A METHOD OF TESTING AND QUALIFYING SHIELDED LOW-FREQUENCY CABLES

By

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(Received September 16th, 1976)

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1. Introduction

With the development of the electronic industries there is an increasing demand for suitable shielded small-size cables available at reasonable prices. With the traditional methods, the shield of telecommunication cables is braided or woven from very thin threads of copper. This technology, however, requires much labour and the basic material of the shield is expensive. The Hungarian Cable Works have worked out two new technologies of shielding. One of them provides for shielding by means of an aluminium foil, and a properly placed twisted copper wire is applied for solderability. This type of wire can be applied where it is subject to little bending. In the other solution, shielding is accomplished by a PVC or polythene coating made conductive. Longitudinal conduction is accomplished by means of tinned filaments under the shielding coat, which, at the same time, make soldering possible. This type withstands bending load, is simple and fast to manufacture, and is considerably cheaper than the traditional type. The recently developed types of shielded wires have imposed to compare and qualify the shielding effect of the different types. The Department of Instrumentation and Metrology, Technical University of Budapest, has been concerned with the problem of shielding magnetic and electric fields. The procedures in [1], [2], [3], [4] have not been extended to shielded cables. Even the measuring and qualifying methods [5] cover, first of all, high-frequency cables. The cables examined cannot, of course, be used as high-frequency signal leads, because of their geometry and the measurable cable parameters.

Since no international recommendations and standards for qualifying low-frequency shielded wires are available, the problem has been approached from the user's side. According to our own experience and the consultations with industrial experts, the fields of application of low-frequency shielded wires and the sources of their disturbances can be grouped as follows:

* Hungarian Cable Works

To eliminate disturbances, low-level signal leads are shielded:

— in the audio-frequency parts of radio and TV equipment;
— in sound amplifiers;
— in electronic devices;
— in digital equipment;
— in electrical transducers.

In devices of this kind, shielding is intended to reject or decrease the disturbing voltages rather than the disturbance produced by the shielded conductors, since these cannot conduct high voltages, heavy currents or high frequencies. The applied low frequencies, low voltages and currents do not produce any appreciable radiation.

Disturbing voltages may be due to the following effects:

a) *Electric field*

The electric field produced by a wire at a higher voltage running near the shielded cable produces a parasitic voltage between the shield and the cable core. The quality of shielding can evidently be characterized by the ratio of this voltage produced to the electric field strength.

b) *Magnetic field*

The alternating magnetic field produced by the current flowing in the inductive device (transformer, coil, wire) induces voltage in the distributed loop formed by the shielding coat and the core. The shielding effect can be described as the quotient of the induced voltage by the magnetic field strength.

c) *Combined effect of electric and magnetic fields*

The combined effect of electric and magnetic fields causes disturbances only in the case of high-frequency signals, thus its examination could be omitted. Since, however, simpler shielded cables are extensively used in digital equipment subject to such effects, the supression of disturbances has to be interpreted somehow. Standard methods are advisably replaced by measurement and qualification taking the actual application into consideration. This consists in measuring the so-called transradiation effect, the interaction between two closely adjacent cables.

If a pulse typical of the operation of the digital system is led through one of the cables, transradiation produces a voltage pulse in the other. At the logical threshold value pulse errors may arise.

The degree of protection against these three sources of disturbance can be characterized by an absolute number, e.g. by the ratio of the parasitic voltage to the electric field strength, and its knowledge can help the user to select the cable suitable for his device. It is, however, more expedient to use a ratio of the above parameters to those of known types of shielded cables (with braided or woven shield). Experience available about their disturbance rejection may be of help in selecting the cable.

2. Examination of the shielding of electric field

2.1. *The mechanism of shielding*

Electrode 2 in Fig. 1 has to be shielded with respect to electrode 1 of voltage U_{10}. Shielding is accomplished by electrode 3 which — for reasons of manufacturing — is not, or cannot be, considered as a construction with continuous surface (see: conductive plastic shielding). The cable-shield effectiveness is characterized by the ratio U_{20}/U_{10}. The voltage U_{20} arises from two sources:

On the one hand, impedances Z_{20}—Z_{12} divide voltage U_{10}, on the other hand, the voltage U_{30} divided from U_{10} by impedances Z_{30}—Z_{13} produces, through divider Z_{20}—Z_{32}, the voltage of electrode 2 which is to be protected.

Theoretically, the second source can be eliminated by directly connecting electrode 3 with the ground point of the generator, i.e., by zeroing Z_{30}. In practice, however, the place of electrode 1 is not known — and may also change in time, and thus there is only a theoretical possibility. In the case of more than one disturbing electrode, even this theoretical possibility of decreasing the voltage U_{20} is lost.

2.2. *A network suitable for measuring the ratio U_{20}/U_{10}*

It was intended to construct a measuring network corresponding to the physically realistic Fig. 1, practical construction being shown in Fig. 2.

The tubular electrode 1 surrounds a portion of the shielded cable consisting of core 2 and shield 3. The tubular electrode 0 shields the internal parts. Since the shield is connected with the electrode 0 at the end opposite to the source of disturbance, the impedance Z_{30} cannot be zero.

2.3. *Equivalent circuit diagram of the measuring network*

Fig. 3 shows the equivalent circuit diagram of the measuring network of Fig. 2 with the dominant elements.

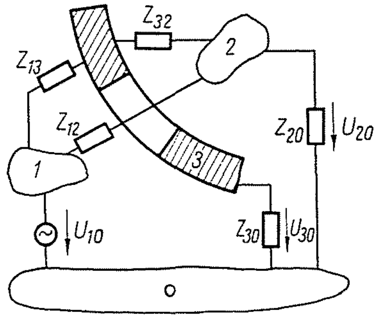

Fig. 1

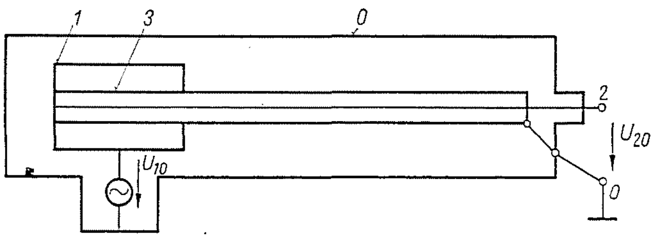

Fig. 2

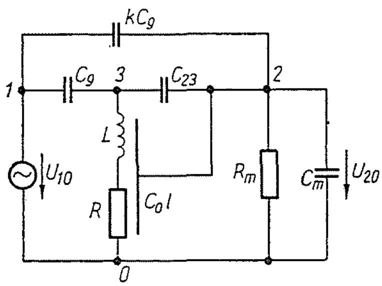

Fig. 3

Legend:

C_g capacitance between tube electrode 1 and the shield 3;

k constant;

$k.C_g$ capacitance between tube electrode 1 and the core of the shielded cable;

L, R inductance and resistance, respectively, of the shielding coat between electrode 1 and the ground point;

l length of the shielded cable from electrode 1 to the ground point;

C_0 capacitance of the shielded cable over unit length between the shield and the core;

C_{23} capacitance between the shield and the core along electrode 1;

R_m, C_m input resistance and capacitance of the measuring equipment, respectively.

Distributed capacitance C_0l connected to circuit L-R is assumed to be concentrated at end points 0 and 3 as capacitances $C_0l/2$. This way they are connected parallel with C_{23} and C_m. The equivalent circuit diagram simplified this way is shown in Fig. 4.
Accordingly:

$$C_t = C_m + \frac{C_0 l}{2}$$

$$R_t = R_m$$

$$C = C_{23} + \frac{C_0 l}{2}$$

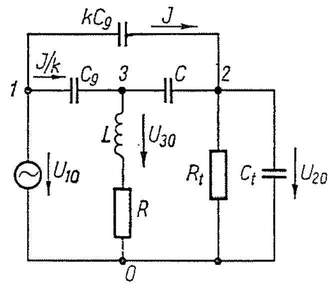

Fig. 4

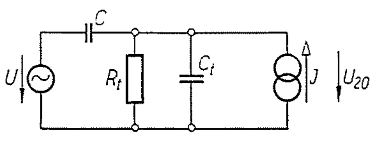

Fig. 5

Transfer function U_{20}/U_{10} is calculated with the following neglects:

a) Since actually $U_{10} > 10$ V: U_{20} and $U_{30} < 10$ mV, capacitances C_g and $k.C_g$ feed points 3 and 2 as current generators.

b) Up to 1 Mc, the circuit L-R feeds as a voltage generator the circuit to its right.

With these approximations the equivalent circuit diagram can be transformed as shown in Fig. 5.

Using the legend symbols, the source quantities are:

$$I = sU_{10}kC_g$$

$$U = sU_{10}C_g(R + sL)$$

The amplitude response varies according to:

$$\left|\frac{U_{20}}{U_{10}}\right| = |F(j\omega)| = C_g\omega R_t\sqrt{\frac{(\omega RC)^2 + (k - \omega^2 LC)^2}{1 + [\omega(C + C_t)R_t]^2}}$$

Examine the amplitude response to ascertain wich parameters are of decisive mportance in the different frequency ranges:

a)

$$\text{If} \quad \omega^2 LC \ll k$$
$$\omega RC \ll k, \text{ and}$$
$$[\omega(C + C_t)R_t]^2 \ll 1,$$
$$\text{then} \quad |F(j\omega)| \approx C_g \omega R_t k$$

For given R_t and C_g, the absolute value of the transfer function is seen to be proportional to the frequency and the factor k.

Thus, for low frequencies a shielding coat with continuous surface can be stated to be the preferable construction, i.e., $k.C_g$ has to be kept as low as possible.

b) At high frequencies, for

$$\omega^2 LC \gg k$$
$$\omega^2 LC \gg \omega RC$$
$$[\omega(C + C_t)R_t]^2 \gg 1$$

one can write

$$|F(j\omega)| \approx C_g \omega^2 \frac{C}{C + C_t} L$$

i.e., the shielding effect decreases in proportion to the square of frequency, and the inductance of the shielding coat is the dominant element.

From the measurement of the elements of the equivalent circuit diagram, the frequency response of the shielding effect of the cable can be drawn in advance.

A comparison between measured and computed frequency responses afforded a good control.

2.4. *The measuring system*

The great number of shielded cable specimens and of measurements required a computer to be used for the measurements and the statistical data processing. The measuring system is shown in Fig. 6.

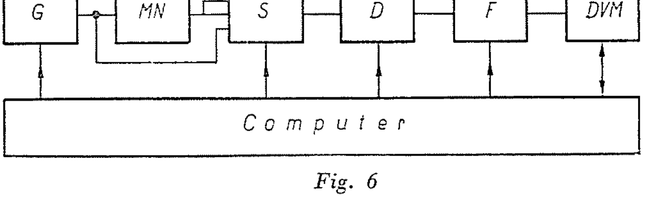

Fig. 6

The blocks can be defined as:

G ... programmable frequency generator
MN ... measuring network
S ... reversing switch
D ... programmable voltage divider
F ... programmable filter
DVM ... digital voltmeter
Computer ... TPA/i small computer

The computer gives the DVM the instruction to measure the input and output voltages of the measuring network selectively in half decades between 100 c/s and 1 Mc. The ratio of the two results is characteristic of the shielding effect of the cable.

Advantages of the method:

a) The generator, the filter and the digital voltmeter are only required short-time stability and linearity.
b) Rapid measurement.
c) Statistically processed output.

The photo of the measuring system is shown in Fig. 7.

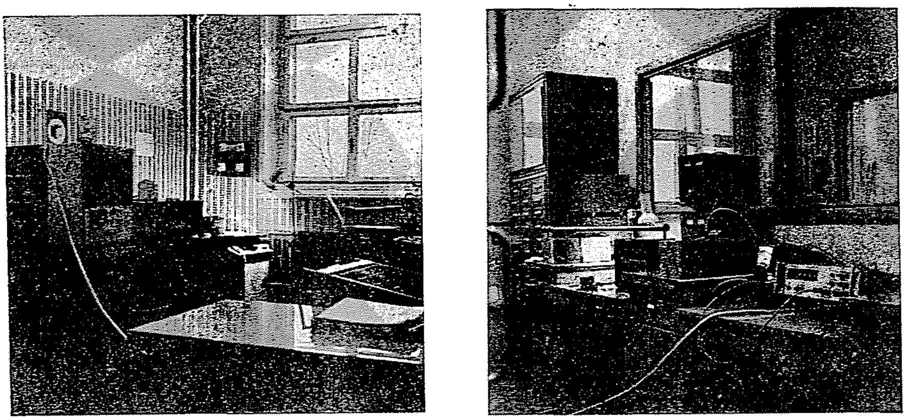

Fig. 7

3. Examination of shielding of magnetic field

3.1. *Mechanism of shielding*

The magnetic shielding effect of the cable examined is illustrated in the model shown in Fig 8.

A portion l of a three-membered conductive frame is exposed to a homogeneous magnetic field of induction B alternating in time. The arising

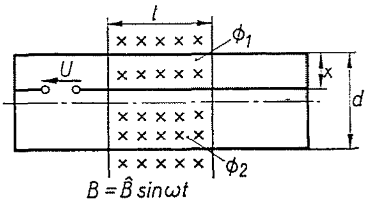

Fig. 8

voltage U can be be calculated as follows:

$$U = 2 \cdot \frac{e}{\mathrm{d}} \cdot \frac{\mathrm{d}\Phi}{\mathrm{d}t}, \quad \text{where} \quad e = x - \frac{\mathrm{d}}{2}; \; \Phi = \Phi_1 + \Phi_2$$

It is evident that in the case of symmetry ($e = 0$) the voltage is zero.

In the case of excentricity, the magnetic field induces a voltage proportional to the excentricity.

Rotation of the conductive frame around its axis induces in it a voltage with periodically changing peak values, with zero transitions, whenever the plane of the frame is parallel to the magnetic field lines.

This model can be considerd as a segment of a simple shielded cable where the core is the central member of the conductive frame.

The shielded cable can be regarded as consisting of a multitude of such conductive frames.

In reality, there are demagnetizing eddy currents arising in the shield, next to imposible to be taken into consideration.

In the case of perfect symmetry — with no frame excentricites — no voltage arises in the shielded cable, i.e., the magnetic field is "shielded".

Evidently in the case of asymmetry, the voltage depends on the angular position and fluctuates periodically with the rotation.

From the viewpoint of magnetic disturbances, the better the cable, the lower the rotation voltage maximum.

3.2. *The measuring equipment*

A homogeneous magnetic field was produced with the arrangement according to Fig. 9.

In the gap of the magnetic circuit shown in Fig. 9 a freely rotating portion of length l of the shielded cable is placed perpendicular to the drawing plane.

On one side of the shielded cable the shield and the core were connected, and to the other side a selective voltmeter was attached.

Connecting the field coil to sinusoidal voltage, an induction changing cosinusoidally arises in the gap.

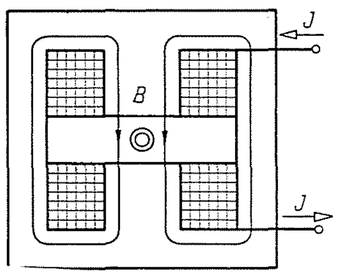

Fig. 9

3.3. *Measurement results*

The angle-dependent voltage maximum was determined for given induction B, frequency f and length l. Since this maximum does not depend on the asymmetry of the shielded cable alone, the result is divided by the quantities B, f and l, thus forming a magnetic transfer factor:

$$F_B = \frac{U}{B \cdot f \cdot l} .$$

Thus F_B is the voltage arising in a shielded cable of unit length placed in a magnetic field of unit induction, and one cycle/sec frequency.

4. Sensitivity to pulse disturbances

4.1. *Measuring method*

Shielded cables running parallel disturb each other. The disturbance can be measured in the arrangement shown in Fig. 10.

Both sides of shielded cable 1 were closed by characteristic wave impedances, then excited by pulses. In the unexcited cable 2 running parallel to it a voltage arises by radiation.

Oscilloscopy of U_2 permits to determine the shape and other pulse characteristics of the parasitic voltage. Fig. 11 shows the photo of the realized measuring arrangement.

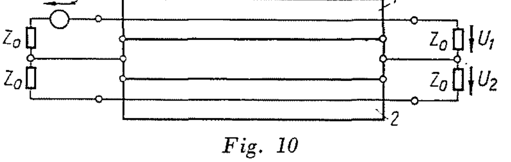

Fig. 10

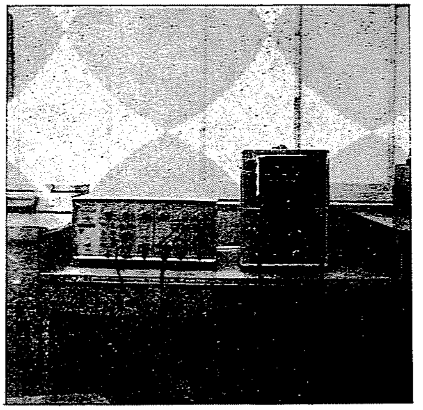

Fig. 11

4.2. *Measurement results*

A pair of cables twisted in unit length was examined. The phenomenon was studied on a photo taken from the oscilloscope screen. The peak value of the parasitic voltage and the pulse-width of the disturbing pulse were measured.

5. Measurement of other characteristics

5.1. *Measurement of capacitance and conductivity*

A WAYNE KERR capacitance and conductance bridge type B 221 A was used to measure capacitance C_0 and conductance G_0 per metre. Depending on the accuracy in the length measurement, an error of 1 per cent in the measurement of capacitance can be expected.

Also the elements C_g, kC_g and C_m of the equivalent circuit diagram of Fig. 3 were measured in the assembled measuring network with the same device.

5.2 *Measurement of inductance*

The inductance per metre of the shielding wires and of the woven or braided shield (inductivity L in Fig. 3) was measured in the assembled measuring network by means of the same device completed with an inductance adaptor.

An error of measurement up to 5 per cent can be expected.

5.3. *Measurement of resistance*

The resistance per metre of the shielding wires and of the woven or braided shield was measured by the comparison method.

Cables of one metre were measured and thus the error of measurement is due to the inaccurary of the length measurement and its expected value is 1%.

5.4. *Measurement of specific resistance*

The specific resistance of the conductive synthetic material was measured between the measuring electrodes according to Fig. 12 by means of a digital ohm-meter.

The specific resistance is

$$\varrho = R\frac{A}{d}.$$

The surface A of the different types amounted to 4. . .10 mm^2.

Distance d was reduced sufficiently to make the resistance independent of the compression.

The distance d was 0.2 to 0.3 mm, and it had been measured with an accuracy of 0.01 mm by means of a micrometer.

A measurement error of 20 per cent is to be expected.

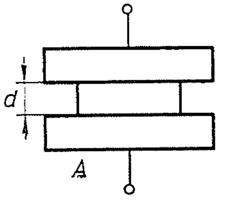

Fig. 12

5.5. *Measurement of induction*

The induction in the aii gap of the equipment serving the examination of the magnetic shielding effect was measured by means of a one-turn coil. The surface of the coil was selected to give

$$B_m = 10\sqrt{2}\,U \;\; [T]$$

at a frequency $f = 50$ c/s. U was measured with a digital multimeter.

A measurement error of 5 per cent is to be expected.

5.6. *Microscopy*

One section of each shielded cable was examined under a workshop microscope, and its characteristic dimensions and asymmetries measured.

Since the latter is much dependent on the place of section, the examination served first of all for identification.

6. Examination results

6.1. *Reference circumstances*

The shielding of electric field was examined on 1.5 m lengths at frequencies of
100, 300 c/s
1, 3, 10, 30, 100, 300 kc and
1 Mc
at a test voltage of 15 V_{eff}.

The capacitance C_m according to Fig. 3 was 25 pF and the resistance R_m was 330 kohm. The electrode 1 in Fig. 2 had a length of 15 cm and an inner diameter of 8 mm.

The magnetic shielding was examined on a 4-cm piece of the sample placed in a field having an induction 0.33 T_{eff} and a frequency 50 c/s.

The sensitivity to pulse disturbances were examined on twisted samples of 1 m in length. An exciting square-wave voltage of $U = 4.5$ V and $f = 1$ Mc was used. The examinations were carried out in laboratory conditions at a temperature of 25 °C.

6.2. *Measurement results*

Out of the 19 experimental cables developed by the Hungarian Cable Works and examined at our institute, one cable had a woven, one a braided, one a foil shield and the 16 others conductive plastic shields.

The following tables contain the measuring data of 3 different cables as typical results.

Mark	Type of shielding
B	braided
C	foil
G	plastic

6.2.1. *Geometry*

	B	C	G
Number of shielding wires	25	3	3
Diameter of shielding wires (mm)	0.2	0.15	0.15
Number of cores	1	1	1
Number of wires in a core	25	1	1
Diameter of wires	0.2	0.5	0.5
Colour of core insulation	gray	yellow	yellow
Outer diameter (mm)	4	2	3
Colour of outer insulation	black	white	grey

6.2.2. *Electrical parameters*

	B	C	G
$C_0 \left(\frac{pF}{m}\right)$	448	316	155
$G_0 \left(\frac{\mu mho}{m}\right)$	0.34	0.30	0.08
L (μH)	0.4	0.6	0.6
$R_0 \left(\frac{\Omega}{m}\right)$	0.03	0.19	0.32
$\varrho \left(\frac{M\Omega mm^2}{m}\right)$	—	—	0.9
C_g(pF)	15	7.8	15
kC_g(pF)	0,016	$< 10^{-3}$ pF (non-measurable)	

6.2.3. *Shielding of electric field (F)*

	B	C	G
100 Hz	$0.31 \cdot 10^{-5}$	$0.58 \cdot 10^{-7}$	$0.46 \cdot 10^{-7}$
300 Hz	$0{,}99 \cdot 10^{-5}$	$0.46 \cdot 10^{-6}$	$0.4 \cdot 10^{-6}$
1 kHz	$0.16 \cdot 10^{-4}$	$0.77 \cdot 10^{-6}$	$0.27 \cdot 10^{-5}$
3 kHz	$0.19 \cdot 10^{-4}$	$0.89 \cdot 10^{-6}$	$0.13 \cdot 10^{-4}$
10 kHz	$0.2 \cdot 10^{-4}$	$0.11 \cdot 10^{-5}$	$0.61 \cdot 10^{-4}$
30 kHz	$0.23 \cdot 10^{-4}$	$0.14 \cdot 10^{-5}$	$0.17 \cdot 10^{-3}$
100 kHz	$0.1 \cdot 10^{-4}$	$0.5 \cdot 10^{-5}$	$0.46 \cdot 10^{-3}$
300 kHz	$0.1 \cdot 10^{-4}$	$0.97 \cdot 10^{-5}$	$0.12 \cdot 10^{-2}$
1 MHz	$0.25 \cdot 10^{-3}$	$0.13 \cdot 10^{-4}$	*$0.32 \cdot 10^{-5}$

Diagram 1 was plotted from the tabulated data. The curves calculated from the measured electrical parameters are also shown in Diagram 1. (The result marked X is erroneous and therefore it has not been plotted).

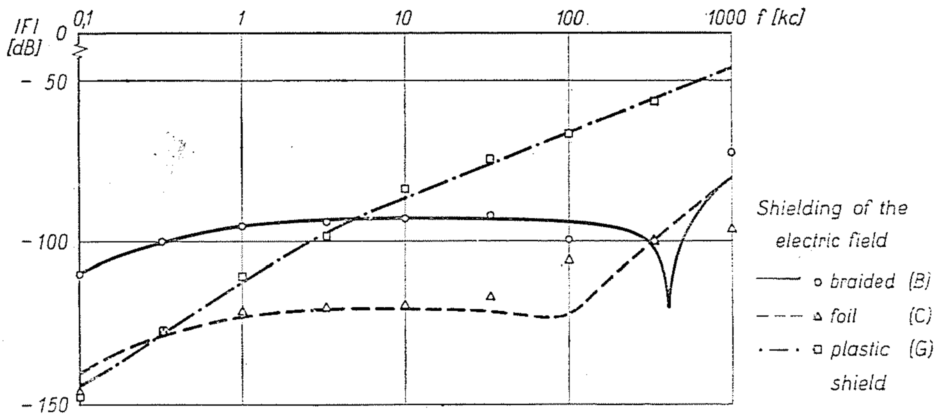

Diagram 1.

6.2.4. *Shielding of magnetic field*

	B	C	G
U (mV)	0.17	2.62	2.5
s (mV)	0.14	0.08	1
F_B (mm)	0.25	3.96	3.78

Here U is the average value of maximum voltages at 50 c/s, s its standard deviation, and F_B the magnetic transfer factor. It is to be noted that F_B was independent of a frequency below 5kc.

6.2.5. *Sensitivity to pulse disturbances*

	B	C	G
U_{zmax} (mV)	4	120	110
τ (nsec)	5	5	5

The pulse disturbance sensitivity of the shielded cables of types B, C and G is shown in Figs 13 to 15. In the photographs the upper curves show the form of the excitation voltage, and the lower ones that of the disturbing voltage. The photos to the right were made with a tenfold time-extension.

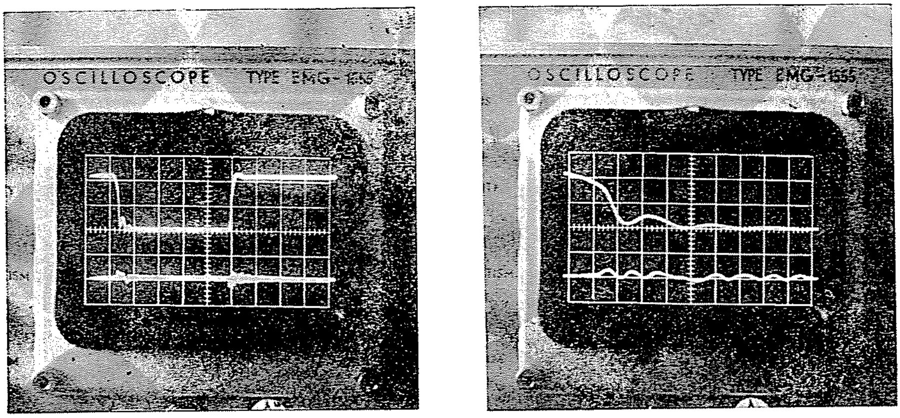

Fig. 13. Pulse disturbance sensitivity of a cable with braided shield (B)

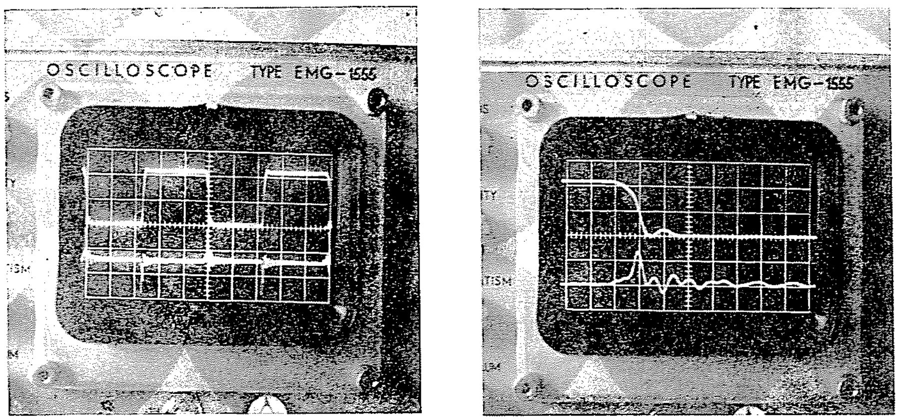

Fig. 14. Pulse disturbance sensitivity of a cable with foil shield (C)

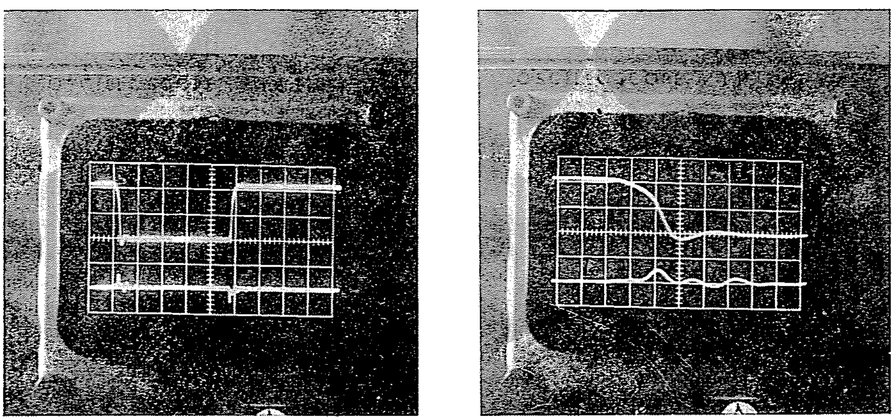

Fig. 15. Pulse disturbance sensitivity of a cable with plastic shield (G)

Summary

Diagram 1 showing the frequency response of electric field shielding demonstrates a fair agreement between the results calculated from the electrical parameters of cables and the measured ones.

The examinations afford a possibility to make the following comparisons between the experimental cable samples:

Concerning the ability to shield electrical fields up to 1Mc, cables with foil shielding exhibit the most favourable behaviour. Up to the frequency limit of 10 kc, the cable shielded with conductive plastic is better than those with braided shielding (diagram 1).

Concerning the shielding of magnetic fields, the braied shielding is superior by an order of magnitude to either the foil shielding or the conductive plastic shielding, the two latter being practically equivalent. According to our experiments, this difference can be decreased by improving the technology (better symmetry).

The sensitivity to pulse disturbances is better by more than one order of magnitude with braided shielding than with the two other types. In our opinion this difference cannot be decreased.

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