200 000

The ranges are switched over with the **S1 RANGE SELECTOR** (Fig. 7). Each position of the selector is designated with the respective range factor. The sequential number of the range is also indicated by the display **RANGE**.

Data measured by the digital voltmeter are indicated by the display **DATA** with 3 1/2 digits, i.e. the value shown is within the range 0 to ± 1 999.

The directional **TSB** of the specimen with the holder is calculated according to equation

$$\vartheta'_{D} = K \times 10^{-6} \qquad (24)$$

where **K** is the range factor, **X** the reading of the display **DATA**.

5.2 INSTRUCTIONS FOR MEASUREMENT

In this section we are referring to Fig. 7.

5.2.1 Switching on and off

It is necessary to make sure that the voltage on the type label is the same as that of the mains.

The bridge is switched on by setting the switch **S** (POWER) to the position. The operating state is indicated by the green **LED** diode **LD** on the panel. The bridge then transfers to the status **WAIT** (red **LD1**), or to the status **READY** (green **LD2**). Also the displays **RANGE** and **DATA** light up.

The bridge is switched off by setting the switch **S** (POWER) to the position **OFF**.

5.2.2 Zeroing

The zeroing is manual and automatic. In manual zeroing the real component of unbalance (corresponding to detuning in the inductive component, i.e. in **SB**) as well as the imaginary component (corresponding to detuning in the resistive component). Automatic zeroing concerns the real component only and within the lowest 6 ranges it also includes automatic drift compensation. The zeroing is performed with the specimen out of the bridge.

Manual zeroing must be performed after switching the bridge on and repeated during the operation if, in the chosen measuring range, any of the indicators **M1** R_E and **M2** I_M shows a deflection exceeding 1/2 of the scale.

Manual zeroing is performed in the status **WAIT** (red **LD1** on) or **READY** (green **LD2** on). If the bridge is in the status **HALT** (red **LD4**), it is brought to **WAIT/READY** by pressing the button **PB1 START/RESET**. If the bridge is in the status **MEASURE** (yellow **LD3** on), it enters the status **HALT** automatically. Then **PB1** is pressed.

The procedure is as follows:

1. Check if needles of panel meters R_E and I_M are within the scale range. If so, go to 3.
2. Turn **RANGE SELECTOR** clockwise until needles of R_E and I_M are within the scale range.
3. Set zero on R_E with the button on the pick-up unit, set zero on I_M with the potentiometer I_M.
4. If the chosen range (i.e. the range in which we intend to measure) is identical with the range set, the zeroing is accomplished.
5. Turn the **RANGE SELECTOR** counter-clockwise and improve the accuracy of zeroing until the chosen range is reached.
   The zeroing is accomplished.

Note: As we sometimes do not know in advance in which range we shall measure, it may be useful to increase the accuracy of zeroing until the first range is reached.

If the bridge is manually zeroed or if at least the needle deflections on R_E, I_M are within the tolerance, automatic zeroing is going on in the statuses **WAIT**, **READY** and **HALT**. In the status **WAIT**, its course can be observed on the display **DATA**.

Let us presume that after the operation with the bridge (zeroing, range switching, removal of the specimen at a wrong moment) the reading of the display **DATA** is not zero and the bridge is in the status **WAIT**. The voltmeter measures repeatedly the residual unbalance that drops to zero in the lowest 6 ranges with one overshoot, in the other ranges aperiodically. After some time the display reading drops to zero. With a delay of several seconds the bridge converts to the status **READY** and is ready for measurement.

It may occur that in the status **READY** the balance is disturbed due to an outside effect. In such a case the bridge passes to the status **WAIT**. However, within a short time it reverts to the status **READY**.

5.2.3 Measurement of **TSB** of specimen with holder

The measurement of directional **TBS** is a basis for measuring the mean **SB** and the anisotropy of **SB** (see 5.3 and 5.4). Of special importance is the selection of the measuring range (5.2.4).

The procedure of measurement:

1. Set the bridge to the status **WAIT** or **READY** according to 5.2.2.
2. By turning **RANGE SELECTOR** set the chosen (corrected) measuring range. If necessary, perform zeroing manually.
3. If the bridge is in the status **WAIT**, wait until it converts to the status **READY** by automatic zeroing.
4. Press the button **START/RESET**, the bridge enters the status **MEASURE**. Insert the specimen into the pick-up coil as quickly as possible and remove hands from the pick-up unit.
5. Approx. 4 s after pressing **START/RESET** an acoustic signal sounds. Take the specimen out quickly and remove hands.
6. After another 3 s the bridge enters the status **HALT**. If blinking 1999 appears in the display **DATA**, the bridge is overloaded and the measurement must be repeated in a higher range.
   If the display does not flash, judge, according to the criteria in 5.2.4, whether the appropriate measuring range has been selected. If so, record the reading. Otherwise change the range.

If the second or any subsequent measurement of the directional **TSB** of the same specimen is concerned, and the bridge is not overloaded, record the reading.

7. Press the button **START/RESET**. The bridge enters the status **WAIT** or directly the status **READY**.
8. If the range need not be changed, continue from item 3. In the opposite case find the corrected range according to 5.2.4 and continue from 2.

Note: In the status **WAIT** the button **START/RESET** is disabled so that the measurement cannot be started. Similarly, the push-button is disabled in the status **MEASURE**.

The directional **TSB** of a specimen with holder is calculated according to eq. (24).

5.2.4 Measuring range selection

This is a slightly complicated matter as there is a great number of ranges, and each switching of the range selector means a loss of 10 - 20 s before the bridge reaches the steady state again.

As mentioned in 4.4 and 4.5, several directional **TSB**´s are measured on one specimen: to determine the mean **SB** usually 3 **TSB**´s, to determine anisotropy 15 **TSB**´s. All these directional **TSB**´s must be measured in one range. We try to find the lowest range in which the bridge will not be overloaded by any of the directional **TSB**´s measured.

In order to be able to select the measuring range according to certain rules, we shall assume that the values of the second and of any subsequent directional **TSB** are 25 % higher at the most than the first **TSB** measured, according to which the range is being selected. This assumption can be changed with respect to the degree of anisotropy of the particular material studied.

When measuring the mean **SB** we shall limit ourselves to the decadic ranges only, i.e. ranges 2, 5, 8, 11 with corresponding factors 0.1, 1, 10, 100 x 10^{-6}.

By way of trial the decadic range where the value **X** of the first **TSB** measured is within 160 - 1600. We can end in the first decadic range without fulfilling this condition; we shall then measure in this range. Similarly, we can end in the highest range without fulfilling the condition. If there is no overload when the first directional **TSB** is measured, we can try to make the whole measurement because it is likely that the overload will not occur during measurements of further **TSB**´s.

When measuring the anisotropy of **SB** we make use of all ranges in order not to lose the resolving power.

For the directional **TSB** we are seeking a range where **X** is roughly within 640 - 1600 and 800 - 1600; for the ranges 4, 7, 10, and for the remaining ranges, respectively. Limitations in the lowest and in the highest range are analogous to the previous case.

To seek the range just by trial and error would be too tedious in this case. Therefore, we shall use a different way. First we try to find the decadic range where **X** is within 32 - 1999. (If we do not reach the value 32 even in the lowest decadic range, we shall measure in the first range). We shall then correct the range according to the table:

Reading **X**	Range Correction
1600 - 1999	+1
800 - 1599	0
320 - 799	-1
160 - 319	-2

Reading **X**	Range Correction
80 - 159	-3
32 - 79	-4

Example: In the range 8 we have found that $X^{\cdot} = 220$. Therefore, we shall measure 2 ranges lower, i.e. in the range 6.

5.2.5 Measurement of the **TSB** of the holder

The **TSB** of the holder ϑ_H is measured in the same way as the directional **TSB** of the specimen with the holder described in 5.2.3. It is a certain simplification that the measurements are always made in the lowest range. There are **N** measurements (usually N = 5) made for the given holder. The arithmetic mean is taken for the result,

$$\vartheta_H = 0.05 \, \frac{1}{N} \sum_{i=1}^{N} X_i \, , \tag{25}$$

where X_i is the reading of the display **DATA** for the i-th measurement.

5.2.6 Calibration

It is essential to calibrate the bridge every day before begining the work. Besides, the instrument must be calibrated always when the pick-up unit is changed.

For calibration we use the respective standard. We read the range sequential number and the nominal reading X_N on the display **DATA**, see section 5.1.3. We shall then zero the bridge, set the range **R** and measure the directional **TSB** of the standard. If the indicated value **X** is higher (lower) than the nominal value X_N, we turn the potentiometer **CALIBRATION** counter-clockwise (clockwise). We repeat the procedure several times until **X** and X_N coincide.

The instrument should be calibrated at a temperature of approx. 22° C.

5.2.7 Setting the phase conditions

This is performed in longer time intervals and always when the pick-up unit is changed.

In range **5** the bridge is accurately zeroed. With the knob I_M set about 1/2 of the f.s.d. of the meter I_M. In connection with this the reading of the meter R_E may change. The meter R_E is reset to zero by the potentiometer **PHASE**. The procedure is repeated several times.

5.2.8 Check of the stability of zero

Errors in measurements of specimens with low **SB**, and thus also the sensitivity, depend on the stability of zero. The stability is influenced by the noise of the instrument, the irregular thermal drift of coils, disturbing magnetic fields, mechanical vibrations, etc.

The stability of zero can be checked. We zero the bridge in the lowest range and measure a "zero specimen", i.e. we do not insert any specimen in the measuring coil. The instability of zero is usually due to inconvenient working conditions. On the other hand, the instability may indicate a defect of the instrument.

5.3 MEASUREMENT OF THE ANISOTROPY OF SUSCEPTIBILITY

To determine the anisotropy of **SB** means finding the tensor of **SB**, a system of three principal **SB**´s and a system of the respective principal directions.

For the measurement of the anisotropy of **SB** we choose the rotatable pattern of 15 directions described in (1). In this system the respective directional **TSB**´s are measured.

In measuring in the lowest ranges it is recommended to measure each directional **TSB** twice and to calculate the average that is taken for the result. If the difference of the two values for a certain **TSB** is too great, the measurement should be repeated.

Now we shall show how the rotatable pattern mentioned is applied to a cubic and to a cylindrical specimen. (As the measurement of a spherical specimen is too special, it will not be described here).

Note that the system of directions is defined in the so-called specimen coordinate system, the axes x_1, x_2 and x_3 of which are associated with the characteristic directions in the geometrical shape of the specimen.

5.3.1. Cubic specimen

The axes of the coordinate system are identical with the edges of the specimen. The specimen is marked with a simple, a double, and a triple arrow as illustrated in Fig. 11.

The specimen is inserted in the holder so that it successively assumes all the 15 positions shown in Fig. 12.

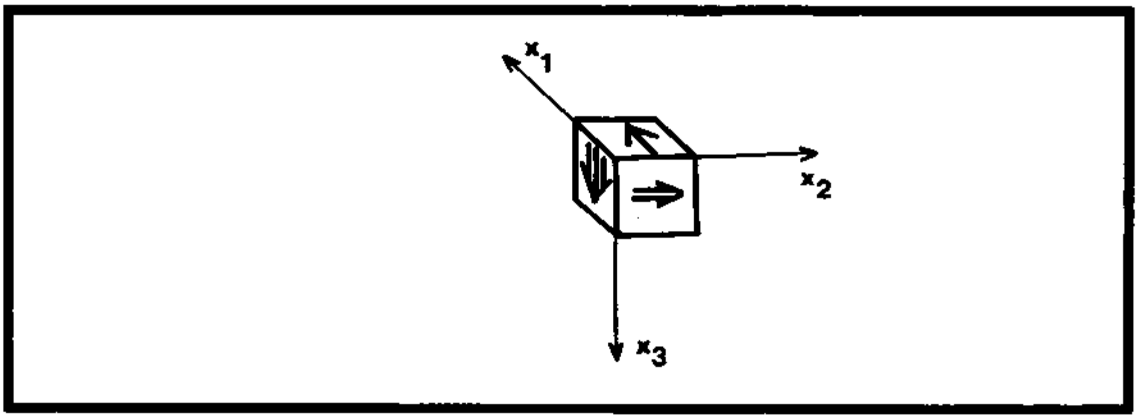


Fig. 11. Cubic specimen marking for anisotropy measurements

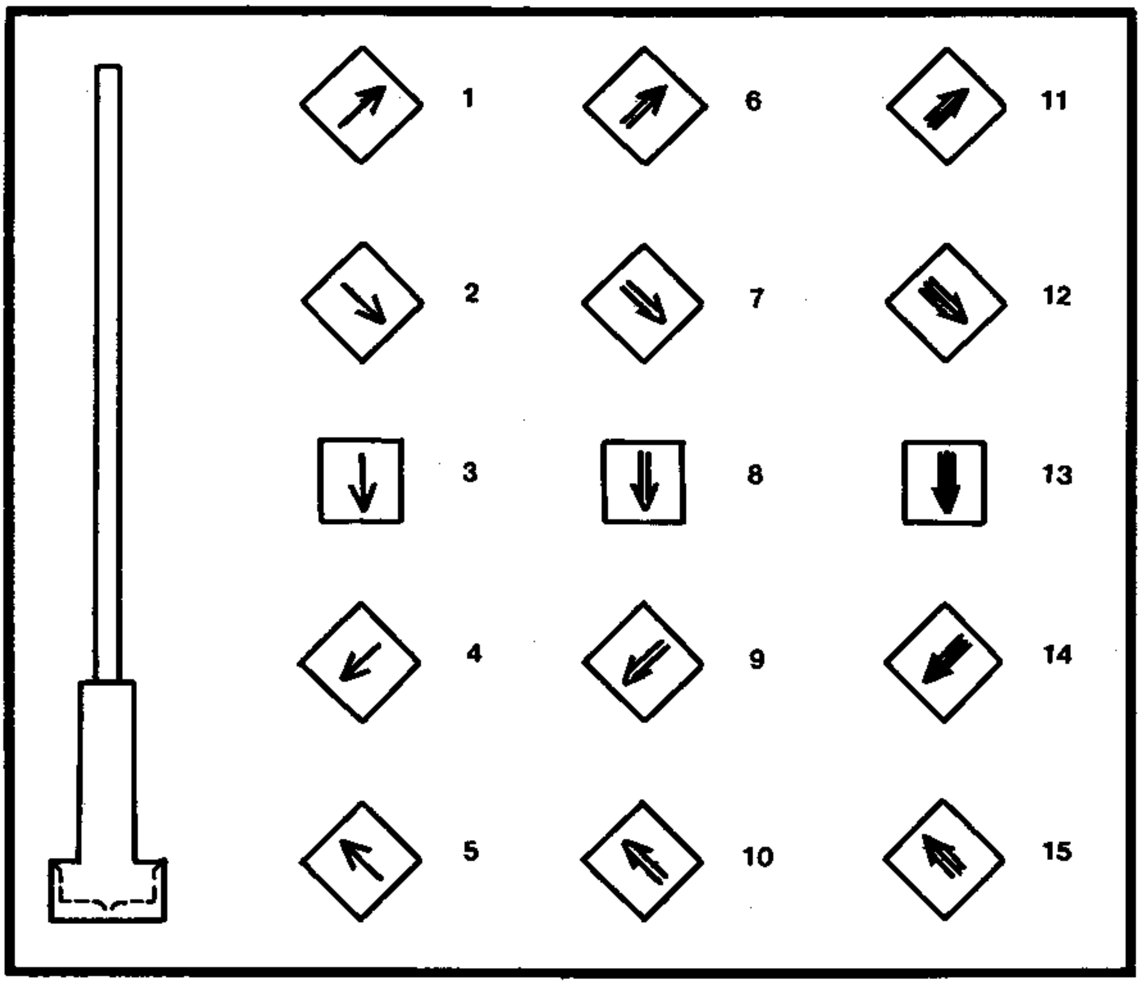


Fig. 12. Implemenation of the rotatable pattern of 15 measuring directions for a cubic specimen

5.3.2 Cylindrical specimen

The axis x_1 is identical with the arrow on the base of the cylinder, the axis x_2 is identical with the abscissa leading from the arrow, the axis x_3 is identical with the axis of the cylinder, see Figs. 13a and 15a.

The cylindral capsule is cut along the surface line. The specimen can be pressed into the capsule. For correct orientation of the specimen with respect to the capsule there are five signs at the edge of the capsule, see, e.g., Fig. 13b.

In the first five measuring positions, the position of the capsule towards the holder is fixed, the axis of the capsule is constantly horizontal. In manipulating with the holder, the operator turns it with the capsule to wards him as illustrated in Fig. 14 (upper left). He turns the specimen to positions 1 - 5.

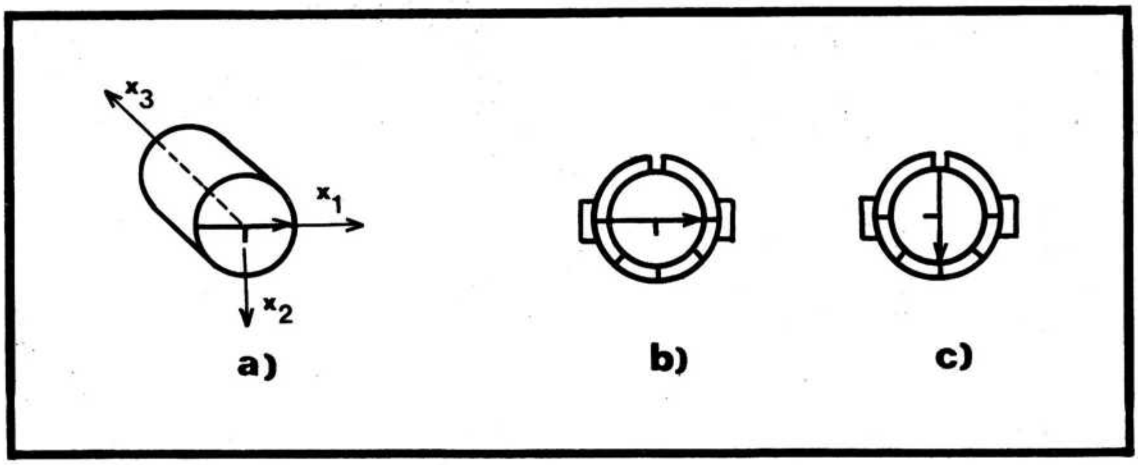


Fig. 13. a) Cylindrical specimen marking for anisotropy measurement
b) Cylindrical specimen position in cylindrical capsule for measuring positions 6 to 10
c) the same for measuring positions 11 to 15

In the second (third) five measuring positions the specimen is in a fixed position towards the capsule as in Fig. 13b (13c). The operator turns the holder towards him as illustrated in Fig. 14 (below left). The capsule with the specimen is inserted into the holder so that the double (triple) arrow on the protrusion of the capsule can be seen in positions 6 - 10 (11 - 15).

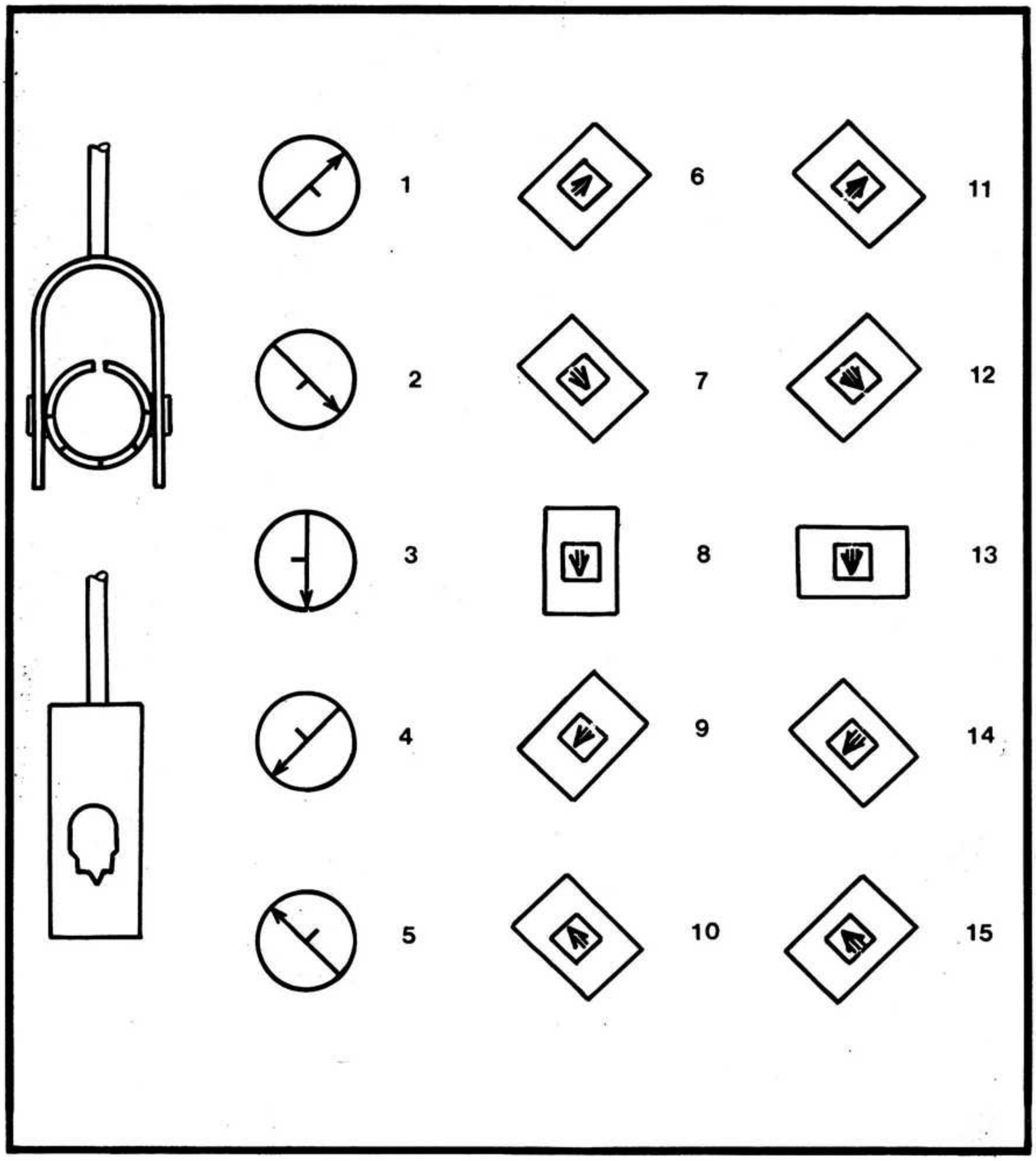


Fig. 14. Implementation of the rotatable pattern of 15 measuring positions for cylindrical specimen in the holder with cylindrical capsule

The measurement with the holder with the spherical capsule is slightly simpler. Before the measurement the specimen is fixed in the capsule. The capsule is screwed apart, a rubber inset is inserted into the lower part (without the cut) and the specimen is placed on it with the marked side up. The upper part of the capsule (with the cut) is fitted on. The arrow on the specimen must coincide with the line on the upper part of the capsule. The line perpendicular to the arrow must point to the cut. With his thumb the operator will fix the specimen in this position through the cut, and screw the lower part of the capsule tight.

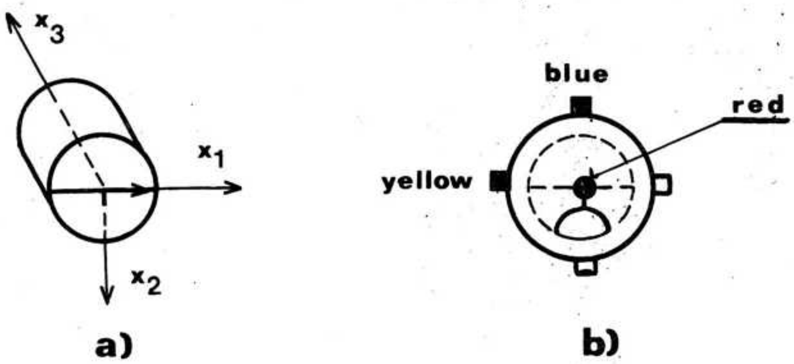
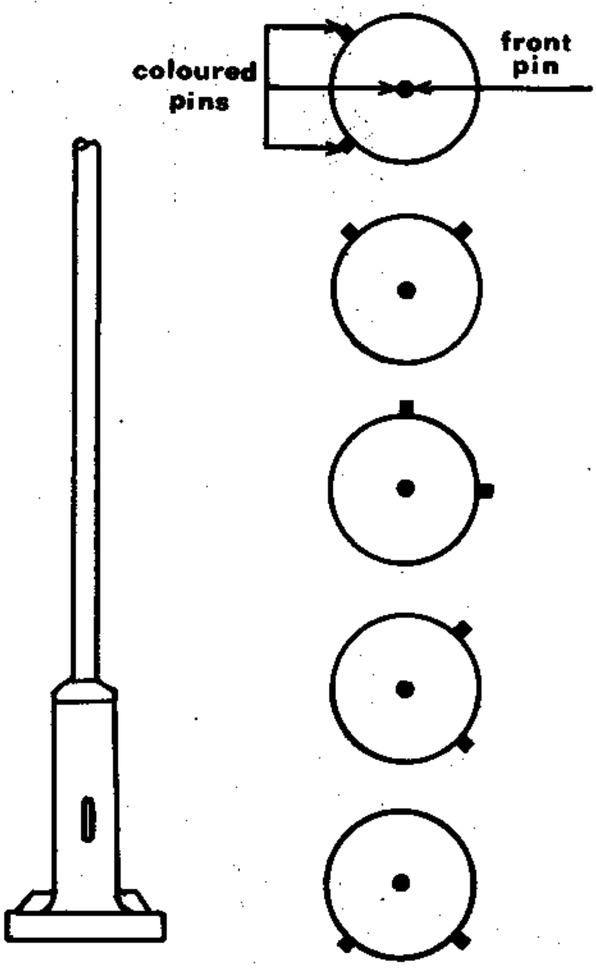


Fig. 15. a) Cylindrical specimen marking for anisotropy measurement
b) Cylindrical specimen position in spherical capsule

The specimen will successively assume the 15 positions marked in Fig. 16. There are 6 pins protruding from the spherical capsule for fixing the specimen in these positions. 3 of these pins (red, yellow and blue) serve for identification.



	front pin	
red	yellow	blue
1	6	11
2	7	12
3	8	13
4	9	14
5	10	15

Fig. 16. Implementation of the rotatable pattern of 15 measuring positions for cylindrical specimen in the holder with spherical capsule

5.3.3 Processing

The result of the measurement are 15 directional **TSB**´s of the specimen with the holder ϑ_{Di}. After subtracting the **TSB** of the holder ϑ_H according to (23) and the correction for volume according to (19) we obtain

15 directional **SB**´s $\varkappa_{Di}$ of the specimen itself. The tensor of **SB** is then determined according to (10). Further we can calculate the principal **SB**´s and the principal directions as eigenvalues and eigenvectors of the matrix $\underline{\mathbf{k}}$.

If the demagnetization effect cannot be neglected in the highest ranges, we shall not calculate the tensor of susceptibility $\underline{\underline{\mathbf{k}}}$, but the tensor of apparent susceptibility $\underline{\underline{\mathbf{k}}}^{*}$. The tensor $\underline{\underline{\mathbf{k}}}$ can be determined approximately according to (21).

The processing of the anisotropy measurements is described in detail in the monograph (1) where also static tests, calculation of the so-called anisotropy factors, statistic estimates of precision of the results and transformation between different coordinate systems are included. The demagnetization effect is not taken into account.

In the monograph (1) the function of the computer program ANISO 10 written in FORTRAN IV language is explained. This program has been written for complex processing of data obtained by measurements with the KLY-1 bridge, the predecessor of the KLY-2. The listing of the ANISO 10 program is given in (2). For processing the data obtained by measuring with the KLY-2 a modified ANISO 11 program has been written also in FORTRAN IV.

5.4 MEASUREMENT OF THE MEAN SUSCEPTIBILITY

5.4.1 Cubic, cylindrical and spherical specimens

First we shall measure three directional **TSB**´s of the specimen with the holder ϑ'_{D1}, ϑ'_{D2}, ϑ'_{D3} in three mutually perpendicular directions. (With cubic and cylindrical specimens the directions may be those corresponding to positions 3, 8, 13).

We shall now calculate the arithmetic mean ϑ' and subtract the **TSB** of the holder from it. In this way we shall obtain the approximate mean **TSB**ϑ.

From this value, in accordance with (19), we shall calculate the mean **SB**

(26) $$\varkappa = \frac{V_0}{V}\,\vartheta$$

where V_0 , as already mentioned, is the nominal volume of specimen (10 or 65 cm^3) and **V** is the actual volume of the specimen.

If the demagnetization effect cannot be neglected (range 9 - 11) we shall calculate the approximate mean **SB**

(27) $$\varkappa^* = \frac{V_0}{V}\,\vartheta$$

and hence the approximate value of the mean **SB** according to (22). However, this procedure can only be used for specimens that are not highly anisotropic.

Often it is sufficient to measure one directional **SB** only and to interpret it as the mean **SB** affected by an error due to anisotropy. This simplified procedure can only be applied if we have made sure in previous measurements that the error due to the anisotropy of the rock considered is not too big.

5.4.2 Fragment specimens

We shall crush the specimen into fragments with which we fill the measuring vessel. If there is no other possibility, only one fragment of a sufficient size can be used.

The mean **SB** must be so low that neither the demagnetization effect of the fragments nor their mutual interaction need be considered. On this assumption, the mean **SB** of the adapted specimen in the measuring vessel is equal to the mean **SB** of the original specimen; however the adapted specimen is less anisotropic.

If this is not true, an error appears in the measurement that we can easily correct.

Now we shall measure the directional **SB** of the specimen in the measuring vessel several times, and after each measurement we shall shake the vessel and thus change the positions of the fragments inside. We shall calculate the arithmetic mean of the obtained values $\vartheta'_{D1}, \vartheta'_{D2}, \ldots, \vartheta'_{Dn}$. We shall then subtract the **TSB** of the specimen ϑ . The mean **SB** is then calculated according to the equation

$$\varkappa = \frac{V_0 \, s_0}{m} \, \vartheta \qquad (28)$$

where $\mathbf{V_0}$ is the nominal volume, $\mathbf{s_0}$ the bulk density of the specimen, **m** the mass of the specimen.

If the anisotropy of the rock is low and/or the number of the fragments in the measuring vessel is large enough, a single measurement will suffice.

5.5 A NOTE ON THE SENSITIVITY OF THE BRIDGE

We shall define the sensitivity of the bridge in the following way. Let us measure the directional **TSB** of the specimen repeatedly. Let the value of the measured quantity be very small so that the measurement can be made in the lowest measuring range. By the sensitivity of the bridge we shall understand the standard error of the measured directional **TSB**.

If the volume of the measured specimen is equal to the nominal volume V_0, the sensitivity is obviously equal to the standard error of the directional **SB** of the specimen.

The sensitivity of the bridge has been verified by measuring a perspex (methylacrylate) specimen. The voltmeter has been expanded by another, less significant digit; quantization noise corresponding to the usual number of digits has been included. A series of twenty measurements, repeated several times, has enabled us to estimate the sensitivities of the KLY-2.1 and KLY-2.2 units at 3×10^{-8} and 2×10^{-8}, respectively. In the specifications we have intentionally given a "safer" value, i.e. 4×10^{-8}.

If the anisotropy of **SB** of the specimen with a low **TSB** is measured, the standard error of the directional **TSB** may be a little higher than the sensitivity. Here additional disturbing effects associated with turning the specimen in the holder appear.

6. FINAL INFORMATION

6.1 MAINTENANCE

In routine operation the instrument does not require special maintenance. The surface of the bridge should be dusted, as well as the inside of the tubular inset of the pick-up coil. The holders should be cleaned.

6.2 SERVICING

It is recommended to call our servicing engineers to make all repairs and resetting of the instrument. Please contact the manufacturer:

Geofyzika n.p. Brno, Ječná 29a, 612 46 Brno, Czechoslovakia

6.3 STORAGE AND TRANSPORTATION

The wrapped instrument can be stored and transported at a temperature from -25°C to +55°C and relative humidity up to 80%. In both cases the instrument should be stored in suitable premises, free of dust and chemical evaporations.

6.4 WARRANTY

All information concerning the period of guaranty is given in the certificate of warranty.

6.5 COMPLETE DELIVERY

Measuring unit **KLY-2.0**

Standard pick-up unit **KLY-2.1**

Unit for large specimens **KLY-2.2** (optional)

Accessories:

Mains cord
Interconnecting cable
Holders of specimens (according to the packing list)
Standards (according to the packing list)
Spare fuses
Instruction manual including diagrams
Packing list
Certificate of warranty

7. BIBLIOGRAPHY

(1) V. JELÍNEK: The statistical theory of measuring anisotropy of magnetic susceptibility of rocks and its application.
Geofyzika Brno. Brno 1977.

(2) V. JELÍNEK, M. FRANKOVÁ: Program ANISO 10.
Geofyzika Brno. Brno 1977.