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A measuring bridge for studying the dielectric properties of highly conducting liquids in the frequency range 1 kHz–30 MHz

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Abstract. A measuring bridge is described which is applicable in the 1 kHz–30 MHz region to the determination of the impedance of biological material and highly conducting liquids characterised by a very high loss factor. The novelty in this bridge is the use, as the resistance standard, of two trimming potentiometers and two small ferrite shielded transformers as the output to the detector. This makes it compact, versatile and free of inductive and capacitive effects.

1. Introduction

Measurements of the electrical properties of biological material and highly conducting liquids are difficult, especially in the low frequency range (< 1 MHz), because a cell filled with a system characterised by a very small phase angle φ_x ($\tan(\varphi_x) = 5.560 \times 10^{-13} \times f(\varepsilon_x/\sigma_x)$ where ε_x and σ_x are the relative electric permittivity and electrical conductivity (in $\Omega^{-1}\,\mathrm{cm}^{-1}$) respectively of the system and f the frequency (in Hz)) will have an admittance vector in the Argand diagram making a very small angle with the real axis and will practically behave as a pure resistance. Mandel and Jung (1952) and van der Touw *et al* (1975) described an impedance bridge for the measurement of impedances with a large loss factor in the kHz region.

In conventional bridges above 1 MHz inductive and capacitive effects start to emerge in the resistance unit and inductive effects in the capacitance unit, wherefore corrections are necessary.

2. The bridge construction

We describe here a bridge covering the frequency range from 1 kHz to 30 MHz. The fundamental network is represented in figure 1. The bridge uses a substitution method to determine the capacitance and the resistance of the cell, thus eliminating any errors that could emerge because of the asymmetry of the ratio arms, inductance effects, and stray capacitances (Oncley 1938). The novelty in this bridge is the use, as the resistance standard, of two trimming potentiometers instead of a resistance box, the advantage of this being that the unit is free of inductive and capacitive effects; its resistance can be measured with a digital ohmmeter, or a previous calibration using a precision multidial (e.g. Spectrol models 18 or 21) can be made.

Details of the mounting of the potentiometers are given in figure 2: we use homemade panel mount adapters, in which a blade engages the trimmer screw driver shaft slot and the shaft is inserted into the rear of the bushing, even though potentiometers of Spectrol Reliance Ltd, Swindon, Wiltshire, England, with panel mount adapter model 6, could be used. Only one knob is used to turn both potentiometers through four 45° gears. In the 'up' position the 200 Ω one is operated and in the 'down' position the other. Another way would be to use two knobs and avoid the gears, but we tried to build the bridge in the most compact way possible in order to avoid electromagnetic losses.

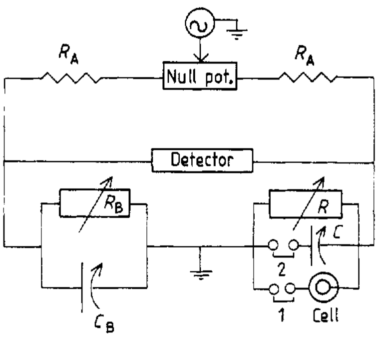

Figure 1. Fundamental bridge network.

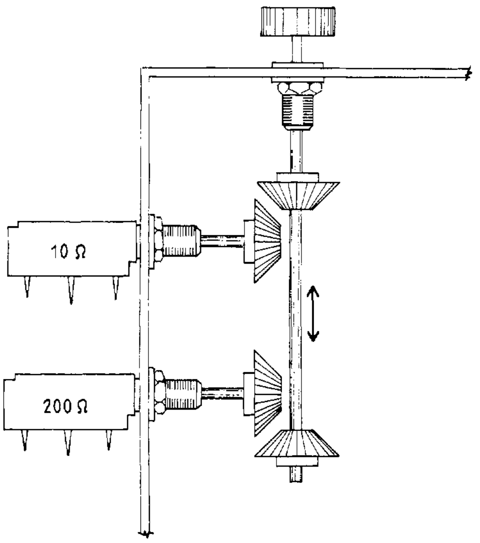

Figure 2. Potentiometers mounting.

The 20 Ω central potentiometer is for compensating some resistive asymmetries that could emerge in the upper arms of the bridge. The capacitance on each arm consists of a variable air capacitor used in radio transmission immersed in chlorodiphenylbenzene ($\varepsilon = 4.5$, dielectric rigidity 25 kV/0.1″) this gives to the capacitance unit a high stability, low temperature coefficient and very low losses. Only the measurement arm capacitor needs to be calibrated using a precision multidial.

The hermetically sealed aluminium cans where the capacitors are immersed have diameter 100 mm and height 120 mm. Each capacitor has a maximum capacitance of approximately 1000 pF after the chlorodiphenylbenzene is introduced.

The schematic representation of the bridge construction is given in figure 3. It shows all the components, their connections and shielding. The whole bridge is enclosed in an aluminium case (150 mm high, 250 mm wide and 400 mm long) at earth

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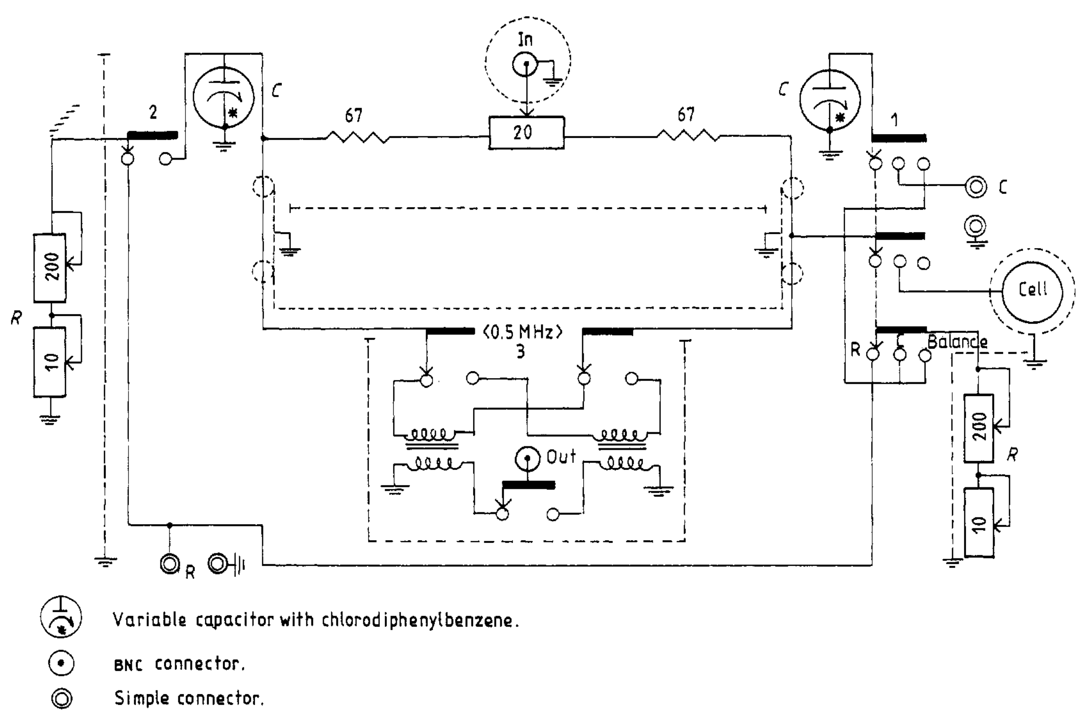

Figure 3. Schematic representation of the bridge construction.

potential. The switch on the left ('2' in figure 3) has one porcelain disc with two positions, namely, 'R' and 'Normal'. The right switch ('1' in figure 3) has three porcelain discs with three positions, namely, 'R', 'C' and 'Balance'.

Position 'R' on the left puts the left potentiometers in parallel with the 'R' terminals when the right switch is in the 'C' or 'Balance' position; this position is to calibrate or measure the resistance of the left potentiometers. Even though it is not necessary, it facilitates the setting of the initial equilibrium position of the bridge. Position 'R' on the right switch is for measuring or calibrating the right potentiometers when the left one is in the 'Normal' position. The detector is connected to the bridge by means of two interchangeable ferrite shielded transformers (homemade). One works up to 0.5 MHz and the other from 0.5 to 30 MHz. Both are ring shape; the first one is 7 mm high, 5 mm internal diameter and 7.5 mm external diameter; the second one is 7 mm high, 12 mm external diameter and 9 mm internal diameter. The primary and secondary consist of approximately 100 turns of 0.1 mm thick conducting wire. Switch '3', figure 3, selects one or other transformer depending on the frequency range.

3. Measuring procedure

The measuring procedure is as follows.

(1) The cell and potentiometers '*R*' (set at 200 Ω) are connected in parallel, terminals '1' closed and '2' open in figure 1 (left switch in 'Normal' and right switch in 'C' in figure 3); then R_B and C_B (left potentiometers and capacitor, figure 3) are balanced.

(2) The cell is removed and condenser *C* is put in its place, terminals '2' closed and '1' open in figure 1 (left switch in 'Normal' and right switch in 'Balance' in figure 2); then '*R*' and '*C*' are adjusted until a balance is again obtained. The reading on '*C*' is the capacitance of the cell.

The conductance of the solution is given by

$$G_x = G_2 - G_1 \qquad (1)$$

where G_1 and G_2 are the conductances of initial and final resistance settings respectively.

4. The cell construction

The cell is made from a pyrex glass tube (80 mm high, 17 mm diameter) and is of the micrometer type with two circular (12 mm diameter, 0.5 mm thick) platinum sheet electrodes, one mounted on the spindle of a micrometer screw (at earth potential) and the other fixed, soldered to the glass. Underneath it is a loose micro stir bar covered with teflon. This type of cell avoids corrections produced by electrode polarisation, in the measurements of dielectric constants at low frequencies (Fricke and Curtis 1937). The stir bar is moved by a record turntable motor in which a magnetic bar (20 mm in length) was fixed in its axis 20 mm apart from the electrode. This allows a uniform agitation of the solution.

The electrode spacing *d* is known to have an accuracy of 10^{-2} mm. The temperature of the cell is controlled to within ± 0.1 K by circulating water from a thermostat through the copper jacket enclosing it.

5. Bridge test and accuracy

In order to test the bridge we built a circuit consisting of a 300 Ω resistance of very low residual reactances, in parallel with a 150 pF capacitor of very low residual inductance. Measured values of *R* and *C* are presented in table 1.

In all measurements the initial setting of the bridge potentiometers (*R* in figure 1) was $R_1 = 200.00\ \Omega$ and *R* was calculated by formula (2), namely

$$\frac{1}{R} = \frac{1}{R_2} - \frac{1}{R_1}.$$

It was verified experimentally that the bridge covers the range 1 kHz to 30 MHz for systems with loss tangent, $\tan(\delta) = 1/\tan(\varphi_x) \leqslant 10^4$, at 1 kHz. In systems in which the loss

Table 1.

f (kHz)	R_2 (Ω)	R (Ω)	C (pF)
1	120.00	300.00	151.0
10	120.00	300.00	150.0
100	120.00	300.00	149.5
1000	120.00	300.00	149.0
10000	120.10	300.62	148.5
20000	120.15	300.94	148.0
30000	120.20	301.25	147.0

Table 2.

f (kHz)	$\sigma \times 10^6$ (Ω^{-1} cm^{-1})	ε
1	146.95	78.65
10	146.95	78.60
100	146.96	78.55
1000	146.97	78.55
10000	146.98	78.50
20000	146.99	78.00
30000	148.00	77.90

tangent is greater than 10^4 the range is reduced. At 1 kHz frequency the relative error in the capacitance was $(\Delta C)/C = 10^{-2}$, giving a minimum phase angle measured of $\Delta\varphi_x = \tan(\varphi_x)(\Delta C)/C = 10^{-6}$.

At frequencies greater than 10 kHz the accuracy in the capacitance increases to 0.2 pF.

The accuracy in G_x can be calculated by

$$\Delta G_x = \Delta R(G_2^2 + G_1^2). \tag{2}$$

The settings R_1 and R_2 were measured with an accuracy $\Delta R = 0.01\ \Omega$; this means $\Delta G_x \leqslant 2.5 \times 10^{-6}$ for $R_x \geqslant 100\ \Omega$.

For testing the bridge with a highly conducting liquid, we filled the cell with 1 mM KCl solution of known conductivity $\sigma = 0.0001469\ \Omega^{-1}\ \mathrm{cm}^{-1}$ at 298 K. This solution is an appropriate test for the bridge, comparing its conductivity with that of our bi-distilled and de-ionised water $\sigma = 1.1 \times 10^{-6}\ \Omega^{-1}\ \mathrm{cm}^{-1}$ at 298 K.

The cell capacitance C is given by the equation

$$C = C_0 + K\varepsilon/d \tag{3}$$

where C_0 is the distributed capacitance, and the electrode area A in cm is numerically equal to $K/0.08854$ when K is expressed in pF cm; our electrode diameter was 1.22 cm, which gives an electrode area of 1.178 cm^2 and therefore $K = 0.103$ pF cm. We determined K and C_0 experimentally from the plot of C against $1/d$ using methanol $\varepsilon = 32.7$ at 298 K. The obtained values of K and C_0 were 0.0998 pF cm and 3.0 pF respectively.

The value of $\tan(\varphi_x)$ at 1 kHz was 3×10^{-4} and the corresponding minimum phase angle $\Delta\varphi_x$ detectable, considering $(\Delta\varepsilon)/\varepsilon \simeq \Delta C/C \simeq 10^{-2}$, and $\varphi_x \simeq \tan(\varphi_x)$ at this frequency, is given by

$$\Delta\varphi_x = \frac{\Delta C}{C}\,\frac{\varepsilon_x f}{\sigma_x} \times 0.556 \times 10^{-12} = 3 \times 10^{-6}. \tag{4}$$

For determining the dielectric constant ε_x of the solution we used the formula given by Shaw (1942) up to frequencies of 10 kHz, namely:

$$\varepsilon_x = \frac{[d_2^2(C_2 - C_0) - d_1^2(C_1 - C_0)]}{[K(d_2 - d_1)]} \tag{5}$$

where C_1 and C_2 are the measured capacitances corresponding to the electrode spacings d_1 and d_2. Formula (5) avoids correction caused by electrode polarisation effects. For higher frequencies we used formula (3). The conductivity σ_x in $\Omega^{-1}\ \mathrm{cm}^{-1}$ was determined using the equation

$$\sigma_x = 0.08854(d/K)G_x. \tag{6}$$

Table 2 summarises the results for this solution.

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