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A new method of capacitively coupled contactless conductivity detection based on series resonance

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A B S T R A C T

Based on the series resonance principle, a new method of capacitively coupled contactless conductivity detection (C^4D) is proposed to improve the detection resolution and to expand the detection range of the C^4D. With the introduction of an inductor module, at series resonance, the influence of the coupling capacitances formed by the metal electrodes, insulating pipe and electrolyte solution on conductivity detection is eliminated. Meanwhile, a new shield configuration is designed to remove the influence of the stray capacitances. The experiment results show that the proposed method is an effective detection method. Compared with the existing C^4D methods, it has the advantages of high resolution and wide detection range.

1. Introduction

Electrical conductivity is one of the basic physical characteristics of electrolyte solution. The on-line detection of electrical conductivity plays an essential role in scientific research and industrial production [1]. The conventional conductivity detection method is the contact conductivity detection method, which has been studied for many years and widely applied to many research fields. The contact conductivity detection method usually uses metal electrodes that are immersed directly in the electrolyte solution. Due to the contact between electrodes and electrolyte solution, the polarization effect and the electrochemical erosion effect will arise and the performance of the contact conductivity detector will deteriorate [2].

In 1980, capacitively coupled contactless conductivity detection (C^4D) was firstly proposed by Gas et al. [3], who adopted a four-electrode contactless detector setup. In 1998, Zemann et al. [4] and da Silva and do Lago [5] independently made a significant contribution to C^4D by introducing an axial arrangement of C^4D [4–7]. The complicated four-electrode contactless detector setup was simplified to two-electrode setup. In this configuration, the detector consists of two tubular electrodes: an excitation electrode and a pick-up electrode, which are placed cylindrically around the outside of the insulating pipe and separated with a detection gap. Electrodes, insulating pipe and the electrolyte solution can form coupling capacitances, and the solution can be equivalent to a resistor. Hence, the two electrodes, insulating pipe, and the electrolyte solution can be equivalent to an alternating current (AC) path. If an AC voltage is applied to the excitation electrode, an AC current which contains the information of the solution conductivity can be obtained on the pick-up electrode.

Based on C^4D, the direct contact of the electrodes with the solution is not necessary in the detection process, so it can avoid the polarization of the electrodes and the electrochemical reactions on the electrode surfaces, which exist in the conventional contact conductivity detection methods. Moreover, C^4D is more easily implemented and more robust [6,8]. So this method has received great attention of scientific researchers since it appeared, especially in the research field of analytical chemistry, showing great development potentialities and broad industrial application prospects [6–13].

However, as a relatively new conductivity detection method, the existing C^4D methods still have some drawbacks. Compared with the conventional contact conductivity detection, the resolution and the detection range of C^4D should be improved [8,9]. One of the main factors is the two coupling capacitances formed by the two electrodes, the insulating pipe and the electrolyte solution [6,8]. From the viewpoint of impedance detection, only the impedance of the resistor (electrolyte solution) is the useful signal, and the impedances of the two coupling capacitances are the unfavorable background signals [6,8,10]. The existence of the background signal has negative influence on the conductivity detection

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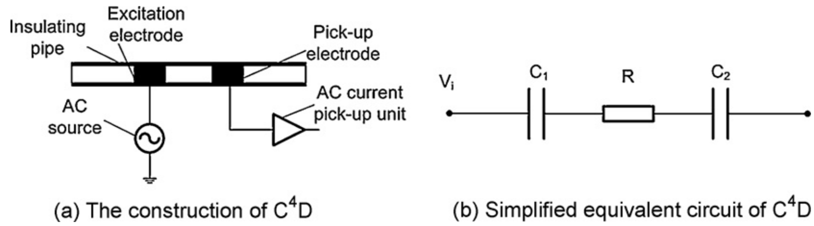

Fig. 1. Schematic drawing of C^{4}D measurement principle. (a) The construction of C^{4}D. (b) Simplified equivalent circuit of C^{4}D.

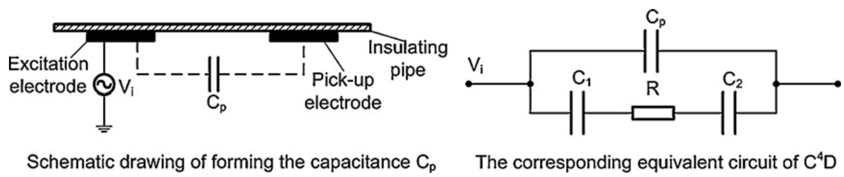

Fig. 2. Schematic drawing of forming the capacitance C_p and the corresponding equivalent circuit of C^{4}D.

and limits the resolution and the detection range [6,8]. Meanwhile, the influence of the stray capacitances on the conductivity detection is another factor and should be removed by the specific design of electric circuit.

This work aims to improve the performance of C^{4}D. Firstly, the latest achievements and progresses of C^{4}D are summarized. Secondly, based on the series resonance principle, a new method of C^{4}D is proposed to overcome the influence of the coupling capacitances on the conductivity detection. Meanwhile, a new shield configuration is designed to remove the influence of the stray capacitances. Finally, the experiment results, the comparisons and some discussions are presented.

2. Principle and state-of-the-arts of C^{4}D

Fig. 1 illustrates the measurement principle of C^{4}D. As shown in Fig. 1a, the construction of C^{4}D includes an insulating pipe, two metal electrodes (an excitation electrode and a pick-up electrode), an AC source and an AC current pick-up unit. The two electrodes are fixed cylindrically around the outside of the insulating pipe. The AC source generates AC signal on the excitation electrode and the AC current pick-up unit measures the AC current from the pick-up electrode. The simplified equivalent circuit of C^{4}D is depicted in Fig. 1b. Two electrodes, the insulating pipe and the electrolyte solution form two coupling capacitances C_1 and C_2, and the solution is equivalent to a resistor R. That forms an alternating current path. The application of an AC voltage on the excitation electrode leads to an AC current flowing through the AC path. And then, from the AC current obtained by the AC current pick-up unit, the conductivity detection can be implemented.

In fact, there is a stray capacitance C_p arising from direct coupling between the electrodes through air, as shown in Fig. 2. C_p is an influence which is not desired as it forms a current bypass which leads to a background signal [6,8,10]. The negative influence of C_p can be minimized by introducing a shield between the excitation electrode and the pick-up electrode [6,10], as shown in Fig. 3a. With the shield, two extra stray capacitances C_{d1} and C_{d2} arise, as shown in Fig. 3b. C_{d1} is the capacitance formed by direct coupling between the excitation electrode and the shield, and C_{d2} is the capacitance formed by direct coupling between the pick-up electrode and the shield. C_{d1} is in parallel with the AC source, and the current across C_{d1} does not flow through the detection path, so it has no influence on the detection. C_{d2} usually connects with the inverting input of an operational amplifier (the input port of the AC current pick-up unit), it also has no influence on the conductivity detection. Thus, the shield can remove the effect of the stray capacitance C_p and has no influence on the detection. Meanwhile, Gas et al. [2] and Kuban and Hauser [10] have indicated that the introduction of the shield can contribute to the improvement of the detection resolution.

The shield can remove the influence of the stray capacitance C_p, while the coupling capacitances C_1 and C_2, as parts of the AC path, still exist. As mentioned in Section 1, only the impedance of R is the useful signal, and the impedances of C_1 and C_2 are unfavorable background signals. The existence of C_1 and C_2 has negative influence on the conductivity detection and limits the resolution and the detection range. To solve this problem, some researchers have conducted some useful studies [8,14–15].

Laugere et al. have developed a four-electrode C^{4}D device [14,15], in which four electrodes are fixed on a channel axially: the outer two are excitation electrodes and the inner two are pick-up electrodes. A fixed AC current source I_i is connected between the outer electrodes, and the resulting differential voltage V_0 between two inner electrodes is measured with a high input impedance voltmeter. The solution resistance is retrieved from the ratio V_0/I_i [14,15]. Although this method needs four electrodes to measure a weak current and its construction is relatively complicated, it allows to measure the solution impedance value independently of the coupling capacitances (C_1 and C_2) and it can increase the linearity, accuracy and resolution of the detection.

Shih et al. have proposed a new method based on parallel resonance [8]. The equivalent circuit of this method is illustrated in Fig. 4, where an inductor L_s with an internal resistance R_{LS} is in par-

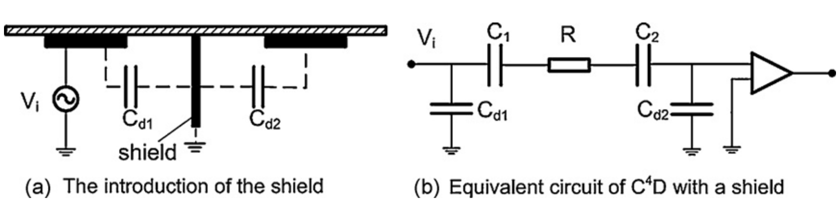

Fig. 3. Schematic drawing of C^{4}D with a shield principle. (a) The introduction of the shield. (b) Equivalent circuit of C^{4}D with a shield.