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Design of capacitive sensor for water level measurement

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Design of capacitive sensor for water level measurement

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Abstract. Capacitive sensor for water level detection has been fabricated. It has, typically, high-impedance sensor, particularly at low frequencies, as clear from the impedance (reactance) expression for a capacitor. Also, capacitive sensor is a non-contacting device in the common usage. In this research, water level sensor based on capacitive principal created using two copper plates with height (h), width (b), and distance (l) between two plates, respectively, 0.040 m, 0.015 m, and 0.010 m. 5 V_{pp} 3 kHz AC signal is used as input signal for the system. Dielectric constant between two plates is proportional to water level. Hence, it can be used to determine water level from electrical characteristic as it inversely proportional to sensor impedance. Linearization, inverting amplifier, and rectifier circuits are used as signal conditioning for the system. Based on conducted experiment, the relationship between water level (x), capacitance (C), and output voltage (V_{dc}) can be expressed as $C(x) = 2.756x + 0.333 \, \text{nF}$ and $V_{dc}(x) = 15.755 + 0.316$ V.

1. Introduction

Measurement of liquid level inside a container with various methods has been developed occasionally [1] [2]. Liquid level measurement can be utilized from the characteristic of the liquid itself; such as permittivity, permeability, conductivity, et cetera. One type of sensor which developed for liquid level measurement is capacitive sensor [3] [4] [5] [6].

Capacitive sensor can be categorized as reactive sensor. Hence, it is influenced by its input frequencies. Generally, capacitive sensor has non-contact characteristic. It also needs specific signal conditioning devices [7].

The research on development of capacitive sensor has been done by some researchers. Paczesny, et. al, conducted experiment in the capacitive sensor for liquid level measurement made with ink-jet printing technology [3]. Furthermore, Wei, et. al, conducted a research in implementation and characterization of a femto-Farad capacitive sensor for pico-liter liquid monitoring [4].

In this research, water level measuring device is designed based on capacitive sensor. The sensor is made from two plastic-insulated copper plates and it connected into signal conditioning devices. The change of the water level detected by the sensor will results the change of capacitance value in the sensor and represents as the change of voltage on the output.

2. Sensor Fabrication

The capacitive sensor is formed from two conductive plates (figure 1). Both plates have ability to store electrical charges. The value of capacitor C obtains from equation (1); where l is the

distance between two plates, and ε is dielectric constants of the insulator materials between two plates (which it consists of ε_o (permittivity of vacuum) and ε_r (relative permittivity))(equation (2)).

$$C = \varepsilon \frac{A}{l} \tag{1}$$
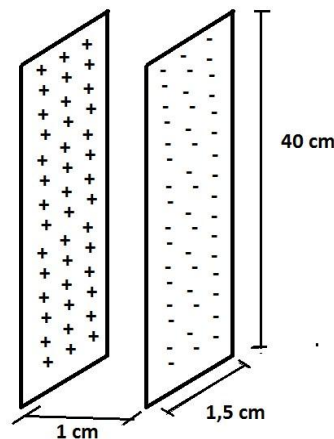
$$C = \varepsilon_o \varepsilon_r \frac{A}{l} \tag{2}$$

Figure 1. Visualization of charge storage on the plates

From equation (1), the capacitance (C) value is affected by the value of ε, A, and l. Hence, equation (3) and (4), which shows the influence of the variables to sensor's capacitance value, can be derived from equation (1).

$$\ln C = \ln \varepsilon + \ln A - \ln l \tag{3}$$

$$\frac{\Delta C}{C} = \frac{\Delta \varepsilon}{\varepsilon} + \frac{\Delta A}{A} - \frac{\Delta l}{l} \tag{4}$$

$$S = \frac{\Delta C}{\Delta A} = \frac{1}{b} \frac{\Delta C}{\Delta x} = \frac{\varepsilon}{l} \tag{5}$$

Because of the level role as the measuring object, the ideal sensor's sensitivity can be written as equation (5) where l represents level of the liquid and b is width of the sensor. It shows the sensitivity of the sensor depends on water level is a constant if the values of ε and l are also constants.

3. Implementation with Signal Conditioning Devices

The sensor is made from two copper plates which had dimensions, for every plate, are 0.4 m in height (h), 0.015 in width, and 0.001 m in thickness. Both plates separated 0.01 meter from each other and insulated with plastics to avoid direct contact with another substances. It helps to give some room for another substance infiltrated between plates and to reduce, or even remove, the possibility of electrical short-circuit between two plates when ac input is applied. In the experiments, capacitive sensor is used to measure liquid level inside a container with 30 cm of maximum depth. The type of liquid used is water (ε_r = 80.1 in 20° C). Figure 2 shows when the sensor is placed inside of water container. All experiments are conducted on room temperature.
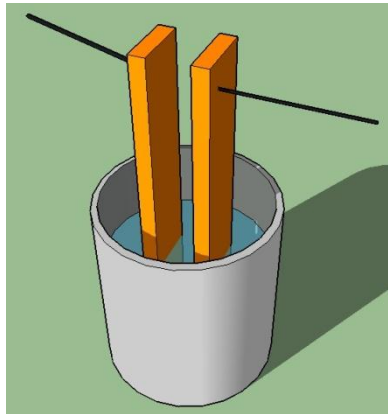
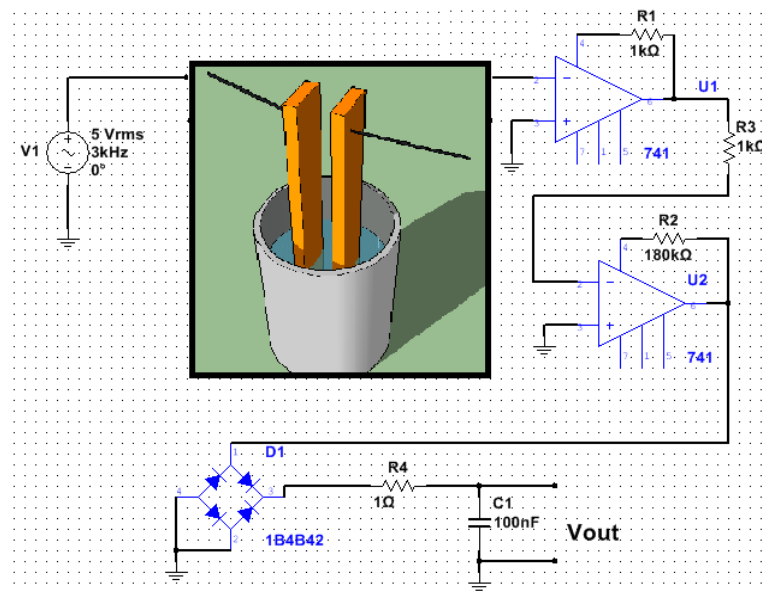**Figure 2.** Location of the sensor inside the container

Figure 3. Schematic figure of devices integration

Capacitive sensor is a passive sensor [1, 7]. Therefore, it needs some signal conditioning device(s) to obtain other quantities (voltages or currents) which can be processed on the other conditioning or processing devices. In this research, there are three types of signal conditioning circuits: (1) linearization circuit; (2) Op-Amp inverting amplifier circuit; and (3) rectifier (see figure 3). The sensor is located between power source and linearization circuit. Linearization circuit is a circuit which used to obtain linear correlation between its input and output signal. It used as the feeder of other devices. It consists of resistor, Op-Amp device, and the capacitive sensor. As the ac input applied, the output equation can be expressed as equation (6) where f is the input frequency, R_l is the value of resistor in the circuit, V_{il} represent ac input signal, and V_{ol} is the output of linearization circuit. Assuming the values of V_{il}, R_l, and f are constant, the value of V_{ol} is proportional to C.

$$V_{ol} = 2\pi f C R_l V_{il} \tag{6}$$

Other signal conditioning devices which are used in these experiments are operational amplifier and rectifier. Operational amplifier is operated on the inverting mode since it has linear amplification characteristics (equation (7)) where R_{fa} in the value of feedback resistor, R_{ia} in the

value of feedback resistor, and V_{oa} represents the output voltage value of the amplifier. In the other hand, rectifier circuit is used to convert ac signal into dc to approach compatibility with data acquisition or processing devices.

$$\frac{V_{oa}}{V_{ol}} = -\frac{R_{fa}}{R_{ia}} \tag{7}$$

4. Results and Discussion

4.1 Capacitance Value of Sensor

The connection between level (in meter) and capacitance value (in nF) shown by figure 4. The correlation between capacitance value and water level, as informed by the figure, is proportional. The regression correlation equation satisfies equation (8) where x represent water level, and $C(x)$ is the capacitance value of the sensor regarding to water level.

$$C(x) = 2.759x + 0.333 \tag{8}$$

Regarding on conducted experiments, the sensor capacitance has non-zero initial value. This result caused by the non-ideal condition of the conducted experiments. Some part of the sensor which is not submerged into the water also had contribution of the capacitance value. It also creates the non-linear characteristic of capacitance value on the real condition. Figure 4 also shows the change of capacitance value became slower when the sensor submerged deeply into the water. This condition can be expressed, if the sensor impurities are ignored, as equation (9).

$$C(x) = \frac{\varepsilon_o b}{l}\left(\varepsilon_{r_{water}} x + \varepsilon_{r_{air}}(h - x)\right) \tag{9}$$
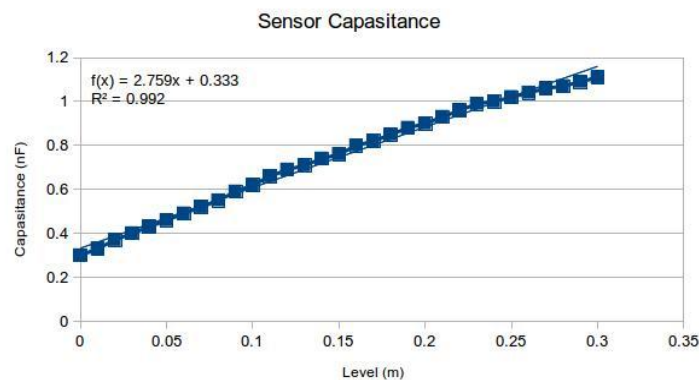

Figure 4 Sensor capacitance value

4.2 Signal Conditioning Output

Figure 5 and 6 shows the connection of the water level and output voltages. In both figures, the output voltage increase almost proportionally with the water level and can be expressed as equation (10) and (11) where $V_{ol}(x)$ and $V_{dc}(x)$ are the output voltages of linearization and rectifier circuit, respectively.

$$V_{ol}(x) = 0.286x + 0.046 \tag{10}$$
$$V_{dc}(x) = 15.755x + 0.316 \tag{11}$$

The correlation between V_{ol} and C is linear and proportional as stated in equation (6). But, the results which displayed on figure 4 and 5 were have a wavy or curved patterns. It occurs because of non-ideal characteristics of op-amp, such as dc imperfection and slew rate. It also caused by the impurities of the sensor itself.

As shown in figure 3, amplification value of the inverting mode op-amp circuit is -180 times. However, the average gain value after the signal pass the rectifier circuit is only 27.639 times. The slew rate, the dc imperfection, the loss in rectifying process, and the loss caused by line impedance are the caused of the problem.
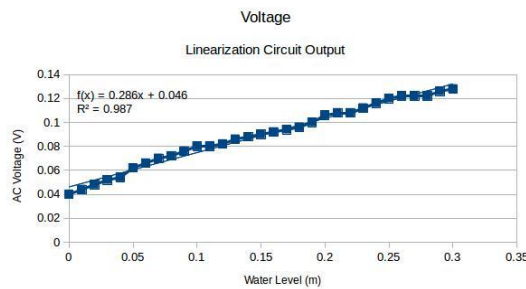
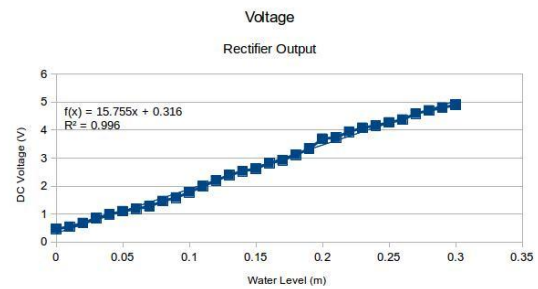**Figure 5.** Linearization circuit output voltage   **Figure 6.** Rectifier Circuit Output Voltage

The effect of non-zero initial condition and non-linear condition can be reduced by either hardware or software approximations. In hardware approximation, adjustment and addtitional filter circuit are added between rectifier and data aquitition device. In the other hand, statistical methods are used in software approximation.

5. Conclusion

A capacitive sensor for water level measurement had been developed and tested. It connected into 5 V_{pp} 3 kHz ac input voltage, and signal conditioning devices(linearization, inverting mode op-amp, and rectifier circuits) to obtain output voltage signal. Depending on the water level, the capacitance of the sensor varies from 0.300 nF (at 0 m) to 1.110 nF (at 0.300 m) and can be approximated by the equation $C(x) = 2.759x + 0.333$. Furthermore, the correlation between water level and dc output voltage can be expressed as $V_{dc}(x) = 15.755x + 0.316$.

The results of the experiments also inform the effect of non-ideal condition. It creates non-constant sensitivity value since the capacitance equation became $C(x) = \frac{\varepsilon_o b}{l}\left(\varepsilon_{r_{water}} x + \varepsilon_{r_{air}}(h - x)\right)$. Moreover, the slew rate of the op-amp at high frequency, the loss in rectifying process, and the loss because of line impedance caused the average gain became under the designed value.

6. References

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