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Improved C5D Electronic Realization of Conductivity Detector for Capillary Electrophoresis

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***Abstract*—The axial C4D (Capacitively Coupled Contactless Conductivity Detection) measurement electronics for capillary electrophoresis is considered and a new improved C5D compensated detection concept is proposed and tested. Using the idle compensation channel with inversed signal and immediate analogue summation of the active and idle channel currents yields effective suppression of the influence of the parasitic stray capacitance. Preliminary experiments have confirmed at least three-fold improvements of measurement resolution. Realisation of electronics allows flexible tuning of frequency from 0.2 MHz to 2 MHz. The relatively high voltage supply of 15 V for the AC measurement units together with 24-bit accurate analogue-to-digital converter yields additional improvement for the sensitivity.**

***Index Terms*—Capillary electrophoresis; contactless conductivity measurement; C4D, inversed compensation channel; parallel compensation scheme.**

I. INTRODUCTION

The electrophoresis effect, *i.e.* separation of dispersed particles in fluid under the influence of constant electric field, has been known over two centuries by now, first discovered by Ferdinand Frederic Reuss in Moscow University in 1807 [1]–[7]. The electrophoresis became a chemical analysis method by the pioneering works of Arne Tiselius from Uppsala University in 1930s yielding Nobel Prize in chemistry in 1948 [1]–[9]. The capillary electrophoresis (CE) that registers the differences in the movement of molecules and ions in capillaries became usable technology in the middle of 1960s due to works of the Uppsala group, *e.g.* [9]. Actually electrophoresis may include different optical, electrical and other detector types [1]–[9].

The use of C4D (Capacitively Coupled Contactless Conductivity Detection) method in CE was started by the work of Gas *et al.* in 1980 [5]. Their arrangement consisted of four radially arranged electrodes around the capillary with inner diameter of 0.45 mm. The modern *axial* arrangement that has become common case for thinner capillaries was introduced in 1998 by two groups [6], [7].

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Figure 1 explains the axial arrangement of C4D using two tubular electrodes. The applied frequency must be high enough in order to make AC capacitive impedance between electrodes and the tested fluid (*i.e.* "wall capacitances") reasonably low so that the conductivity of the fluid inside the capillary fragment between the electrodes could be defined. However, the stray capacitance between two tubular electrodes creates a shunting capacitive conductivity at higher frequencies. This problem is explained by the Fig. 2. The main unwanted consequences of that leakage via stray capacitance are the remarkable narrowing of the useful plateau in frequency domain, impossibility of using higher frequencies and the limitation of the measuring range of the conductivities.

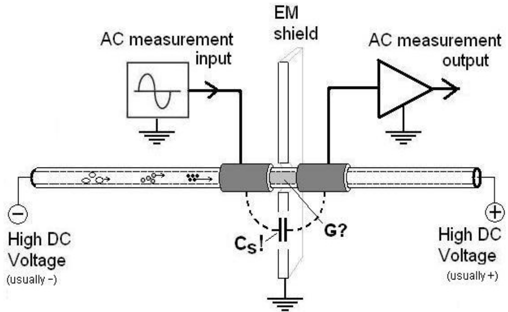


Fig. 1. Conventional axial arrangement of capacitively coupled contactless conductivity detector (C4D) for capillary electrophoresis. The applied frequency must be high enough that AC conductive impedance between tubular electrodes and the tested fluid becomes negligibly small compared to the measured resistance of the fluid fragment. The problem is that the parasitic stray capacitance between input and output electrodes shunts the measured resistance at the higher frequencies.

Below we will offer a new improved compensated C4D (Capacitively Coupled Contactless Conductivity *Compensated* Detection) electronic arrangement that excludes the stray capacitance leakage effect by introducing the parallel idle channel with inversed AC input signal. The present study extends the electronic realization principles of the CE apparatus earlier described in [10].

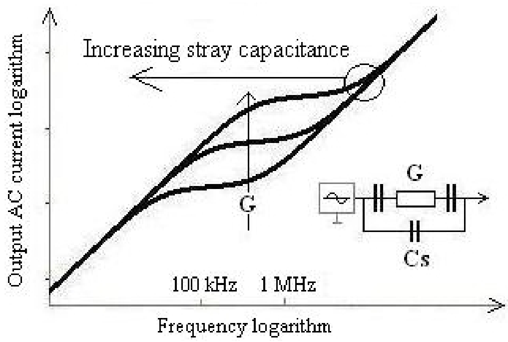


Fig. 2. Explanation of the main problem of the conventional C4D arrangement of the capillary electrophoresis. At higher frequencies the parallel current of the parasitic stray capacitance shunts the current through the tested fluid fragment. The unwanted consequences are the narrowing of the useful plateau in frequency domain, restricted use of higher frequencies and the limited range of measured conductivities.

II. Conventional C4D Approach

The accurate modelling of tubular electrodes arrangement presented in Fig. 1 requires full 3D electromagnetic modelling of electric fields or usage of distributed equivalent circuits with large number of elementary components [2], [7], [11]–[13]. It has been found that for majority of practical purposes the 4-element C-R-C||C circuit presented in Fig. 3 yields reasonable accuracy [2], [11].

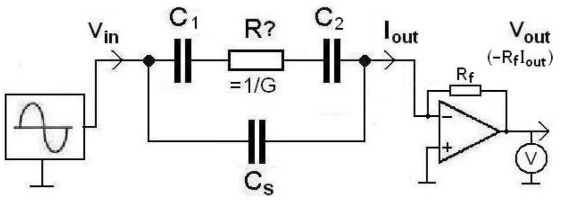


Fig. 3. Conventional equivalent 4-element circuit model for C4D measurement cell consisting of C-R-C circuit with parallel parasitic stray capacitance. The input source of AC signal and the first I/V conversion stage on the output side are also shown.

Circuit from Fig. 3 yields the I/V transfer characteristics (Bode plot of conductivity) as shown in Fig. 2 with two corner frequencies f_1, f_2 and the plateau between them. Taking into account that the two capillary wall capacitances C_1 and C_2 actually merge together to one resulting capacitance

$$C_{12} = 1/(1/C_1 + 1/C_2), \tag{1}$$

the two characteristic time constants and the relevant corner frequencies are defined by the following simple formulas:

$$\begin{cases} \tau_1 = C_{12}R, \\ f_1 = 1/(2\pi\tau_1), \end{cases} \tag{2}$$

$$\begin{cases} \tau_2 = C_s R, \\ f_2 = 1/(2\pi\tau_2). \end{cases} \tag{3}$$

As operational amplifier based output stage in Fig. 3 converts the output current to the output voltage with the coefficient $-R_f$, the actual AC voltage transfer formula for the circuit in Fig. 3 may be written as following

$$V_{out} = -V_{in}R_f\left(j\omega C_s + 1/(R + 1/j\omega C_{12})\right). \tag{4}$$

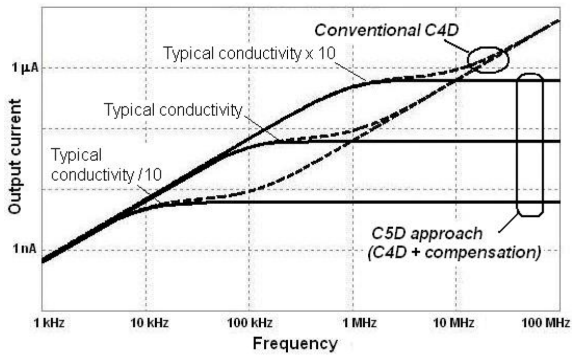


Fig. 4. Simulated I/V transfer characteristics for the traditional C4D approach and the improved compensated C4D approach with parallel stray capacitance compensation channel (see definitions in the text). The equivalent circuits from Fig. 3 and Fig. 5 are used with estimated typical axial capillary electrophoresis component parameters. The AC input amplitude was fixed at 1V and the stray capacitance was assumed to be 20 times smaller than the capillary wall capacitances of the tubular electrodes.

In Fig. 4, the simulated output of the circuit of Fig. 3 in frequency domain is presented by the dashed lines. In the simulation, the estimated typical capillary electrophoresis parameters (C_1 = C_2 = 2 pF, assumed “typical” R = 1.59 MΩ, and $C_s = C_1/20$) were used in order to obtain the round corner frequencies f_1 = 100 kHz and f_2 = 1 MHz. Input AC voltage source amplitude was set to V_{in} = 1 V thus obtaining output current value that may also interpreted as the conductivity of the circuit. As one can see, the 20-fold ratio of capillary wall and stray capacitances yields a rather small 10-fold difference in corner frequencies that makes the plateau regions of the Bode plots in Fig. 4 narrow indeed. Additionally, the position of this plateau in frequency domain is very inconveniently shifted by the actual conductivity under test.

III. Improved Compensated C4D Approach

The improved compensated C4D approach for stray capacitance compensation using the parallel idle channel with inversed input signal is explained in Fig. 5 and Fig. 6.

Proposed compensated C4D approach for stray capacitance compensation using parallel idle channel applies the following ideas (denotations defined in Fig. 5):

1. Inserting inversed signal $V'_{in} \approx -V_{in}$ from source generator to the idle channel that do not contain fluid to be measured ($R' \to \infty$) but has approximately the same stray capacitance than the active channel $C'_s \approx C_s$;

2. Performing analogue summation of the output currents from two channels $V_{out} = -R_f(I_{out} + I'_{out})$;

3. Introducing inversed signal amplification adjustment $V'_{in} \approx -KV_{in}$ where $K = 1$ corresponds to the ideal case of equal stray capacitances of two channels.

Using the equivalent circuit model from Fig. 5, these ideas of compensation method may be described by the following formulas:

$$I_{out} = V_{in}\left(j\omega C_s + 1/(R + 1/j\omega C_{12})\right), \tag{5}$$

$$I'_{out} = V'_{in}\left(j\omega C'_s\right), \tag{6}$$

$$V_{out} = -R_f\left(I_{out} + I'_{out}\right), \tag{7}$$

yielding the resulting output voltage

$$V_{out} = -V_{in} R_f \left(j\omega C_s - j\omega K C'_s + \frac{1}{R + 1/ j\omega C_{12}} \right). \quad (8)$$

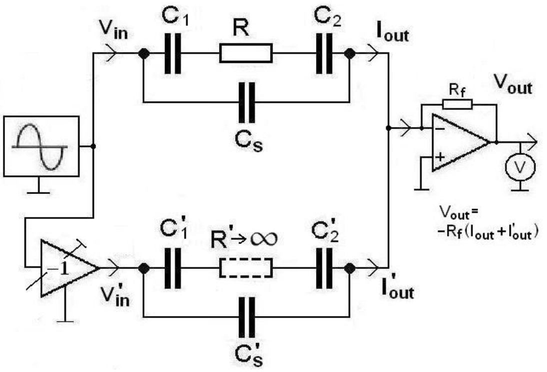


Fig. 5. Equivalent circuit based explanation of the compensation idea of using an parallel idle channel with the inversed AC signal. The adjusted amplification of the inversed signal followed by the immediate analogue summation of two output currents allows to obtain the efficient compensation of the stray capacitance leakage even for the case of unequal stray capacitances of the two channels.

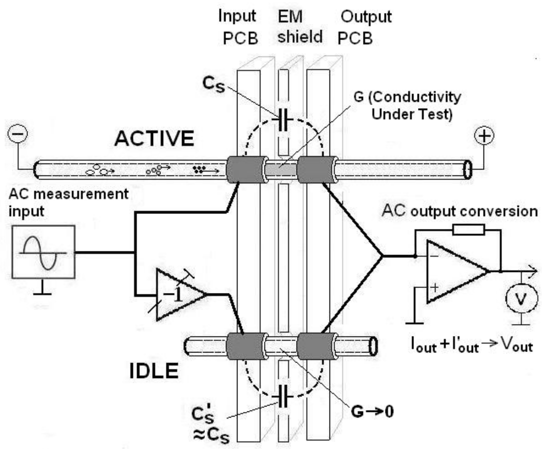


Fig. 6. Schematic presentation of the physical realization of the compensated C4D measurement arrangement of capillary electrophoresis. (PCB = Printed Circuit Board).

Equation (8) confirms that if we adjust the absolute value of the amplification coefficient of the inversed compensation channel equal to the value

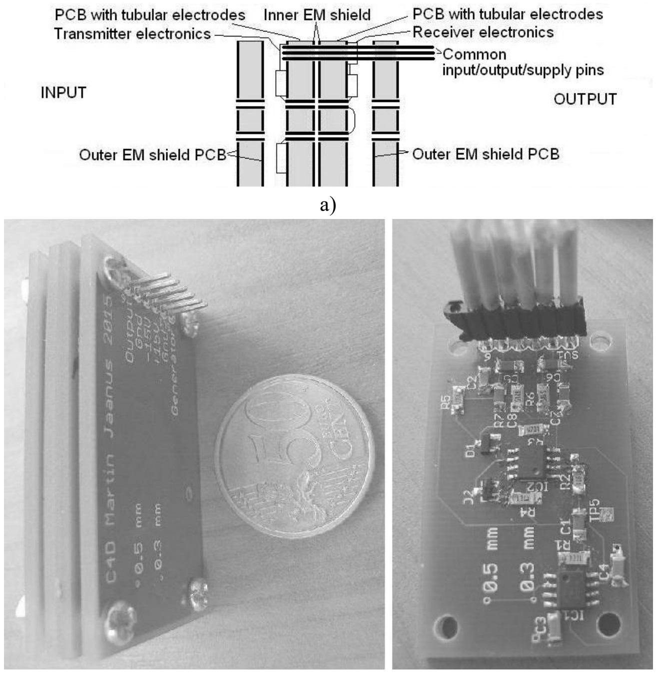
$$K = C_s / C'_s, \quad (9)$$

then the full compensation of the influence of the stray capacitance should be achieved within the frames of the equivalent circuit model of Fig. 5.

The idea described by (5)–(9) is confirmed by circuit simulation results presented in Fig. 4 above. As one can see, the total compensation of stray capacitance influence is indeed confirmed within the frames of the used equivalent circuit analysis. If we take into account that the real measurement arrangement is somewhat more complex than the simple equivalent circuit model of Fig. 5 and thereby the total compensation of C_s for all frequencies may be difficult, the presented new approach still predicts essential weakening of high frequency limitations of the capillary electrophoresis method.

IV. Physical Realization of the Improved Detector

Physical realization of the improved detector is explained in Fig. 7. Setup consists of four double-layer PCBs (Printed Circuit Boards). Two outer PCBs with holes (vias) for capillaries and electronic pins serve as auxiliary electromagnetic shields only. Important internal shield between transmitter and receiver boards is formed by two internal copper layers of those two boards.



a)

b) c)

Fig. 7. Physical realization of the detector on the basis of four 2-layer PCBs: a) explanation of the function of joined PCBs (shield – transmitter – receiver – shield); b) general view of four joined PCBs; c) receiver PCB. Common pins for input signal generator, measurement output and supply ±15 V go through the vias (isolated or connected) from the receiver side. Internal electromagnetic isolation between input and output is formed by two adjacent copper layers of two internal PCBs.

In contrast to previous basic design (Fig. 5 from [10]), the present electronic solution uses some advanced features. The measurement signal is generated using microprocessor and Voltage Controlled Oscillator LTC6990 and its frequency can be varied between 0.1 MHz and 2 MHz. The obtained signal is reformed to the sine wave by filtering and amplified to the relatively high level of 25 V peak-to-peak in order to make possible measurement of smaller conductivities. The analogue output signal from compensated C4D detector is rectified and sampled using high precision 24 bit A/D converter AD7710 that forms digital output for following analysis by software.

V. The Preliminary Test Results

The stray capacitance compensation methodology with applying parallel inversed signal channel was preliminary tested for two cases without fluid within the range of operation frequencies of 0.2 MHz–2 MHz of the designed electronics. For the new compensated realization scheme, the parallel channel amplification K was adjusted (see formula (9)) at lowest frequency 200 kHz to obtain the minimal output. Experiments showed that this adjusted K also remains close to the optimal at the higher frequencies. Results are presented in Table I and Table II.

The first CE experiments with real fluids showed that the measured fluid volumes could be decreased approximately by factor 3 due to the use of the compensation channel even in the case of non adjusted, fixed K = 1. This decrease of necessary volumes follows from the fact that small volumes mean higher resistances and thereby lower corner frequency f_2 (see (3) and Fig. 2). Compensated methodology, on the other hand, is constructed to suppress the appearance of f_2 (see the ideal compensation case in Fig.4).

TABLE I. TESTING RESULTS 1 (WITHOUT CAPILLARIES).

f [MHz]	Vout [mV] without compensation	Vout [mV] with compensation	Improvement ratio
0.2	98	4.2	23.3
0.25	146	6.7	21.8
0.3	180	9.8	18.4
0.5	364	37	9.8
0.8	597	75	8.0
1.0	720	97	7.4
1.5	938	151	6.2
2.0	996	175	5.7

TABLE II. TESTING RESULTS 2 (WITH CAPILLARY IN ACTIVE CHANNEL).

f [MHz]	Vout [mV] without compensation	Vout [mV] with compensation	Improvement ratio
0.2	89	13.2	6.7
0.25	134	20.4	6.6
0.3	176	28	6.3
0.5	344	65	5.3
0.8	574	116	4.9
1.0	712	152	4.7
1.5	902	226	4.0
2.0	945	254	3.7

VI. CONCLUSIONS

In the present paper, we introduced a new improved compensated (compensated C4D = C5D) electronic realization of the conventional C4D approach of conductivities measurement in the capillary electrophoresis. One of the main problems in the measurement of the conductivities of the microscopic substance volumes is the current leakages via the stray capacitances. To compensate the unwanted influence of this effect, the new methodology introduces the parallel idle channel with inversed AC measurement signal and subsequent immediate analogue summation of currents of active and idle channels prior to any further signal processing. Preliminary testing has shown noticeable 3-fold decrease of measurable volumes (*i.e.* CE method resolution) even without adjustment of inversed channel amplification. Our electronic realization of the CE apparatus includes also flexible adjustment of the measurement frequencies in the range of 0.2 MHz–2 MHz. We estimate that compensated C4D measurement concept may be easily applied also in the new emerging field of microchip electrophoresis.

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