



# On the presumed inductive behaviour of electrolyte solutes in low frequency conductance. Part I: Deficiency of the employed measurement technique

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## ABSTRACT

A measurement technique is examined that served to investigate the low frequency conductance of electrolyte solutes. The set-up, analyzed on the basis of its equivalent circuit, shows major deficiencies, which actually caused the observed frequency dispersion and the presumed inductive behaviour. The problem, basically, is due to the use of non-contacting electrodes for signal in/out coupling, in combination with a capillary flow cell as sample holder.

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## 1. Introduction

In a 2005 contribution on AC conductance [1], inductive behaviour of 1:1 electrolytes in low frequency conductance was reported, on grounds of experimental observations. The results, however remarked, ever since, never were confirmed nor denied. Classic theories [2,3] and more recent studies [4–6] on the contrary, predict such behaviour to occur only at much higher frequencies. Inductive behaviour in the low-frequency range, clearly, would compromise any measurements where the conductivity is supposed to be frequency independent. This would be the case, more specifically, of cell/particle counting and sizing in liquids (Coulter technique, electronic gating, and flow cytometry), and, of several variants of bio-impedance measurements (physiologic-, neurologic-). The dilemma, for such reasons, deserves due attention. Key information in this context is that the questionable experiments [1] took place with a measurement cell of the type shown in Fig. 1.

The flow cell in Fig. 1 is a modified version of the one proposed by Frascassi da Silva and Do Lago [7] and by Zeman et al. [8], for use as a detector in capillary electrophoresis: the electrode distance, for the present purposes, was increased from about 2 mm to 1 cm. The use of non-contacting electrodes in the present and in its original application was intended [1] to avoid disturbing effects of polarization.

The cell reactance, as Fig. 1 suggests, is essentially capacitive. Its alleged frequency response (Fig. 2) actually served as a reference [1]: any deviation thereof, i.e. the occurrence of a current maximum, was attributed to LC series resonance, hence, to inductive behaviour of the sample. The set-up of Fig. 1 is examined in more detail hereafter, on the basis of its equivalent circuit and its frequency response, with the range of interest extending from DC to 1 MHz.

## 2. Deficiencies of the measurement set-up

The set-up of Fig. 1, on closer scrutiny, in no way responds to the alleged equivalent circuit in Fig. 2: the measurements appear inherently disturbed by the oscilloscope's input capacitance, by cable capacitance and by parasitic capacitance of the current sensing resistor  $R_s$ . That capacitance, even with a metal film resistor in use, is in the order of 2 pF [9]. The cable capacitance, e.g. for RG58 coax, is in the order of 100 pF/m. A more realistic equivalent circuit, for such reasons, looks like the one in Fig. 3. Its frequency response for samples of various resistivity, is shown in Fig. 4.

The extremes in Fig. 4 perfectly coincide with the ones mentioned in [1]. However, so as it appears, they are caused by stray/parasitic capacitance, never by inductive behaviour of the sample.

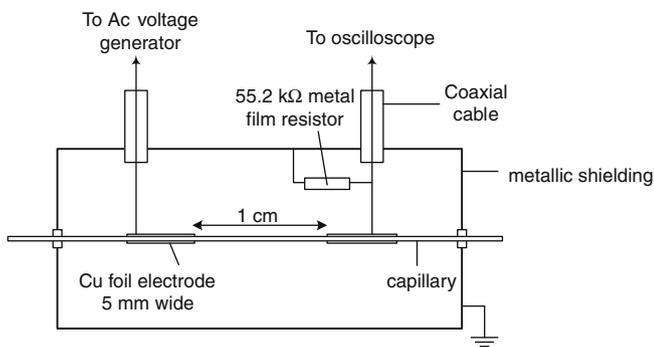
Obviously, the question arises whether this situation could be alleviated, or not. Indeed, a voltage-divider probe could be used to increase the oscilloscope's input resistance, and to decrease the cable capacitance. In addition to that, the current sensing resistor could be reduced in value, e.g. by a factor 10, to decrease the impact of parasitic capacitance. However, even then, the frequency response remains non-uniform and, more problematic, signal levels become prohibitively low (Fig. 5).

Inadequate frequency response and deficient sensitivity, presently, appear due to stray capacitance, high sample resistance, and, to the use of cylindrical capacitors as non-contacting electrodes (Fig. 1): the electrolyte solution inside the capillary hereby functions as the inner conductor/electrode, the copper foil as the external one and the capillary wall as the dielectric.

The implementation of non-contacting electrodes of this type, in fact, has more consequences: The capacitance ( $C$ ) is known [10] as

$$C = \frac{2\pi\epsilon L}{\ln(b/a)} \quad (1)$$

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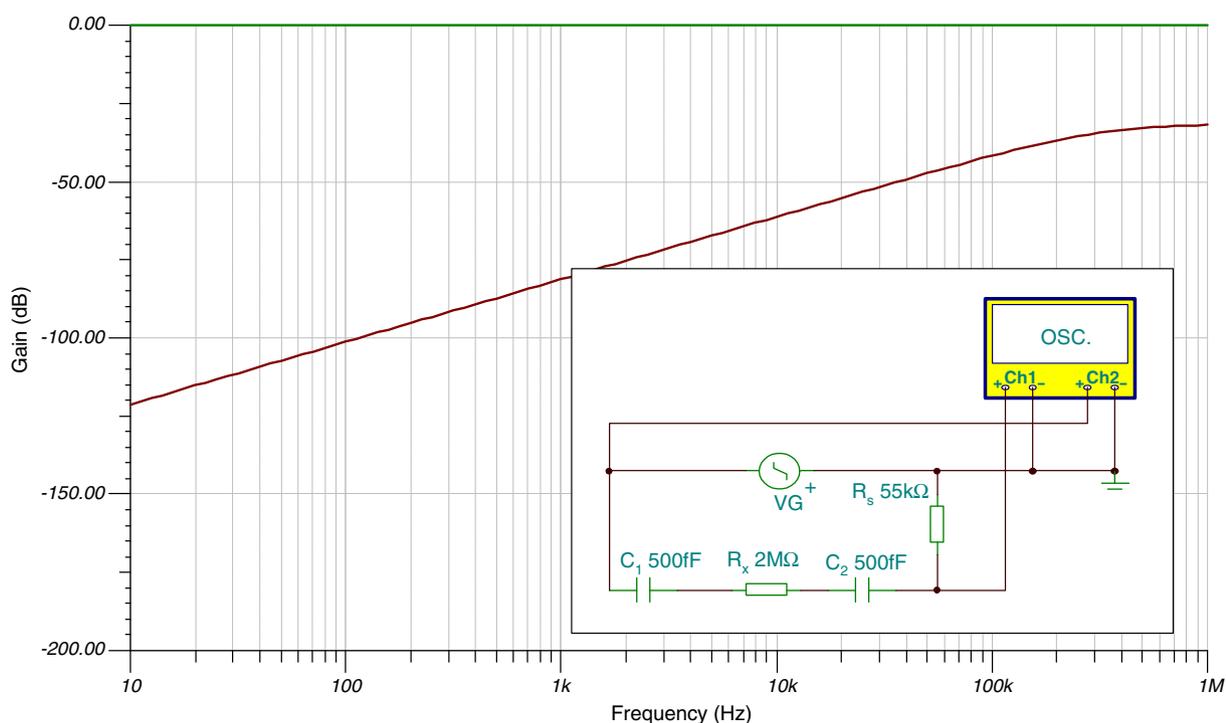
**Fig. 1.** Conductance measuring cell, using a capillary sample holder and cylindrical copper foils as non-contacting electrodes. The 55.2 k $\Omega$  resistor serves as a current-to-voltage converter.

where  $\epsilon$  is the permittivity of the dielectric;  $a$ ,  $b$  is the inner/outer radius; and  $L$  is the (axial) length.

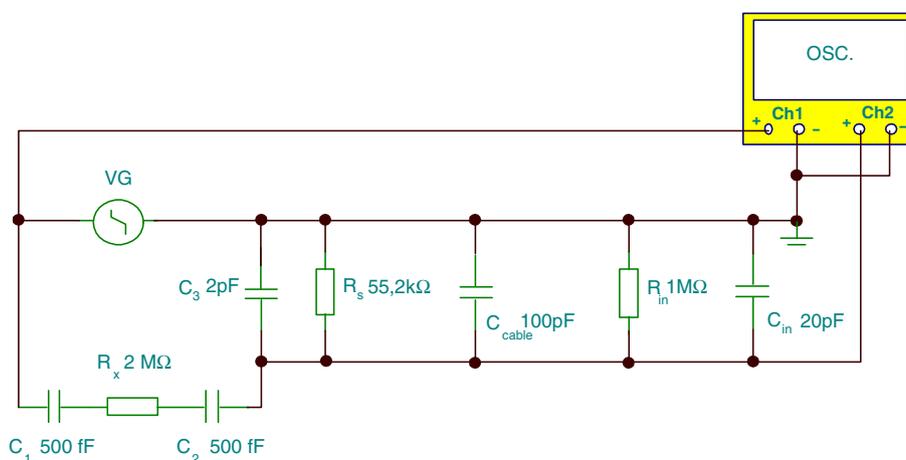
As the equation shows, a low  $b/a$  ratio is necessary to obtain adequate capacitance, hence the need of capillary tubing as sample holder and of tightly wound copper foils as electrodes (Fig. 1). However, the realized capacitance, in the order of 0.5 pF, for the present purposes remains too low: the capacitive coupling in combination with the current sensing resistor ( $R_s$ , Fig. 3), so as Fig. 5 shows, actually behaves as a frequency dependent voltage-divider.

### 3. Summary – conclusions

(a) The equivalent circuit and the physical model mentioned in [1] is incomplete: it does not account for inherent capacitance of the sample holder, of the current sensing resistor, of the intercon-



**Fig. 2.** Equivalent circuit, according to [1], with its frequency response. The oscilloscope, the current sensing resistor ( $R_s$ ) and the interconnecting cable were supposed free of reactance. VG: signal generator.



**Fig. 3.** Equivalent circuit that accounts for stray capacitance of the current sensing resistor ( $C_3$ , 2 pF), for cable capacitance ( $C_{\text{cable}}$ , 100 pF) and for the oscilloscope's input impedance (20 pF//1 M $\Omega$ ). A 1 m long coax cable is supposed to be in use between the current sensing resistor  $R_s$  and the oscilloscope.

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