

Capacitive Sensing of Biodiesel Water Content: Effect of Input Amplitude Combinations on Phase Shift-Capacitance Correlation

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Abstract

The increasing biodiesel blending ratio in diesel fuel in Indonesia has drawn attention from vehicle manufacturer, who demand higher biodiesel quality. Water content is one of the critical quality parameters of biodiesel. Coulometric Karl Fischer titration is a commonly used for water content measurement method, however it is costly. This study investigates the feasibility of using a capacitive sensor based on phase shift angle detection to measure water content in biodiesel. Variations in biodiesel water content will change the capacitance of the sensor, which will be converted by an electronic circuit into an electronic signal output. The phase of the output signal is the one to be observed. Experiments were conducted over two different capacitance ranges (ΔC), namely 7.1-7.6 pF and 25.1-25.6 pF, a series of capacitors were used as a dummy sensor. A clear trend of phase shift angles and capacitance values correlation was observed. The strongest correlation was obtained in the ΔC range of 7.1-7.6 pF, with input signal amplitude 10.27 V (S_1) and 6.24 V (S_2). The linear trendline slope was 27.62, sensitivity 27.07 degree/pF, and with a coefficient of determination ($R^2 \approx 0.98$). The selected capacitance measurement range has significant influence on the measurement performance and, consequently, should be considered in determining the dimensions of the capacitive sensor. This result demonstrate that the proposed phase shift based capacitive sensing method is a promising and cost-effective approach for biodiesel water content measurement.

Keywords: biodiesel water content; capacitive sensors; input signal amplitude; phase shift angle

Abstrak

Peningkatan campuran biodiesel di dalam bahan bakar solar di Indonesia menarik perhatian pabrikan kendaraan diesel, mereka menuntut kualitas biodiesel yang lebih tinggi. Salah satu parameter yang sangat penting di dalam biodiesel adalah kadar air. Titrasi Coulometric Karl Fischer merupakan salah satu metode yang digunakan untuk mengukur kadar air di dalam biodiesel, namun demikian memerlukan peralatan yang mahal. Penelitian ini mempelajari kemungkinan penggunaan sensor kapasitif berbasis pergeseran sudut fase sinyal untuk mengukur kadar air biodiesel. Perubahan nilai kapasitansi dari sensor kapasitif terjadi akibat perubahan kadar air biodiesel. Perubahan nilai kapasitansi ini oleh rangkaian elektronik diubah menjadi sinyal listrik berupa pergeseran sudut fase sinyal pada sisi keluaran rangkaian elektronik. Pada eksperimen yang dilakukan pada dua rentang nilai kapasitansi ΔC yang berbeda yaitu 7,1-7,6 pF dan 25,1-25,6 pF didapatkan trend perubahan sudut fase sinyal yang jelas. Pada penelitian ini digunakan rangkaian kapasitor sebagai pengganti sensor. Korelasi terbaik antara nilai pergeseran sudut fase dan ΔC diperoleh pada rentang nilai ΔC 7,1-7,6 pF dengan amplitudo sinyal masukan S_1 10,27 Volt dan S_2 sebesar 6,24 Volt. Gradien garis trend pada kondisi tersebut adalah 27,62, sensitivitas sensor 27,07 derajat/pF, dengan koefisien determinasi ($R^2 \approx 0,98$). Ini menunjukkan hubungan yang jelas antara nilai ΔC dengan nilai pergeseran sudut fase sinyal sehingga metode ini memungkinkan untuk diterapkan dalam pengukuran kadar air biodiesel yang efektif dan murah. Pemilihan rentang ukur kapasitan sangat berpengaruh terhadap kualitas pengukuran, maka hal ini harus diperhatikan dalam penentuan dimensi sensor kapasitif.

Kata kunci: amplitudo sinyal input ; kadar air biodiesel; pergeseran sudut fase; sensor kapasitif

1. Introduction

Increasing public awareness of environmental sustainability has encouraged the adoption of more environmentally friendly fuels. Biodiesel, which is produced from renewable plant-based feedstocks, is considered an environmentally

friendly fuel because the CO₂ released during its combustion is largely offset by the CO₂ absorbed by the feedstock during plant growth, thereby minimizing its contribution to the net accumulation of atmospheric CO₂. During growth, plants absorb CO₂ from the atmosphere through photosynthesis and convert it into biomass, including oil-rich seeds and fruits that can be processed into biodiesel. This characteristic is consistent with the role of renewable energy in reducing carbon emissions as reported by Naeem *et al.* [1].

The adoption of alternative fuels requires adjustment to existing fuel specifications, consideration of environmental factors, and, in some cases, modifications to equipment designed to operate with conventional fuels. Water content is one of the critical quality parameters of biodiesel. Biodiesel tends to absorb moisture from the surrounding, resulting in an increase in water content during storage [2]. The presence of water in biodiesel promotes microbial growth, which can subsequently lead to sludge formation [3-4] and accelerate fuel degradation. During long-term storage, biodiesel can also contribute to the corrosion of metal storage tanks [4]. Therefore, continuous monitoring of biodiesel water content during storage is of considerable importance. Coulometric Karl Fischer titration is a widely used method for determining water content with high accuracy [5]. The chemical reaction between water and the reagents used in this method provides highly reliable measurement results. However, this technique requires specialized laboratory facilities and equipment, which may not readily be available in remote areas. In addition to chemical methods, water content can also be determined using spectroscopic techniques. Near-Infrared (NIR) spectroscopy has been applied for the determination of water content in olive oil [6]. NIR Spectroscopy is a non-destructive analytical technique in which water content is determined from changes in the optical spectrum caused by the absorption of specific wave length by water molecules.

Capacitive sensing techniques have also emerged as a promising alternative for accurately measuring water content in transformer oil Islam *et al.* [7]. Ahmad *et al.* [8] investigated moisture, humidity and liquid level using CPW-based interdigital capacitive sensor. In addition to sensor design, the sensitivity and resolution of capacitive sensing system are sinusoidal configuration have been developed to improve the sensitivity and resolution of capacitive measurement system [9, 10]. One such configuration is the charge amplifier, which can convert small capacitance variations into measurable phase shifts, thereby enabling the detection of very small changes in capacitance. Charge amplifiers are commonly employed as charge-sensing circuit in nanoscale electronic devices [11, 12], and can also be utilized for two phase fluid level measurement. Zubair *et al.* [13] investigated the application of phase shift based capacitive sensor for determining water content in crude oil. Suryana *et al.* previously investigated the use of phase-shift-based capacitive sensor for measuring water content in biodiesel by converting sinusoidal signals into square signals and employing an XOR logic gate for phase-shift detection [14]. In our previous study, the measurement performance of a phase-shift-based capacitive sensor for biodiesel water content determination was further optimized by adjusting the excitation-signal frequency [15]. Building upon these previous studies, the present work focuses on evaluating the effects of capacitance variation, ΔC , and the combination of input signal amplitudes, S_1 and S_2 , on the measured phase shift and on the quality of the correlation between phase shift and ΔC . The objective is to identify the input signal amplitude combination that provides the strongest and most linear relationship between phase shift and capacitance variation, thereby establishing an appropriate operating condition for sensitive biodiesel water content measurement.

2. Material dan Method

A semi-cylindrical capacitive sensor consists of two semi-cylindrical copper electrodes attached to the outer surface of dielectric tube, with a specified gap between the electrodes [16]. The dielectric tube serves as an insulating medium,

while the capacitance of this sensor depends on the dielectric properties and composition of the fluids inside the tube between the two electrodes.

Figure 1 illustrates an example of a semi-cylindrical capacitive sensor fabricated using a glass tube. The two sensor electrodes are connected to the electronic circuit at point A and B, respectively. The electronic circuit converts changes in the sensor capacitance into electrical signal, which subsequently processed by the measurement system to determine the phase shift. The key geometric parameters of the sensor are the sensor diameter ($D=16$ mm), sensor height ($h=60$ mm), and electrode gap ($d=1$ mm).

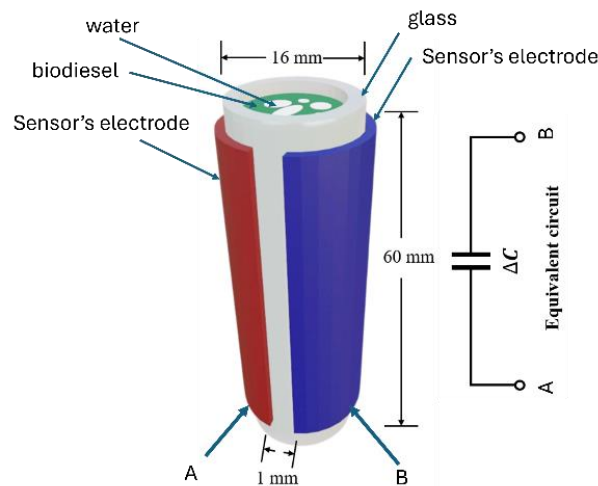


Figure 1. Semi-cylindrical capacitive sensor, sensor's height $h=60$ mm, diameter $D=16$ mm, gap between the electrodes $d=1$ mm

The capacitance of the sensor depends on its geometric dimensions, and the dielectric properties of the medium between the two electrodes. For an empty sensor, in which the tube contains only air, the capacitance can be calculated using Equation (1) [16]. In this equation, ϵ_0 denotes the permittivity of free space, ϵ_1 is the permittivity of air, n is the number of electrode elements, and d is the gap between two electrodes, and Δd represents the increment in the electrode gap between successive electrode element.

$$C_0 = \sum_{i=1}^n 2 * \epsilon_0 * \epsilon_1 * A * \left[\frac{1}{d + (i-1)\Delta d} \right] + \left[\frac{\epsilon_0 * \epsilon_1 * A}{2R} \right] \quad (1)$$

The capacitance of the sensor depends on the dielectric material located between two semi-cylindrical copper electrodes. In the present sensor configuration, at least two dielectric media are present; glass forming the tube wall and the fluid contained within the tube between the electrode. Accordingly, the total capacitance of the sensor can be considered as the sum of the capacitance contributions from the glass and the fluid. The total capacitance can therefore be calculated using Equation (2) [13].

$$C_t = \left[\frac{C_a * C_w}{C_a + C_w} \right] \quad (2)$$

Since the dimensions and material properties of the tube wall remain constant, its contribution to the total capacitance remains essentially constant. Consequently, variations in the sensor capacitance are primarily determined by the composition and dielectric properties of the fluid inside the tube, denoted as (C_a). The relative permittivity of the fluid can then be determined using Equation (3) [13].

$$\epsilon_a = \left[\frac{V_w * \epsilon_w + V_b * \epsilon_b}{V_t} \right] \quad (3)$$

Where V_w is the water volume in the fluid, V_b is the volume of biodiesel, and V_t is total volume of the fluid between the electrodes. The parameter ϵ_w and ϵ_b denote the permittivities of water and biodiesel, respectively. Equation (1) can then be used to calculate the capacitance of the sensor filled with biodiesel containing a specific water content by replacing ϵ_1 with the effective permittivity of biodiesel-water mixture, ϵ_a . Using numerical approach, the capacitance of sensor with specified geometric dimensions can therefore be calculated for a known water content in biodiesel.

In this study, a phase-shift-based capacitive sensing system was employed to measure the water content of biodiesel. The measurement system consists of a semi-cylindrical capacitive sensor, an electronic circuit, a sinusoidal signal generator and oscilloscope integrated into a Digilent Analog Discovery 2, and a personal computer (PC) for system control and data acquisition, as illustrated in Figure 2. Two sinusoidal signals with a 180° phase difference were generated by the Digilent Analog Discovery 2. These signals were applied to the electronic circuit at four input point (A, B, C and D), while the corresponding output signals at point E and F were acquired using the oscilloscope integrated into the Digilent Analog Discovery 2. The amplitude and phase of the output signals were subsequently recorded and processed by the PC [17].

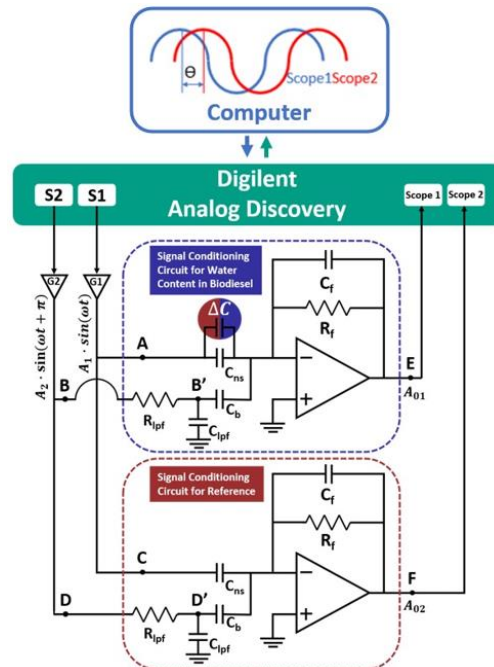


Figure 2. Biodiesel water content measurement system consisting of semi-cylindrical capacitive sensor, electronic circuit for capacitance to electric signal conversion, Digilent Analog Discovery 2, and a PC [16]

The sinusoidal signal $S_2 \cdot \sin(\omega t + \pi)$ is applied to the electronic circuit through point B in the upper branch of the circuit (measurement circuit) and point D at the lower branch (reference circuit). In both branch the signal passes through a low-

pass filter (LPF), which introduces a small phase shift ψ . Although this phase shift is small, it can significantly affect the sensitivity of the output phase shift [18]. After passing through the LPF, signal can be expressed as $S_2 \cdot \sin(\omega t + \pi - \psi)$ [20, 21] after passing the LPF. The second sinusoidal signal, $S_1 \cdot \sin(\omega t)$, is applied to the electronic circuit through point A in the measurement circuit and point C in the reference circuit. In the measurement circuit, the signal applied at point A passes through the capacitive sensor, whose capacitance variation is denoted by ΔC . The signals in both the measurement and reference circuits are then processed by operational amplifier (Op-amps). The resulting output signals at point E and F are connected to channel 1 and 2 of the oscilloscope, respectively. The ratios of the output amplitudes to the corresponding input signal amplitudes can be calculated using Equation (4) and (5) [17].

$$\frac{S_{01}}{S_1} = \left(-\frac{C_{ns} + \Delta C}{C_f} \right) \sin(\omega t) - \frac{C_b}{bC_f} \sin(\omega t + \pi - \psi) \quad (4)$$

$$\frac{S_{02}}{S_2} = \left(-\frac{C_{ns}}{C_f} \right) \sin(\omega t) - \frac{C_b}{bC_f} \sin(\omega t + \pi - \psi) \quad (5)$$

$C_b = b \cdot C_{ns}$ then equation [4] and [5] can be written as:

$$\frac{S_{01}}{S_1} = \left(-\frac{C_{ns} + \Delta C}{C_f} \right) \sin(\omega t) - \frac{C_{ns}}{C_f} \sin(\omega t + \pi - \psi) \quad (6)$$

$$\frac{S_{02}}{S_2} = \left(-\frac{C_{ns}}{C_f} \right) \sin(\omega t) - \frac{C_{ns}}{C_f} \sin(\omega t + \pi - \psi) \quad (7)$$

Hence, the phase difference between output signals at point E and F can be calculated using Equation (8) [17]:

$$\phi = \tan^{-1} \left(\frac{\sin(\psi)}{\frac{C_{ns} + \Delta C}{C_{ns}} - \cos(\psi)} \right) - \tan^{-1} \left(\frac{\sin(\psi)}{1 - \cos(\psi)} \right) \quad (8)$$

The first term in Equation (8) represent the phase of the output signal from the measurement circuit, whereas the second term represent the phase of the output signal from the reference circuit.

In this study, particular attention was given to evaluating the correlation between the input signal amplitude combination (S_1 and S_2) and the resulting output phase shift. The electronic circuit shown in Figure 2 was implemented using the following component values: $C_b = 69$ pF, $C_{ns} = 39,5$ pF, $C_f = 100$ pF, $R_f = 1M\Omega$, $C_{lpf} = 160$ pF dan $R_{lpf} = 1$ k Ω .

For this experiment, the experimental apparatus shown at Figure 3 consisted of a power supply, a Digilent Analog Discovery 2, the electronic circuit, personal computer (PC), and dummy sensor comprising a series of capacitor used to represent the capacitance variation ΔC . The experiment was conducted by applying two sinusoidal signal S_1 and S_2 to the electronic circuit, at a frequency of 70 kHz. The two input signals had a phase difference of 180°. The amplitude of S_1 and S_2 were independently, using 12 amplitude levels for each signal, resulting in a total of 144 S_1 and S_2 amplitude combinations. For each ΔC value of the dummy sensor, all 144 combinations of S_1 and S_2 were applied to the electronic circuit. The amplitudes and phases of the output signals at point E and F were then acquired and recorded for subsequent analysis.

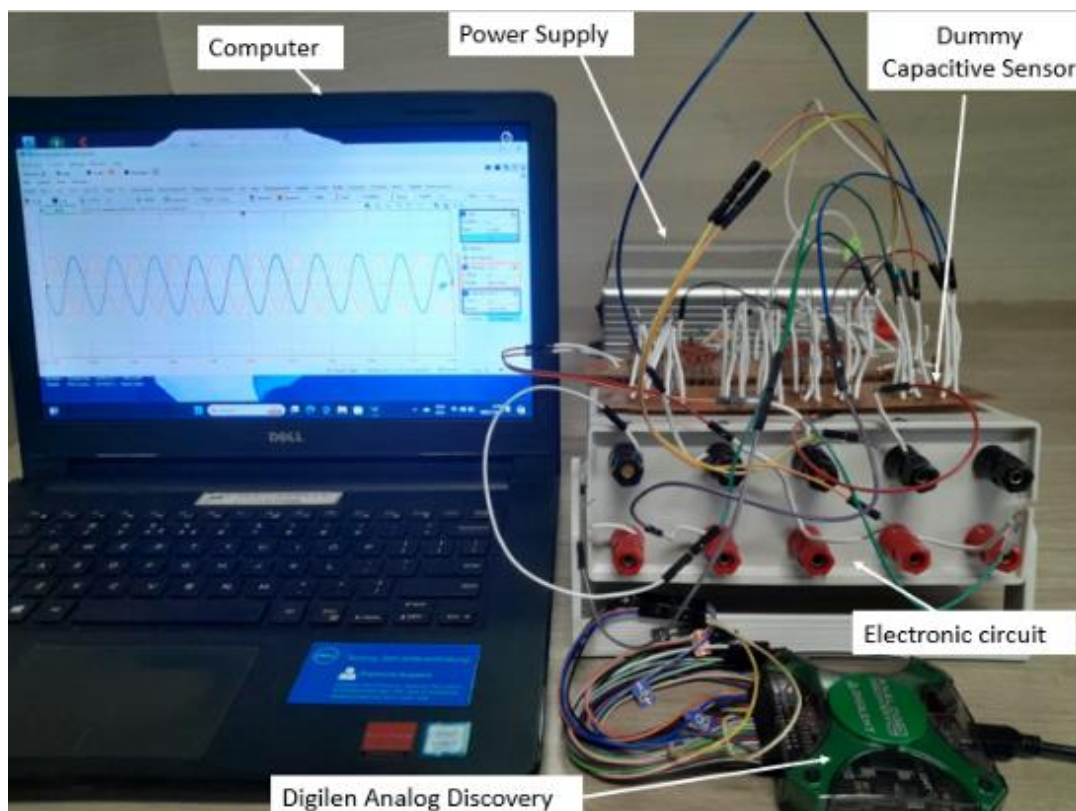


Figure 3 Experiment equipment consisting of power supply, electronic circuit, Digilent Analog Discovery 2, personal computer (PC), and a series of capacitor as dummy sensor

Based on biodiesel water-content range of 500-1000 ppm, the capacitance of the semi-cylindrical capacitive sensor was calculated using the sensor dimensions of 60 mm in height, 16 mm in diameter, and a 1 mm gap between electrodes. The relative permittivity of water and biodiesel were 80 and 2.35. Using equation [3] and numerical calculation, the corresponding sensor capacitance values were determined for water content ranging from 500 to 1000 ppm, as presented in Table 1.

Tabel. 1 Calculated capacitance of a semi-cylindrical capacitive sensor at several biodiesel water content

No.	Biodiesel Water Content (ppm)	ΔC (pF)
1	500	6.994
2	600	7.192
3	700	7.391
4	800	7.589
5	900	7.787
6	1000	7,986

The experiment was conducted using a series of capacitors with capacitance values ranging from $\Delta C = 7.1$ to 7.6 pF, corresponding to the calculated capacitance range of the semi-cylindrical capacitive sensor when filled with biodiesel containing 500-1000 ppm water. An additional experiment was conducted using higher ΔC values, ranging from 25.1 to 25.6 pF, to evaluate the behavior of the measurement system over broader capacitance range.

3. Results and Discussion

Figure 4 presents contour plots of the output phase-shift as a function of the input signal amplitudes S_1 (0.5-12.4 V) and S_2 (0.5-13 V) for ΔC values of 7.1, 7.2, 7.3, 7.4, 7.5 pF, and 7.6 pF. The input signals had a frequency of 70 kHz and initial phase difference of 180°. In the contour plots, red represents higher phase-shift values, whereas the color gradually changes from yellow to blue as the phase-shift value decreases. The high-phase-shift region forms an inclined triangular pattern that extends from the lower-left corner and becomes wider toward the upper-right corner. Two high-phase-shift boundary lines are also observed along the left and right edges of the plots. The points within this high-phase-shift region correspond to combinations of S_1 and S_2 amplitudes that produce relatively large phase shifts for ΔC values ranging from 7.1 to 7.6 pF. As ΔC increases, the triangular high-phase-shift region becomes progressively wider. This observation indicates that the combinations of S_1 and S_2 amplitudes producing high phase shifts vary with ΔC . In other words, for the same combination of input amplitudes, different ΔC values produce different output phase-shift. This dependence of the output phase shift on both the input signal amplitudes and capacitance variation provides a basis for using the proposed phase-shift-based capacitive sensing approach to determine water content in biodiesel.

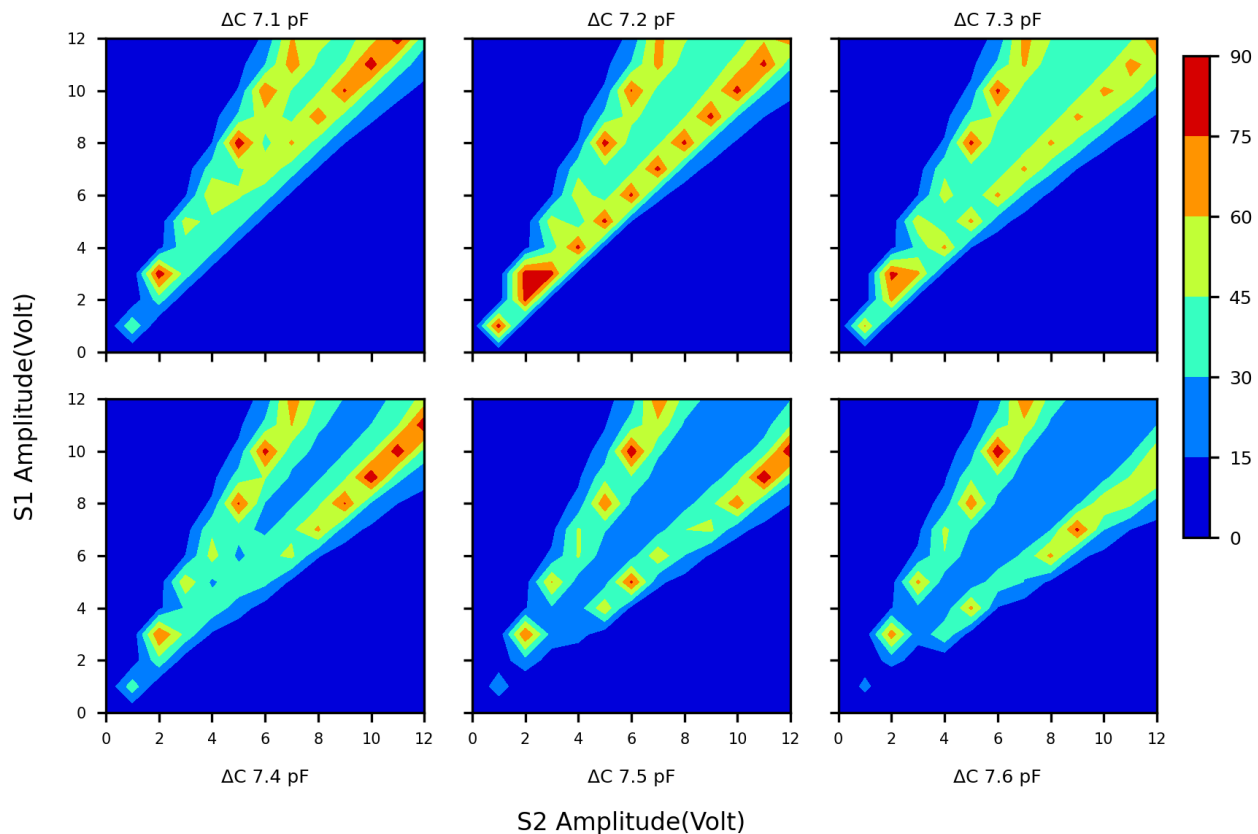


Figure 4. Contour plot of phase-shift, as a function of the input signal amplitudes S_1 and S_2 , for ΔC 7.1-7.6 pF

Figure 5 presents contour plot of phase-shift for various combinations of the input signal amplitudes S_1 and S_2 at ΔC values ranging from 25.1 to 25.6 pF. A trend similar to that observed for the ΔC range from 7.1 to 7.6 pF is evident, indicating that the same phase-shift measurement principle can also be applied to a higher capacitance-variation range.

Figure 4 and Figure 5 illustrate the influence of S_1 and S_2 amplitude combination on the measured phase-shift for different ΔC values. By extracting the phase-shift values corresponding to the same S_1 and S_2 amplitude combination

across different ΔC values, the correlation between the phase-shift and ΔC can be evaluated. This analysis provides a basis for identifying the input signal amplitude combinations that yield the strongest and most consistent relationship between phase shift and capacitance variation.

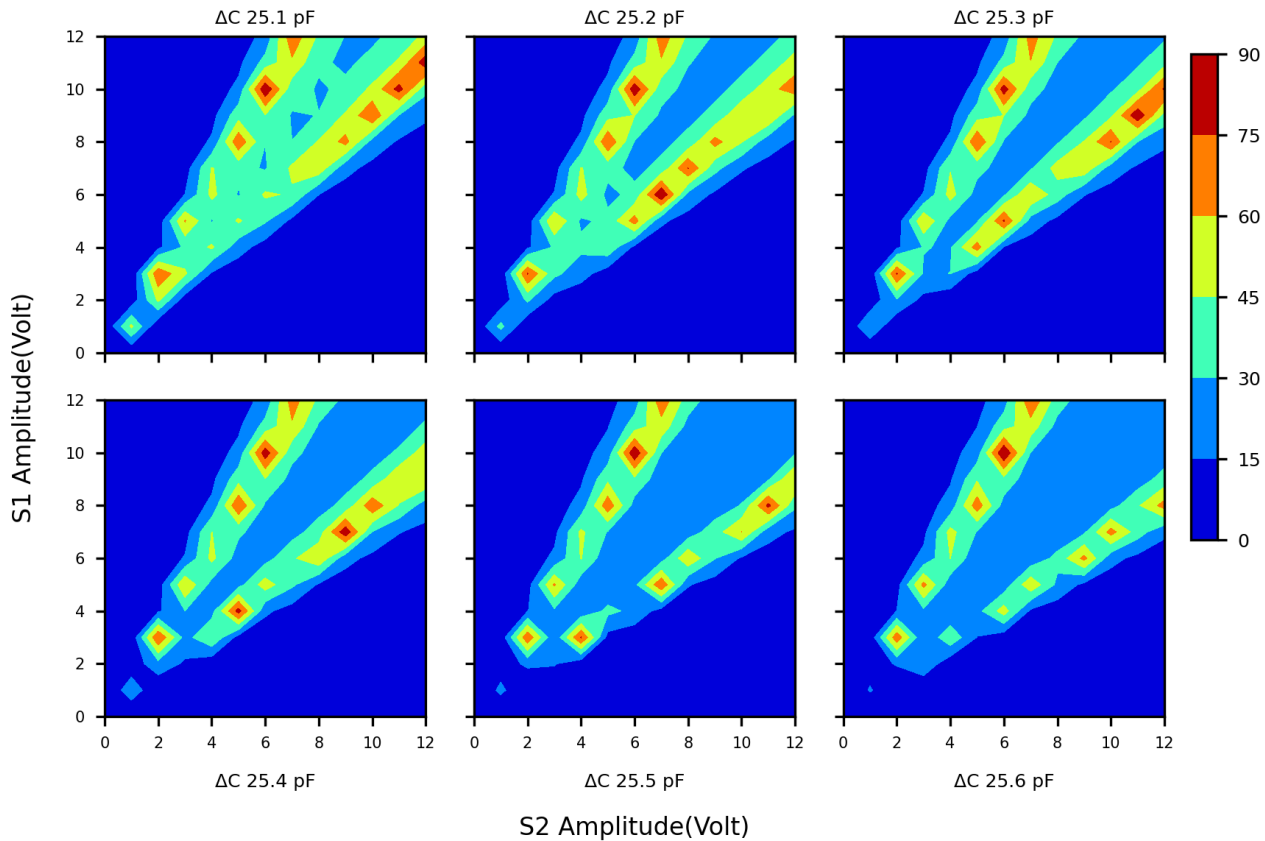


Figure 5. Contour plot of phase-shift, as a function of input signal amplitudes S_1 and S_2 , for ΔC 25.1-25.6 pF

Figure 6 presents the correlation between the measured phase-shift and ΔC for $S_1 = 10.27$ Vt, and six different S_2 amplitudes: 0.57, 1.70, 2.84, 3.97, 5.11, and 6.24 V. Figure 6(a) shows the phase-shift response for the ΔC range of 7.1-7.6 pF, whereas figure 6(b) presents the corresponding response for the higher ΔC range of 25.1-25.6 pF.

As shown in figure 6a, the phase shift increases with increasing ΔC for all investigated combinations of S_1 and S_2 . The largest phase shift was obtained for $S_1 = 10.27$ V and $S_2 = 6.24$ V, corresponding to an amplitude ratio of ($S_1/S_2 \approx 0.6$). A similar result was reported by N. Suryana *et al.* who observed the maximum phase-shift at an input amplitude ratio of ($S_1/S_2 \approx 0.5$) [20]. Among the investigated combinations, the strongest linear correlation between phase shift and ΔC was obtained at $S_1 = 10.27$ V and $S_2 = 6.24$ V within the ΔC range of 7.1-7.6 pF, yielding a maximum linear-fit gradient of 27.62.

Figure 7 presents the correlation between the phase-shift and capacitance variation, ΔC , when the electronic circuit was excited with $S_1 = 11.35$ V and six different S_2 amplitudes: 0.57, 1.70, 2.84, 3.97, 5.11, and 6.24 V. Figure 7(a) shows the phase-shift response for the ΔC range of 7.1-7.6 pF, whereas Figure 7(b) presents the corresponding response for the ΔC range of 25.1-25.6 pF. The curves in Figure 7(a) exhibit a trend similar to that observed in Fig. 6(a), with the maximum linear-fit line gradient of 16.25 obtained for the input signal combination of $S_1 = 11.35$ V and $S_2 = 6.24$ V.

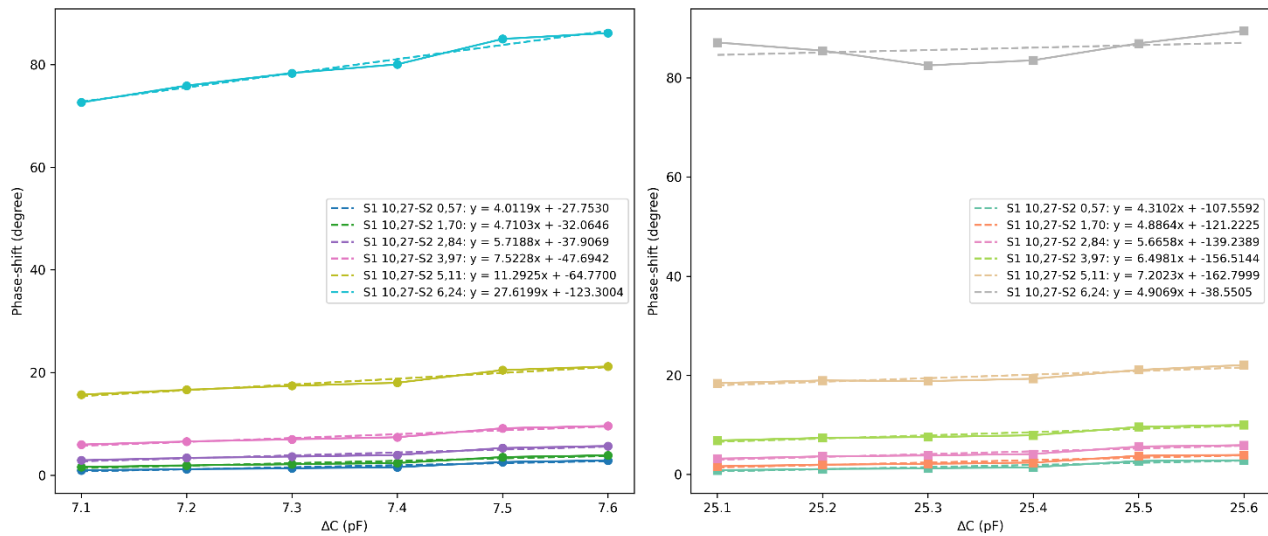


Figure 6. Phase-shift to ΔC correlation curve at S_1 10.27 volt and S_2 0.57, Volt, 1.70 Volt, 2.84 Volt, 3.97 Volt, 5.11 Volt, and 6.24 Volt, (a) for ΔC 7.1-7.6 pF, and (b) for ΔC 25.1-25.6 pF

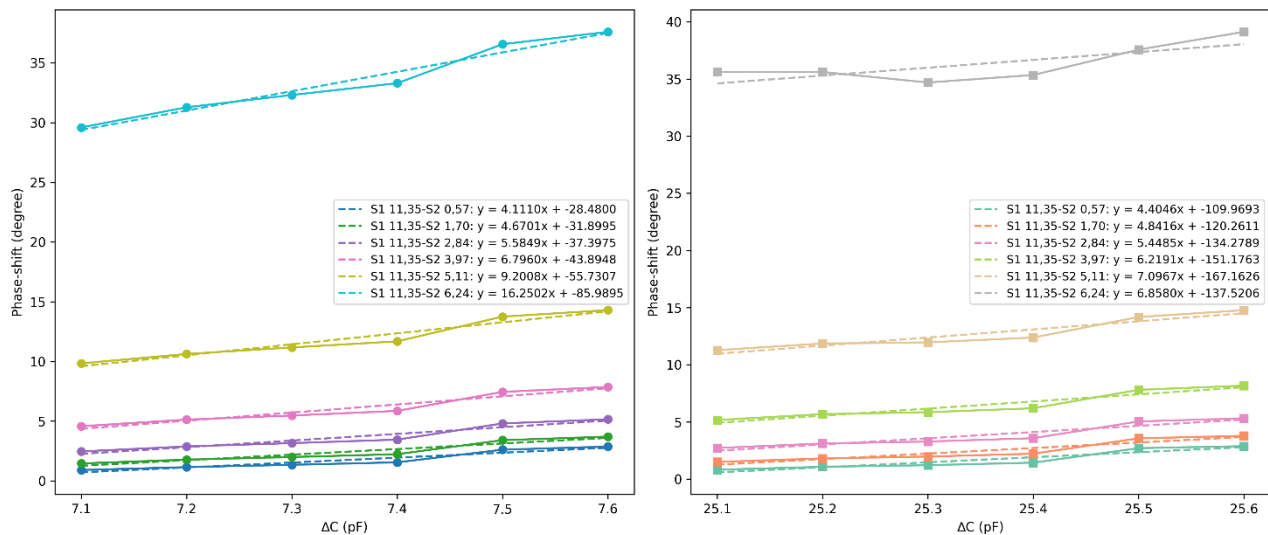


Figure 7. Phase-shift to ΔC correlation curve at S_1 11.35 volt and S_2 0.57, Volt, 1.70 Volt, 2.84 Volt, 3.97 Volt, 5.11 Volt, and 6.24 Volt, (a) for ΔC 7.1-7.6 pF, and (b) for ΔC 25.1-25.6 pF

Figure 8 presents the correlation between phase-shift and capacitance variation, ΔC , when the electronic circuit was excited with input signal $S_1 = 12.43$ V and six different S_2 amplitudes: 0.57, 1.70, 2.84, 3.97, 5.11, and 6.24 V. Figure 8(a) shows the phase-shift response for the ΔC range of 7.1-7.6 pF, whereas Figure 8(b) presents the corresponding response for the ΔC range of 25.1-25.6 pF. The curve in Figure 8(a) exhibit a trend similar to that observed in Figure 6(a), with the maximum linear-fit gradient of 11.78 obtained for the input signal combination of $S_1 = 11.35$ V and $S_2 = 6.24$ V. A similar trend was also observed in our previous study on phase-shift-based capacitive sensing for biodiesel water-content measurement [17]. These results demonstrate that the input signal amplitude combination, particularly the ratio between S_1 and S_2 , plays an important role in determining the measurement sensitivity. Therefore, appropriate selection of the S_1 and S_2 amplitude is essential for achieving optimum sensitivity in the proposed capacitive sensing system.

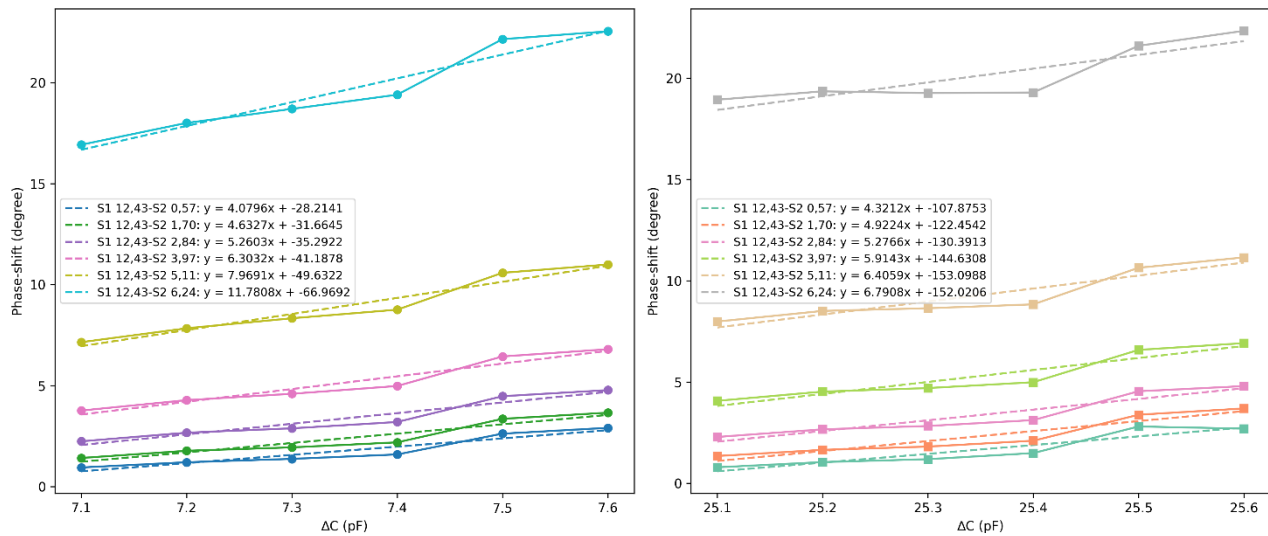


Figure 8. Phase-shift to ΔC correlation curve at S_1 12.43 volt and S_2 0.57, Volt, 1.70 Volt, 2.84 Volt, 3.97 Volt, 5.11 Volt, and 6.24 Volt, (a) for ΔC 7.1-7.6 pF, and (b) for ΔC 25.1-25.6 pF

4. Conclusion

The experimental results demonstrate a strong correlation between the measured phase-shift and capacitance variation, ΔC . The results also indicate that, for a given ΔC range, an optimum combination of input signal amplitudes, S_1 and S_2 can be identified to achieve a strong and approximately linear relationship between the phase-shift and ΔC . In this study, the optimum input signal combination was $S_1 = 10.27$ V and $S_2 = 6.24$ V for the ΔC range of 7.1-7.6 pF, yielding a linear phase-shift response with a maximum linear-fit gradient 27.62, sensor sensitivity 27.07°/pF, and coefficient of determination ($R^2 \approx 0.98$). The selected capacitance measurement range has significant influence on the measurement performance and, consequently, should be considered in determining the dimensions of the capacitive sensor. These findings further demonstrate the potential of the proposed phase-shift-based capacitive sensing approach for measuring water content in biodiesel. Further investigation using actual biodiesel samples with water contents ranging from 304 to 712 ppm demonstrated a strong linear relationship between the measured phase shift and water content, with a coefficient of determination ($R^2 \approx 0.959$) [15]. This result provides further evidence of the feasibility of the proposed approach for low-level water content measurement in biodiesel.

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