A portable and low-cost parallel-plate capacitor sensor for alkali and heavy metal ions detection

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A portable and low-cost design of parallel-plate capacitor sensor is proposed and investigated for detection of heavy and alkali metal ions concentration in liquid solution. The application of a thin and long-sided parallel PCB plate allows one to measure the dielectric response of each sample through capacitive sensing technique. The measurements were based on the peak output voltage corresponding to the capacitance of the output measured by an oscilloscope with metal ions concentration of the solution varying from 0 to 10 ppm and input frequency ranging from 1 kHz to 10 MHz. The ICF of Li, Na and K in chloride solution was 2.4, 2.1 and 1.9 MHz, respectively. The ICF of Na and K in hydroxide solution was 1.5 MHz and 1.1 MHz, respectively, while the ICF of $\text{Pb}(\text{NO}_3)_2$ was 490 kHz. The detected ICF was applied to further construct the portable sensor system, which is simple in design, low-cost in fabrication and easy to operate. The finding of ICF of each chemical element is necessary to solve the selectivity challenge of the capacitance-based sensor, which will be appropriate for chemical, environmental and engineering applications.

Keywords: Capacitive sensing; capacitor sensor; characteristic frequency; metal ions detection; parallel-plate capacitor.

1. Introduction

Capacitive sensing¹ is becoming an increasingly popular technology to replace optical and mechanical methods for motion detection applications,² material analysis,³ and liquid level⁴ sensing. The main advantage of capacitive sensing over other methods is to detect a variety of materials (leather, plastic, metal and liquid), simple system design, comfortable and practical operation and low cost, so it is possible to be mass-produced.¹ In addition, in the field of material analysis, the methods that are often used are chemical analysis methods such as spectrophotometry and chromatography. The drawback is that the sample of the chemical composition should be taken and tested in the laboratory, so it is not possible to test it in real-time in the field. This constraint can be avoided by utilizing capacitive sensing techniques for certain samples requiring real-time and continuous measurements, such as the measurement of salinity of seawater and the level of pollution of waste at aquatic sources.

Capacitive sensing is a sensor that works by using the principle of capacitor.¹ One of the simplest capacitor forms is the parallel-plate capacitor. The parallel-plate capacitor consists of two conductor plates with a particular surface area, which is positioned parallel to each other and separated by a certain distance. Since the cross-sectional area and the spacing between the two plates are set constant, the only factor that will affect the measured capacitance value is the dielectric constant of the material. This is the basis for the application of parallel-plate capacitors for material analysis.

The measurement of the dielectric response can provide a valuable understanding of the electrostatic and electrokinetic properties of the colloidal dispersion and its constituent particles.⁵ The dielectric constant will be affected by many factors, including material type, concentration, solvent polarity, temperature, humidity and air pressure.^{1,6} Since the dielectric constant is affected by moisture, then by assuming that the air pressure and the temperature is constant, the capacitance method can be used as an air humidity sensor.^{7–10} In practice, however, external factors such as temperature, humidity and air pressure in the laboratory are considered constant and can be ignored in the calculations.

In addition to some of the advantages they has, parallel-plate sensors have a significant disadvantage in terms of selectivity. The poor selectivity of parallel-plate sensors is due to the physical properties of the parallel-plate capacitor, i.e., the capacitance value of the sensor depends on the dielectric constant value of the measured material. The dielectric constant expresses the permittivity of the flux relative to a vacuum, i.e., the density of the electrostatic flux when given a certain external electrical field. The dielectric constant is influenced by various factors both internal and external, such as the type of material, concentration, polarity solvent, temperature, humidity and pressure.¹¹ In practice, the measurement of the capacitance response is sensitive to the input signal frequency.¹ This frequency, which is, also the characteristic of each material, is after this referred to as the internal characteristic frequency (ICF). To overcome the selectivity problem of the parallel-plate capacitor sensor,

the material analysis needs to be done at this particular frequency. Therefore, it is necessary to find out the ICF of each material.

This study aims to design a sensor based on parallel-plate capacitors that can detect certain elements such as alkali and heavy metals ions, identifying variations of concentration, as well as finding the frequency characteristics of these elements. The samples used in this study are several types of alkali and heavy metals solutions with various concentrations, namely LiCl, NaCl, KCl, NaOH, KOH and $\text{Pb}(\text{NO}_3)_2$. The proposed sensor measured the output voltage, which is influenced by the dielectric changes of the samples. This technique offers simplicity, reliability and continuous measurement capability.

2. Experimental Details

2.1. Sensor design and fabrication

The process of making a parallel-plate capacitor sensor begins with the preparation of copper-coated fiber plate in the form of printed circuit board (PCB) plate as the main body of the sensor. The selection of PCB plate is based on the criteria of thin flat metal requirement but has a high rigidity as a sensor support. These requirements are filled with PCB made of a nonconductive fiber material with evenly coated metal layers. To facilitate the preparation stage, PCB plate was cut to the same size, i.e., 5 cm long and 1 cm wide. The etching process was done to obtain the desired broad size. Before etching process, the PCB is insulated to prevent its reaction with the FeCl_3 solution. The size of the insulation is 4 cm long and 0.5 cm wide to obtain a total of 2 cm^2 cross-sectional area as illustrated in Fig. 1. After the etching process was finished, two identical PCB plates of the exact same size, as expected were obtained. The next step is to install the connecting cable on each plate through the soldering process. Soldering must be neat and thorough, so as not to interfere with the coating process with an insulating material. After the connecting cable is properly installed, then the coating is provided with a permanent insulating material to prevent the conductivity effect of the solution. The insulating layer should be thin and flat, so the changes in dielectric constant due to the insulator thickness can be negligible. The two plates then were placed parallel to each other yet separated by a distance of 4 mm.

Fig. 1. Diagram of parallel-plate capacitor sensor.

2.2. Metal ion solution

Metal ion solutions were prepared from analytical grade lithium chloride (LiCl), sodium chloride (NaCl), potassium chloride (KCl), sodium hydroxide (NaOH), potassium hydroxide (KOH) and lead dinitrate ($\text{Pb}(\text{NO}_3)_2$) (Emsure; 98%, metals basis) using deionized water. Metal powders were weighed with an analytical balance (Fujitsu FS-AR210), dissolved in a certain volume of deionized water until the metal ions content in each solution were in the range of 1–10 ppm. Although humidity and temperature changes affect the dielectric measurement, the humidity and temperature are considered negligible, and the temperature is kept constant at 25°C during the experiment.

2.3. Output voltage and measurements

To find out the optimum response of the parallel-plate capacitor sensor, a series of measurements were conducted. The measurements aim to determine the linear relationship between the measured capacitance to the content of the metal ions solution. LiCl, NaCl, KCl, NaOH, KOH and $\text{Pb}(\text{NO}_3)_2$ solutions with concentrations of 1–10 ppm were used as the samples. To get the ICF of each solution, the input frequency was varied from 1 kHz up to 10 MHz. The sinusoidal waveform was selected because it does not undergo distortion and change when reacting with the capacitive circuit. It is known that sinusoidal wave function will remain unchangeable when interacting with differentiator or integrator circuit.¹² The input signal from a signal generator (Iwatsu Electronic Co., Ltd. FG-350) is connected to the voltage divider circuit, which is composed of the series circuit between the capacitor and the reference capacitor or better known as De Sauty Bridge. Changes in the capacitance can be observed from the output voltage at the terminal between the capacitor sensor and the reference capacitor. Measurement of output voltage was done by using a digital oscilloscope (Atten® Instruments AT7340 40 MHz). The measurement result is the output voltage value as a function of the given sinusoidal wave frequency and the metals ions content in the solution. The experimental setup is shown in Fig. 2.

3. Results and Discussion

Figures 3(a)–3(f) shows the output voltage against the variation of concentration of each metal ion solution. As shown in the figure, the output voltage of the sensor linearly increases as the concentration of the metal solution increases. The results show the degree of linearity of the sensor are 0.9946, 0.9943, 0.9951, 0.8830, 0.9667 and 0.9699 for LiCl, NaCl, KCl, NaOH, KOH and $\text{Pb}(\text{NO}_3)_2$ solutions, respectively. The sensor performance is summarized in Table 1. The sensitivity^{1,13} defines the detection limit, which is the smallest concentration that can be sensed by the sensor, and the best sensitivity is obtained at 0.4 ppm for KCl solution.

Fig. 2. Experimental setup for the proposed parallel-plate capacitor sensor for metal ion detection.

The resolution,^{1,13} on the other hand, is the smallest change that can be detected by the sensor and is obtained at 1 mV for all solutions. The sensor's degree of linearity with the majority value of more than 95% indicates that the parallel-plate capacitor sensor provides a good performance and can be used as an alternative sensor to evaluate the concentration of the solution.

The output voltage that increases linearly with the increasing concentration can be explained using the dielectric concept of the material.¹⁴ Higher ion concentration in the solution reduces the net electric field because the electric dipole within the molecules tends to oppose the external electric field (Fig. 4).¹⁵ As a result, the net electric field will be reduced. The reducing net electric field is described as high dielectric constant; higher dielectric constant indicates higher capacitance. Consequently, the voltage output

Fig. 3. Output voltage against metals ions concentration for (a) LiCl, (b) NaCl, (c) KCl, (d) NaOH, (e) KOH and (f) $\text{Pb}(\text{NO}_3)_2$ solution.

Fig. 3. (Continued)

Table 1. The performance of parallel-plate capacitor sensor.

Parameter	Value					
	LiCl	NaCl	KCl	NaOH	KOH	$Pb(NO_3)_2$
Linearity (%)	99.46	99.43	99.51	88.30	96.67	96.99
Sensitivity (ppm/mV)	14.5	4.8	0.4	18.8	66.5	10.9
Resolution (mV)	1	1	1	1	1	1
Measurement range (ppm)	0–10	0–10	0–10	0–10	0–10	0–10

increases, which will be used as an indicator of different concentration of ion metal solution in this study.

Figures 5(a)–5(f) show the output voltage against variation of the frequency of each metal ion solution. As shown in the figure, the output voltage-to-frequency response for each

Fig. 4. Illustration between dipole moment of dielectric material and external electric field inside a parallel-plate capacitor (d : distance between capacitor's plates; E : electric field).

solution varies. The top of each plot shows the optimal frequency that gives the highest output voltage in each solution. From Fig. 5, it can be found that the optimal frequency for LiCl, NaCl, KCl, NaOH, KOH and $Pb(NO_3)_2$ solutions is 2.4 MHz, 2.1 MHz, 1.9 MHz, 1.5 MHz, 1.1 MHz and 490 kHz, respectively. This optimal frequency, which gives the highest output voltage together with the best linearity degree, is called the ICF. The results from Fig. 5 also proved that the ICF does not change over the variation of concentration, shown by the peak output voltage, which remains constant at the same frequency for all variations in the concentration of the solution used. Hence, it can be concluded that the ICF is a characteristic property of a specific material. The linearly decreased ICFs from LiCl to KCl, and from NaOH to $Pb(NO_3)_2$ agree with the theoretical basis, which says that the ICF of the material will be inversely proportional to the reduced mass of the material.^{16,17} In short, we can expect larger molecules to have smaller ICF and vice versa.

The correlation between ICFs and the highest output voltage can be described using the quantum properties of the material. The electrical signal frequency is a description of the changes of the electric field over time, resulting in a change in the electric dipole orientation of the metal ions solution. The electric dipole in the solution always tends to oppose the external electric field¹⁵ or attempts to maintain its internal electric dipole orientation (Fig. 4). At certain frequencies, the dipole orientation will be in equilibrium between the moment of the force due to the external electric field and the opposing internal force, so that the dipole orientation becomes stable and the solution has a certain polarity. This is called the polarization effect. In polarized conditions, the solution will become ferroelectric, having its

maximum dielectric value.¹⁴ This means that the capacitance of the sensor will be of utmost value, which is indicated by the maximum output voltage when given a specific frequency, as already proved in this study. This certain frequency is associated with the vibration and rotation frequency of the molecules, at which, the value will be inversely proportional to its moment of inertia.^{16,17} In other words, the ICF of the molecules is inversely proportional to its mass.

Finally, we have successfully fabricated the capacitor sensor which can detect the concentration difference in various metal ion solutions. The sensor design as well as the

method of fabrication is very simple and utilizes low-cost materials. This design offers simplicity, reliability and continuous measurement capability. However, despite its advantages as previously mentioned, the major drawback of this sensor is its selectivity issue. All the metal ion solutions used in this study are homogenous solutions, therefore, further research to study the sensor's capability to detect the concentration of a certain ion in a heterogeneous solution is necessary. Further improvement of the sensor's design to increase its sensitivity and detection range also needs to be done.

Fig. 5. Output voltage (Vpp) against input frequency (Hz) for (a) LiCl, (b) NaCl, (c) KCl, (d) NaOH, (e) KOH and (f) $\text{Pb}(\text{NO}_3)_2$ metals solution.

Fig. 5. (Continued)

4. Conclusion

A portable and low-cost sensor is proposed and investigated for the detection of metal ion solution in various concentrations. The main body of the sensor was made of a pair of copper-coated PCB plates connected to the larger capacitor as the voltage divider circuit. For a concentration change from 0 to 10 ppm, the output voltage of the sensor increases linearly with the sensitivity of 66.5 ppm (KOH solution) to 0.4 ppm at best (KCl solution) and the linearity (R^2) of more than 95%. The increment of the content of the solution increases the dielectric constant of the solutions, hence, it increases the capacitance which is proportional to the output voltage. This study also found the ICF of each solution, which is not dependent on the concentration, but rather a characteristic of the specific material. The ICF of LiCl, NaCl, KCl, NaOH, KOH and $\text{Pb}(\text{NO}_3)_2$ solutions is 2.4 MHz, 2.1 MHz, 1.9 MHz, 1.5 MHz, 1.1 MHz and 490 kHz, respectively. This parallel-plate capacitor sensor provides considerable advantages in monitoring the concentration, such as simplicity in design, low-cost fabrication, ease in handling and reliable measurement results.

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