



Article New C⁴D Sensor with a Simulated Inductor

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Abstract: A new capacitively coupled contactless conductivity detection (C^4D) sensor with an improved simulated inductor is developed in this work. The improved simulated inductor is designed on the basis of the Riordan-type floating simulated inductor. With the improved simulated inductor, the negative influence of the coupling capacitances is overcome and the conductivity measurement is implemented by the series resonance principle. The conductivity measurement experiments are carried out in three pipes with different inner diameters of 3.0 mm, 4.6 mm and 6.4 mm, respectively. The experimental results show that the designs of the new C⁴D sensor and the improved simulated inductor are successful. The maximum relative error of the conductivity measurement is less than 5%. Compared with the C⁴D sensors using practical inductors, the measurement accuracy of the new C⁴D sensor is comparable. The research results also indicate that the adjustability of a simulated inductor can reduce the requirement for the AC source and guarantee the interchangeableness. Meanwhile, it is recommended that making the potential of one terminal of a simulated inductor stable is beneficial to the running stability. Furthermore, this work indirectly verifies the possibility and feasibility of the miniaturization of the C⁴D sensor by using the simulated inductor technique and lays a good foundation for future research work.

Keywords: capacitively coupled contactless conductivity detection (C⁴D); contactless conductivity detection (CCD); series resonance; simulated inductor; conductivity measurement

1. Introduction

Electrical conductivity is a key parameter of electrolyte solution. The on-line measurement of conductivity is of great importance to academic research and industrial applications [1–4]. Up to date, the conventional conductivity measurement techniques have mainly been based on contact conductivity detection. The direct contact between the electrodes and the solution may cause the polarization effect and the electrochemical reaction [5–13]. Meanwhile, the electrode contamination may bring about unpredictable measurement error. These drawbacks limit the applications of the contact conductivity detection technique.

The capacitively coupled contactless conductivity detection (C⁴D) technique is a capillary electrophoresis (CE) alternative conductivity detection method [5–35]. Its measurement principle can be briefly illustrated by Figure 1. As shown in Figure 1a, the construction of a typical C⁴D sensor includes two cylindrical metal electrodes fixed around the outside of an insulating pipe, an AC source and a current pick-up unit. Figure 1b shows the equivalent circuit of the typical C⁴D sensor. C_1 and C_2 are the coupling capacitances between the electrodes and the solution through the pipe wall. C_{d1} and C_{d2} are the electrical double-layer capacitances. C_p is the stray capacitance. C_x is the solution capacitance and R_x is the resistor of the solution between the two electrodes. Research works have indicated that [3,7–28,31–35]: (1) The electrical double-layer capacitances C_{d1} and C_{d2} are in series

with the coupling capacitances C_1 and C_2 . The values of C_{d1} and C_{d2} are much larger than that of C_1 and C_2 . Because the capacitance resulting from a series combination of large and small capacitances is determined essentially by the small capacitance, C_{d1} and C_{d2} can be ignored. (2) The solution capacitance C_x is in parallel with the solution resisitor R_x . C_x is of a very small order of magnitude (*i.e.*, the impedance of C_x is much larger than that of R_x in an AC path). Because the impedance resulting from a parallel combination is determined essentially by the small one, the influence of C_x can be ignored. Thus, the influences of the electrical double-layer capacitances (C_{d1} and C_{d2}) and the solution capacitance C_x on the conductivity measurement are not significant and can be neglected. Additionally, the equivalent circuit Figure 1b can be simplified to Figure 1c which is the commonly used equivalent circuit in the C⁴D research field [7–12,17,18,20–27,31–35]. Meanwhile, research works have also verified that the negative influence of the stray capacitance C_p can be overcome by introducing a grounded plane/shield [7–11,20–28]. Thus, the equivalent circuit Figure 1c can be further simplified to Figure 1d. In this work, Figure 1d is used for the following electrical circuit analysis and discussion because a grounded shield is introduced into our new C⁴D senor. When the AC source u_i is applied, the current i_0 (which reflects the information of the solution resistor R_x) flows through the AC path to the current pick-up unit, and then the conductivity measurement is implemented.



Figure 1. Principle of a typical C⁴D sensor: (**a**) Construction; (**b**) Equivalent circuit; (**c**) Simplified equivalent circuit; (**d**) Further simplified equivalent circuit.

Obviously, C⁴D is a contactless detection method. The polarization effect and the electrochemical reaction, which exist in the contact conductivity detection, can be avoided. So, the C⁴D technique has received considerable attention of scientists and engineers since it appeared [5–35]. However, to date, C⁴D has mainly been studied and applied in the research field of analytical chemistry for ion concentration/conductivity detection in a capillary [5–35]. It is still a developing technique, and its resolution and detection range should be improved. As shown in Figure 1d, in the view of electrical impedance measurement, only the resistor R_x is the useful signal. Although the existence of the coupling capacitances C_1 and C_2 makes the contactless conductivity detection possible, the impedances of C_1 and C_2 are background signals which cause the loss of linearity and limit the resolution and the detection range of conductance detection [6–13,16–20,26–35].

To suppress the negative influence of the coupling capacitances, some methods have been proposed. The high-frequency method is a commonly used approach which reduces the influence of the coupling capacitances on the conductivity measurement by increasing the excitation frequency [6–13]. However, despite its usefulness, the application of the high-frequency method may cause higher requirements for the AC source and the design of the electronic circuit, and the stray capacitance is a

problem which must be considered. Laugere *et al.* studied a four-electrode C⁴D sensor in which the solution measurement is realized by a differential voltage signal [17,18,30]. However, the construction is relatively complicated. Shih *et al.* and Zheng *et al.* reported a new method which is based on the parallel resonance principle [31,32]. At the resonant frequency, the negative influence of the coupling capacitances and the stray capacitance can be eliminated. Unfortunately, the resonant frequency of the circuit is related to the resistor R_x and is difficult to determine. Kang *et al.* used the series inductance from a piezoelectric quartz crystal to compensate the conductance from C_1 and C_2 [33–35]. This method can effectively improve the sensitivity and the signal-to-noise ratio. However, it is mainly applied in capillaries and the operating frequency is relatively high [33–35]. Therefore, although many technical achievements have been obtained, more studies should be undertaken.

Currently, our research group has also made some efforts in this area and a new method on the basis of the series resonance principle is proposed [26–28]. Figure 2 is the simplified circuit of the C⁴D sensor based on series resonance, where *L* is a practical inductor connected into the AC path in series. At resonance (the resonant frequency f_0 is determined by $f_0 = \frac{1}{2\pi} \sqrt{\frac{C_1 + C_2}{LC_1C_2}}$), the capacitive reactance of the coupling capacitances will be eliminated by the inductive reactance of the inductor. The reactance of the overall impedance of the detection circuit can be zero and the overall impedance only consists of the resistor R_x which is the useful signal. Our research works have verified that with the introduction of a practical inductor, the negative influence of the coupling capacitances can be overcome, the measurement performance of the C⁴D sensor can be improved, and the C⁴D sensor can successfully implement the conductivity detection in millimeter-scale pipes [26–28].



Figure 2. Simplified circuit of the C⁴D sensor based on series resonance.

However, due to the non-adjustable characteristic of a practical inductor, the C⁴D sensor based on series resonance still has its drawbacks: (1) To implement the conductivity measurement, the frequency of the AC source should be adjusted to the resonant frequency. The resonant frequency is dependent on the inductance value of the practical inductor. For a practical inductor, it is not easy to adjust its inductance value. So, the non-adjustable characteristic of the practical inductor may cause an additional requirement for the AC source, and limit (or narrow) the selection range of the AC source; (2) The non-adjustable characteristic of the practical inductor more or less limits the interchangeableness of the C⁴D sensor and, hence, causes inconvenience for the practical application of the C⁴D sensor. For example, if we hope one detection circuit can be interchangeable in different C⁴D sensors with different inner diameters when the excitation frequency is difficult to adjust or one C⁴D sensor can work at different resonant frequencies, one practical inductor is not enough and different practical inductors with different inductance values should be used to implement the resonance. Therefore, if we can seek a useful approach to overcome the non-adjustable characteristic of a practical inductor, the C⁴D sensor based on series resonance may have broader application perspective.

Fortunately, the emergence of a simulated inductor technique provides an attractive solution. As we know, according to the current technique level, it is relatively simple to reduce the dimensions of resistors, capacitances and operational amplifiers, while it is difficult to reduce the size of practical inductors [36–38]. Meanwhile, it is difficult to implement large-valued inductors [38–42]. The simulated inductor is developed and studied to satisfy the need for small-size inductors in integrated circuits. A simulated inductor is implemented by using active and/or passive components (such as resistors, capacitances and operational amplifiers) and it can function effectively to replace a practical inductor in a circuit [36–38]. Compared with the practical inductor, the advantages of the simulated inductor are adjustable inductance value, small size, wider range of inductance values and

so on [36–45]. Currently, the simulated inductor is mainly studied and applied in integrated circuits. Our experience or knowledge on the application of the simulated inductor technique to other research fields is limited.

The aim of this work is to design an improved simulated inductor which is suitable for the C^4D sensor based on series resonance and, hence, to develop a new C^4D sensor. With the improved simulated inductor, the new C^4D sensor can overcome the influence of the non-adjustable characteristic of a practical inductor on conductivity measurement.

2. Design of New C⁴D Sensor

2.1. Improved Simulated Inductor

The improved simulated inductor is designed on the basis of the Riordan-type floating simulated inductor which is a classic and typical simulated inductor [36,42,44]. Figure 3 shows the circuit of the improved simulated inductor. Compared with the standard Riordan-type floating simulated inductor, the differences (or improvements) of this improved simulated inductor are as follows:

- 1. Considering the practical applications, to avoid the output saturation of the operational amplifiers A_1 and A_3 , two resistors R_4 and R_6 are added between the inverting input and the output of the operational amplifiers A_1 and A_3 , respectively.
- 2. The resistor R_5 is adjustable while it is an invariable resistor in the Riordan-type floating simulated inductor circuit. This modification is to make the equivalent inductance of the improved simulated inductor adjustable.



Figure 3. Circuit of the improved simulated inductor.

Let $R_1 = R_9$, $R_2 = R_8$, $R_3 = R_7$, $R_4 = R_6$, $C_{m1} = C_{m2}$. The impedance of the improved simulated inductor Z_s can be described as

$$Z_{\rm s} = \frac{u_{\rm out} - u_{\rm in}}{i_{\rm in}} = \frac{R_1 R_3 R_5}{R_2 R_4} + j2\pi f \frac{R_1 R_3 R_5}{R_2} C_{\rm m1} = r_{\rm eq} + j2\pi f L_{\rm eq}$$
(1)

The equivalent inductance of the improved simulated inductor L_{eq} is

$$L_{\rm eq} = \frac{R_1 R_3 C_{\rm m1}}{R_2} R_5 \tag{2}$$

The internal resistance of the improved simulated inductor r_{eq} is

$$r_{\rm eq} = \frac{R_1 R_3 R_5}{R_2 R_4} \tag{3}$$

In this work, to adjust the equivalent inductance conveniently, R_5 is chosen as an adjustable resistor, while the values of the other resistors and capacitances (R_1 , R_2 , R_3 and C_{m1}) are fixed. Thus, the equivalent inductance L_{eq} can be adjusted by changing the value of the adjustable resistor R_5 .

2.2. New C^4D Sensor

Figure 4 shows the measurement principle of the new C⁴D sensor. Figure 4a is the construction of the new C⁴D sensor, including an AC source, an insulating pipe, two cylindrical metal electrodes, the improved simulated inductor, a grounded shield and a signal processing unit. The signal processing unit has two parts: a current-to-voltage converter and a rectifier-filter circuit. The improved simulated inductor is introduced to overcome the negative influence of the coupling capacitances.



Figure 4. Measurement principle of the new C⁴D sensor: (**a**) Construction; (**b**) Equivalent circuit; (**c**) Simplified equivalent circuit.

Figure 4b illustrates the equivalent circuit of the new C⁴D sensor, where C_{p1} is the stray capacitance arising between the excitation electrode and the grounded shield, C_{p2} is the stray capacitance arising between the pick-up electrode and the grounded shield, and R_{f} is the feedback resistance. Research

works have verified that the stray capacitances C_{p1} and C_{p2} are very small and their influences can be neglected [20,26–28]. Thus, Figure 4b can be simplified to Figure 4c.

The overall impedance of the detection path is

$$Z = R_{\rm x} + r_{\rm eq} + j \left(2\pi f L_{\rm eq} + \frac{C_1 + C_2}{2\pi f C_1 C_2} \right)$$
(4)

where *f* is the excitation frequency of the AC source. According to the series resonance principle, at the resonant frequency f_0 , the inductive reactance and the capacitive reactance can be eliminated by each other and the reactance of the total impedance is zero. The resonant frequency f_0 is determined by

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{C_1 + C_2}{L_{eq}C_1C_2}}$$
(5)

Thus, the overall impedance Z_R at resonance is

$$Z_{\rm R} = R_{\rm x} + r_{\rm eq} \tag{6}$$

Equation (6) shows that, at the resonant frequency f_0 , the influence of the coupling capacitances C_1 and C_2 can be overcome, the overall impedance only consists of the resistance elements, the resistor of the solution R_x and the internal resistance of the improved simulated inductor r_{eq} . r_{eq} is a background signal. The existence of r_{eq} may, more or less, cause unfavorable influence on the linearity.

Furthermore, it is necessary to indicate that the reason why the improved simulated inductor is connected between the pick-up electrode and the signal processing unit (not connected between the AC source and the excitation electrode) is based on the consideration of the running stability of the simulated inductor. The components (resistors, capacitances and operational amplifiers) of the improved simulated inductor are not ideal. Additionally, the improved simulated inductor is a relatively complicated multi-closed-loop system. As we know, for a practical closed-loop system, its running stability is a problem which should be carefully considered. If the potentials of both terminals of the improved simulated inductor are unceasingly changing, it may bring some undesirable effects into the running stability of the improve the running stability, but also help to reduce the requirement for the relevant detection circuit. As shown in Figure 4b, the output of the improved simulated inductor is connected to the inverting input of an operational amplifier (the input of the current-to-voltage converter in the signal processing unit). That means the potential of one terminal of the improved simulated inductor is connected between the pick-up electrode and the signal processing unit.

3. Experimental Results and Discussion

3.1. Experimental Results

To test the performance of the new C⁴D sensor with the improved simulated inductor, the conductivity measurement experiments were carried out. Figure 5 illustrates the experimental setup for conductivity measurement. In the experiments, the insulating pipes were glass pipes. The electrodes were two rings of silver paint over the glass pipes. Three new C⁴D sensors with different inner diameters (3.0 mm, 4.6 mm and 6.4 mm, respectively) were tested. Table 1 lists the parameters of the three new C⁴D sensors. KCl solution was used as the experimental electrolyte solution and a syringe pump (Syringe Pump Model 33, HARVARD Apparatus Inc., Holliston, MA, USA, 0 mL/min~60 mL/min, $\pm 0.35\%$ full scale (F.S.)) was used to drive the solution into the pipe. A commercial device (cDAQ9172, National Instruments Inc., Austin, TX, USA) was used as the data acquisition unit. The reference conductivity data were obtained by a commercial contact conductivity meter (FE30, Meter Toledo Inc., Greifensee, Switzerland, 0.00 μ S/cm~199.9 mS/cm, $\pm 0.5\%$ F.S.). The

experimental temperature was around 25 °C. For the three new C⁴D sensors with different inner diameters, the improved simulated inductor was the same (its equivalent inductance value was adjusted to 53.0 mH). The components information in the improved simulated inductor circuit were: $R_1 = R_9 = 5.1 \text{ k}\Omega$, $R_2 = R_8 = 1 \text{ k}\Omega$, $R_3 = R_7 = 2 \text{ k}\Omega$, $R_4 = R_6 = 10 \text{ M}\Omega$, $C_{m1} = C_{m2} = 1 \text{ nF}$, the value of the adjustable resistor R_5 ranges from 0 to 10.0 k Ω , C_{m1} and C_{m2} are Multilayer Ceramic Capacitor (MLCC), the amplifiers ($A_1 \sim A_4$) are AD825 (Analog Devices, Inc., Norwood, MA, USA).



Figure 5. Experimental setup for conductivity measurement.

Table 1. Parameters of the three new C⁴D sensors.

New C ⁴ D Sensor	Length of the Electrodes (mm)	Length of the Gap (mm)	Excitation Frequency (kHz)
3.0 mm i.d. ¹ (5.0 mm o.d. ²)	15.0	15.0	164.8
4.6 mm i.d. (7.0 mm o.d.)	23.0	23.0	151.7
6.4 mm i.d. (8.5 mm o.d.)	32.0	32.0	134.8
	1		

¹ inner diameter; ² outer diameter.

The relative error was adopted to assess the conductivity detection performance of the new C⁴D sensor, which is defined as

$$e_{\rm r} = \frac{\rho_{\rm m} - \rho_{\rm f}}{\rho_{\rm f}} \times 100\% \tag{7}$$

where ρ_m is the measurement conductivity value obtained by the new C⁴D sensor and ρ_f is the reference conductivity value.

Figure 6 shows the experimental results of the three new C⁴D sensors. Compared with the commercial contact conductivity meter, the maximum relative errors e_r of the three new sensors are all less than 5%. Compared with the C⁴D sensors using practical inductors [26–28], the measurement accuracy of the new C⁴D sensor with the improved simulated inductor is comparable. Figure 7 shows the sensitivity plots of the new C⁴D sensor with 3.0 mm i.d. and the conventional C⁴D sensor with 3.0 mm i.d. Compared with the conventional C⁴D sensor, the performance of the new C⁴D sensor is better. Meanwhile, the sensitivity plots show that both sensitivities of the new C⁴D sensor and the conventional C⁴D sensor are not constant. At lower concentration, the sensitivities are relatively high while at higher concentration the sensitivities are low. Generally, the sensitivities of the new C⁴D sensor and the experimental results are in accordance with other researchers' study results [12,21–24,34]. The research results indicate that the designs of the new C⁴D sensor and the improved simulated inductor are successful. The improved simulated inductor is suitable for the C⁴D sensor based on series resonance and the measurement performance of the new C⁴D sensor is satisfactory.



Figure 6. Conductivity measurement results of three new C⁴D sensors: (**a**) 3.0 mm i.d.; (**b**) 4.6 mm i.d.; (**c**) 6.4 mm i.d.



Figure 7. Sensitivity plots of the new C^4D sensor with 3.0 mm i.d. and the conventional C^4D sensor with 3.0 mm i.d.

As mentioned in Section 2, the equivalent inductance value of the improved simulated inductor can be adjustable by changing the value of the adjustable resistor R_5 . To test the adjustability of the improved simulated inductor, the relevant experiments are also performed. The test results indicate that the equivalent inductance value of the improved simulated inductor can be successfully changed from 28.8 mH to 74.1 mH by adjusting R_5 from 2.27 k Ω to 6.23 k Ω . This capability of the

improved simulated inductor can greatly reduce the requirement for the AC source and is beneficial for guaranteeing the interchangeableness of the new C⁴D sensor.

In addition, to test the reasonableness of the connection method of the improved simulated inductor, a supplementary C⁴D sensor was developed and a special comparison experiment was carried out. Figure 8 shows the construction of the supplementary C⁴D sensor. Compared with Figure 4a, obviously, unlike the new C⁴D sensor, in the supplementary C⁴D sensor the improved simulated inductor is connected between the AC source and the excitation electrode. Figure 9 shows the output signals of the new C⁴D sensor with 3.0 mm i.d. and the supplementary C⁴D sensor with 3.0 mm i.d. It is clear that the signal fluctuation amplitude of the supplementary C⁴D sensor is greater than that of the new C⁴D sensor can implement the conductivity measurement, its running stability is obviously worse than that of the new C⁴D sensor. This experimental result verifies that our consideration of the running stability of the simulated inductor is reasonable. The connection method in the new C⁴D sensor (the improved simulated inductor is connected between the pick-up electrode and the signal processing unit) is a wise choice.



Figure 8. Construction of the supplementary C⁴D sensor.



Figure 9. Output signals: (a) Supplementary C⁴D with 3.0 mm i.d.; (b) New C⁴D sensor with 3.0 mm i.d.

3.2. Discussion

The research results in this work have proved that the equivalent inductance value of a successfully designed simulated inductor can be adjusted in a relatively wide range (e.g., in this work, the equivalent inductance value of the improved simulated inductor can be changed from 28.8 mH to 74.1 mH by adjusting R_5 from 2.27 k Ω to 6.23 k Ω .). However, the adjustment range of the practical adjustable inductor is usually less than 15%. So, the simulated inductor technique indeed provides a useful approach to overcome the non-adjustable characteristic of a practical inductor. The adjustability

of a simulated inductor is not only beneficial to the design of a sensor, but is also convenient for guaranteeing the interchangeableness of the sensor and its practical applications.

Meanwhile, the research results also indicate that a simulated inductor is a relatively complicated closed-loop system and its components (resistors, capacitances and operational amplifiers) are not ideal. The running stability is really a problem which should be carefully considered. According to our comparison experimental result, it is recommended that making the potential of one terminal of a simulated inductor stable is beneficial to the running stability.

Furthermore, the miniaturization of the C⁴D sensor has become an attractive research area and many researchers have made their efforts in this area [5,7–10,17,18,30]. It is necessary to indicate that, although the aim of this work is not the miniaturization of the C⁴D sensor, the research results can provide a useful reference. As we know, the practical inductor is usually a spiral inductor and its miniaturization is very difficult [36–42]. Unlike a practical inductor, the miniaturization of the components (resistors, capacitances and operational amplifiers) used in a simulated inductor are easy to implement [36,38–40]. This work actually indirectly verifies the possibility and feasibility of the miniaturization of the C⁴D sensor by using the simulated inductor technique and lays a good foundation for future research work.

4. Conclusions

In this work, the simulated inductor technique is introduced into the research field of C⁴D. Based on the Riordan-type floating simulated inductor, an improved simulated inductor is designed to overcome the non-adjustable characteristic of a practical inductor. With the improved simulated inductor, a new C⁴D sensor, which implements the conductivity measurement by the series resonance principle, is developed.

Three new C⁴D sensors with different inner diameters (3.0 mm, 4.6 mm and 6.4 mm, respectively) have been evaluated experimentally. The conductivity measurement results demonstrate that the design of the improved simulated inductor is effective and the new C⁴D sensor is successful. Compared with a commercial contact conductivity meter, the maximum relative error of the new C⁴D sensor is less than 5%. Compared with the C⁴D sensors using practical inductors, the measurement performance of the new C⁴D sensor is comparable.

The test experimental results show that the equivalent inductance value of the improved simulated inductor can be adjusted in a relatively wide range, compared with a practical inductor. Due to the adjustability of the improved simulated inductor, it is easier for the new C⁴D sensor to implement the conductivity measurement and the requirement for the AC source is reduced. The research results also indicate that making the potential of one terminal of a simulated inductor stable is beneficial to the running stability.

This research work verifies the effectiveness and feasibility of the application of the simulated inductor technique to the design of a new C^4D sensor. Meanwhile, this research work expands the application fields of the simulated inductor technique and lays a good foundation for the miniaturization and integration of the C^4D sensor in the future.

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