Measuring on Sugar Content of Sugarcane Based on Phase Locked Loop with Capacitive Sensor

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Abstract. The article proposes instrument construction for measuring the sugar content in sugarcane juice. A interdigital capacitor acting as a sensing element is connected with the sinusoidal generator. Whose output frequency depends on changing the capacitance of interdigital capacitor. To convert the frequency to the direct current (DC) voltage. A sin wave from the generator is converted square wave by comparator circuit before feeding to the phase locked loop circuit. Finally, the DC voltage is changed to concentration of the sugar content in sugarcane juice.

1. Introduction
Currently, technologies for determining the sugar content in agricultural products can be divided in three groups which consist of the optical property, specific gravity and electrical property. The optical properties are divided in near-infrared and visible light. The near-infrared light is used to examine the sugar content in fruit. The reflectance, transmittance and interactance are the properties of light that have been applied to literatures. The reflectance of banana skin surfaces was measured by UV-VIS-NIRS spectrometer. The result indicate that NIR spectra responded directly to pulp sugar and the correlation coefficients is 0.96 Thus, NIR spectroscopy in banana provides valuable information on internal fruit maturity and fruit quality\cite{1}. A spectrum measurement instrument was designed to obtain the transmitted energy spectra. It consisted of two halogen lamps and tray having a small hole at the center was used to hold the pear sample. The results showed the pre-processed by second derivative have a good performance with 0.82 so, the transmittance method is possible for measurement sugar content in pear\cite{2}. Measuring the content of intact carambola by interactance mode, where the light source and detector are positioned next to each other so that the light due to specular reflection cannot enter the detector. The results showed the pre-processed by second derivative with correlation coefficients is 0.82 Thus, the results can be applied to larger frits and broader sugar content ranges \cite{3}. The use of natural light on the refraction. When light through the solution of different concentrations. As the refractive index varies with concentration \cite{4}. But solution must be clear to detect the sugar content accurately. In the wine industry, Specific gravity values are used to measure sweetness of grape juice for calculating the alcohol content in wine\cite{5}. But examination requires a lot of solution. For the more, the electrical properties of the sugar solution were also investigated using time-domain reflectometer. The decreasing of resistance depends on the concentration of the solution but the dielectric constant is increased \cite{6}. The dielectric constant was applied to determine of sugar.
content in food and juice industry by the interdigital capacitor sensor[7]. The frequency range for measurement is investigated and the amplitude value of sinusoidal output signal inversely proportional to the sugar content. However, the generators, oscilloscopes and other devices are required in this system. The research is just a study not making system to work on its own, also requires the generator and oscilloscope etc. In this article presents measurement the sugar content in sugarcane juice the by phase locked loop circuit with interdigital capacitor sensor, it consists of an oscillator generating waveform that whose frequency is variable by the capacitance of the interdigital capacitor and the sine wave from the generator is converted square wave by comparator circuit before feeding to the phase locked loop circuit. After that the output frequency is converted to the DC output voltage which relates with the concentration of sugar content in sugarcane juice.

2. Principles of measuring sugar content in sugarcane juice

Principles of sugar content measurement in sugarcane juice includes interdigital capacitor sensor, quadrature oscillator, comparator circuit and phase locked loop circuit.

2.1. Interdigital capacitor sensor

The interdigital capacitor is conductor plate placed alternate between anode and cathode. The interdigital capacitor, shown in figure 1, is used to measure the sugar content in solution. The total capacitance of the interdigital capacitor has been revealed[8].

\[
C_0 = 2\varepsilon_0 \frac{t_h}{S} + \varepsilon_0 (\varepsilon_1 + \varepsilon_2) \frac{K\left(\sqrt{1-k^2}\right)}{K(k)} (n-\eta)L
\]

(1)

Where \(\varepsilon_0\) is the free space permittivity (8.854x10^{-12}F/m), \(\varepsilon_i\) is the relative permittivity of material between electrodes, \(\varepsilon_s\) is the relative permittivity of the substrate, \(t_h\) is thickness of finger, \(S\) is space between finger, \(K[x]\) is a complete elliptic integral of the first kind, \(n\) is number of finger, \(L\) is length finger and \(k\) is equal to \(s/W\).

![Figure 1. Characteristics of the interdigital capacitor.](image)

From (1) we define \(k_x = \varepsilon_0 \frac{K\left(\sqrt{1-k^2}\right)}{K(k)} (n-\eta)L\) and \(k_y = \frac{2\varepsilon_0}{S} + \frac{k}{\varepsilon_0}\). The total capacitance of interdigital capacitor is rewritten as

\[
C_0 = \varepsilon_0 \left[ (\varepsilon_1 k_x) + k_s \right]
\]

(2)

2.2. Quadrature oscillator

The quadrature oscillator is another type of phase-shift oscillator. The outputs are labelled as sine and cosine because the cosine is actually the same sine shifted to 90 degrees. The frequency is as follow[9]

\[
f_i = \frac{1}{2\pi \sqrt{R_1 C_1 R_2 C_2}}
\]

(3)

In (3), capacitance \(C_i\) is interdigital capacitor \((C_s)\) parallelled with one capacitor constant \((C)\). We define Where \(R_i = R_2 = R_s\) so the frequency in quadrature oscillator can be stated as

\[
f_i = \frac{1}{2\pi R_s \sqrt{C_1 \left(\varepsilon_0 (k_x + (\varepsilon_1 k_s))\right) + C}}
\]

(4)

2.3. Phase locked loop for frequency to DC voltage conversion
The conventional phase locked loop (PLL) is used to converts frequency to DC voltage. Figure 2. Shows the block diagram of the PLL which consists of phase detector (PD), a loop filter or a low pass filter (LPF), voltage controlled oscillator (VCO) and an integrator [10]. The parameters \( \phi_i(s) \), \( \phi_o(s) \), \( \psi_i(s) \), \( V_o(s) \) and \( V_e(s) \) are analyzed by applying the Laplace transform. The parameters \( \omega_o(s) \) and \( \omega_i(s) \) are the output frequency and the running frequency of VCO \( A_o \), \( K_v \), \( K_p \) and \( K_i \) are gain of loop filter, phase detector, VCO and integrator, respectively. The \( F(s) \) is transfer function of a loop filter.

In figure 1, the relationship of the system can be written as \( \phi_i(s) = \phi_o(s) - \phi_o(s) \), \( V_o(s) = K_o(\phi_o(s)) \), \( V_e(s) = F(s)K_o(\phi_o(s)) \), \( \tilde{V}(s) = A_o/\tau \) and \( \omega_o(s) = \omega_i(s) + K_o \psi_o(s) \).

![Block diagram of a conventional PLL.](image)

From (\( \phi_i(s) \), \( V_i(s) \), \( V_e(s) \), \( F(s) \)) and \( \omega_o(s) \), the relationship of system can be written as

\[
\tau s^2 \phi_i(s) + s \phi_i(s) + K_o \phi_i(s) = K_o \phi_o(s) + K_i \omega_i(s) \tau \phi_i(0) + K_i \omega_i(0)
\]

(5)

From (5) we let \( K_T = K_v K_i K_o A_o \) and take inverse Laplace transform to both sides of (5), which can be stated as

\[
\tau \frac{d^2 \phi_i(t)}{dt^2} + \frac{d \phi_i(t)}{dt} + K_o \phi_i(t) + K_i \phi_o(t) = K_i \omega_i(t) + K_i \omega_o(t)
\]

(6)

Generally, \( \phi_i(s) \) is the composed of two parts which are natural response and forced response. For this work, a natural response is zero when the system is in a steady state. Only steady state forced response is of interest. To determine the forced response, the \( \phi_i(t) \) can be assumed as \( \phi_i = \omega_o + \omega_i \), hence

\[
\phi_i(t) = \omega_o(t) + \omega_i(t) + \frac{K_i \omega_i(t)}{K_T} - \frac{\omega_i(t)}{K_T}
\]

(7)

The phase error \( \phi_e(t) \) can be calculated by

\[
\phi_e(t) = \phi_i(t) - \phi_o(t) = -\frac{K_i \omega_i(t)}{K_T} - \frac{\omega_i(t)}{K_T}
\]

(8)

When the system is locked state, the phase error \( \phi_e(t) \) depends on \( \omega_i(t) \) because \( \omega_i(t) \) is constant time increases. From (8), it is seen that the phase error \( \phi_e(t) \) is directly proportional to input signal.

\[
V_e(s) = F(s)K_o(\phi_o(s))
\]

(9)

From (9), time increases \( K_v e^{-t/\tau} \) is zero convergence. \( \phi_e(t) \) from (8) is achieved. When \( \omega_i = 2\pi f_i \), \( \omega_i = 2\pi f_i \) and \( K_v = 2\pi K_o A_o / K_i \) is constant, the \( V_e(t) \) can be expressed as

\[
V_e(t) = K_v e^{-t/\tau} + K_o A_o \phi \phi_e(t)
\]

(10)

From (10), when \( f_i \) is constant, the output voltage \( V_e(t) \) of phase locked loop system depends on \( f_i \). The frequency of input signal is obtained from quadrature oscillator circuit. So output voltage of phase locked loop circuit is

\[
V_e(t) = K_v e^{-t/\tau} + C_i \phi_o k \phi_o k + C
\]

(11)

Let \( C_i = C + C_o k \), the equation (11) is rewritten to be
\[ V_c(t) = K_R \left[ -K_1 f_c \pm \sqrt{2\pi R_t \left( 1 + \frac{C_1}{C_2} \varepsilon \varepsilon_f k_y \right)} \right] \]  

(12)

Distribution of term \( \sqrt{1 + \frac{C_1}{C_2} \varepsilon \varepsilon_f k_y} \) with binomial series of \( \sqrt{1+x} \) [11] is applied in (12). The output voltage can be given by

\[ V_c(t) = K_R \left[ -K_1 f_c - \frac{1}{2\pi R_t \sqrt{C_2}} - \frac{C_1 \varepsilon \varepsilon_f k_y}{4\pi R_t C_2 \sqrt{C_2}} \right] \]  

(13)

We can observe that, the output voltage of the vary with the dielectric constant \( \varepsilon_f \) in sugarcane juice.

3. Experimental setup

The proposed principle can be compound in the circuit as shown in figure 3.

Figure 3. Principle of measuring sugar content in sugarcane juice.

A total of 80 sugarcane is used for the experiment. 50 samples are used for calibration model and 30 samples are used for prediction model. The sugar content in sugarcane juice is detected by a refractometer. The average of measurement results is recorded. And used in later research. After measured sugar content by a refractometer. After that 20 ml of the sugarcane juice is poured on surface of interdigital capacitor sensor. The sample is scanned and the average DC voltage data is saved.

4. Results and discussions

The results of measuring sugar content of part 1 is demonstrated in figure 4 and 5 by using the proposed principle.

Figure 4. Relationship between frequency and capacitance with sugar content in sugarcane juice.  
Figure 5. The results of output voltage with sugar content of sugarcane juice.

The interdigital capacitor sensor is used as a sensing element of the quadrature oscillator circuit. The output signal is a sinusoidal waveform which its frequency can be calculated to capacitance of interdigital capacitor sensor. The frequency, capacitance and sugar content of sugarcane juice measured are plotted in figure 4. The experimental results show that the frequency of the sugarcane juice is increased as the sugar concentrations are increased. On the other hand, the capacitance of the
solutions is decreased as the sugar concentration are increases. In Part 2, the comparison circuit is used to convert the sine wave from quadrature oscillator circuit to square wave for signal to phase locked loop in part 3. The DC output voltage of sugarcane juice are decreased as the sugar concentration increases as shown in figure 5. The comparison between the sugar content measured by the proposed principle the refractometer is shown in figure 6. The correlation coefficient (R²) of the our result is 0.9805.

Figure 6. Sugar content of sugarcane juice measured by principle to present with measured from refractometer.

5. Conclusion
This article reports the principle of measurement sugar content in sugarcane juice. The capacitor sensor is used as sensing element of the phase locked loop. The results show that the values of frequency and output voltage increase as the sugar content in sugarcane juice increases, whereas capacitance decreases. The results of the sugar content measured by the proposed principle are in good agreement with the sugar content measured by the refractometer. The proposed for measuring in sugarcane juice can be applied to measure the different concentration of different solution.

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