Small Capacitance Measuring Circuit For Capacitive Sensors

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Abstract: This paper presents a small capacitance measuring circuit for capacitive sensors. The proposed circuit consists of sine-wave generator, detector and demodulator. Results of experiments are shown that the circuit can be able to measure small capacitance exiting in a capacitive sensor filled with a vegetable oil. The sensitivity of the circuit is from 0.4V/pF to 4V/pF and the resolution is from 0.0025 pF to 0.00025 pF.

Keywords: capacitance measurement, capacitive sensors, square law detector, signal generator

1. INTRODUCTION

Capacitive sensors have been widely used in industry such as material property measurement, liquid level measurement in reservoirs, spacing or thickness measurement [1]. However capacitance of capacitive sensors is usually very small (less than 10 pF). Therefore, a circuit used for this duty has to well design. Many researchers purposed circuits for measuring such a small capacitance as [2-7]. We introduce, in this paper, our new circuit will be used for measuring small capacitance with high sensitivity, high resolution, good stability and suitable for use in small capacitive sensors.

2. CAPACITANCE MEASURING CIRCUIT

The schematic diagram of capacitance measuring circuit is shown in Fig. 1. A sine-wave generator provides a 500 KHz sine-wave excitation voltage of 20 Vp-p to an unknown capacitance, Cx, connected, one side, to a stray-immune detector [2]. Then a.c. flows to the detector providing voltage at the output. The voltage from detector has been amplified before sent to band pass filter (500 KHz) for rejecting any interference. An analogue multiplier circuit provides demodulated signal, from the band pass filter, based on a square law detector. Squared signals from the multiplier circuit consist of DC and 1 MHz sine-wave components. A low-pass filter with cut-off frequency 10 KHz is used to reject 1 MHz component. The d.c. signal from low-pass filter is sent to square rooter circuit to obtain the d.c. level corresponding to the capacitance of Cx.

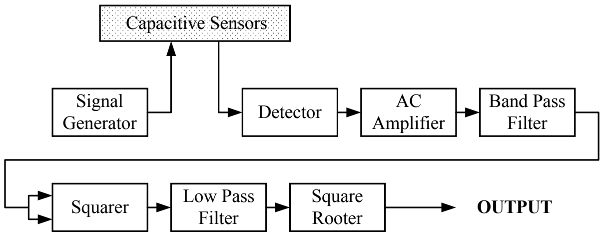

Fig.1 Capacitance measuring circuit diagram

2.1 Signal Generator

Based on the MAX 038, a sine-wave generator circuit is shown in Fig. 2. With minimum of external components, the circuit provides high stable and low distortion sinusoidal waveform. Moreover, the output frequency is controllable over a frequency range of 0.1 Hz to 20 MHz. The output from MAX 038, fixed at 500 KHz, is then amplified by an amplifier (using an op-amp, AD818) to achieve 20 Vp-p and low output impedance before injecting to the unknown capacitance Cx.

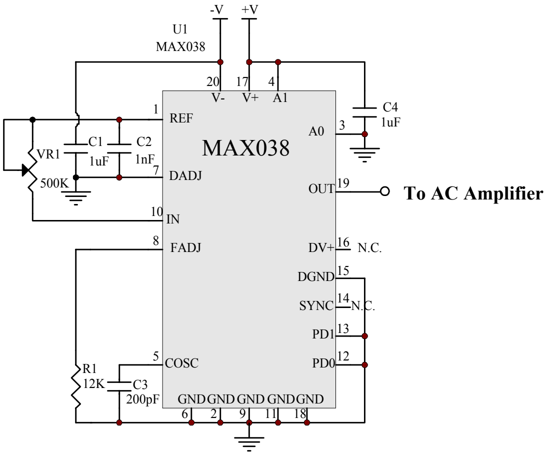

Fig.2 The sine-wave generator circuit

2.2 Charges Detector/Amplifier Circuit

As shown in Fig. 3, since the stray capacitance, Cs1 is directly driven by a low impedance voltage source (signal generator) , it has negligible effect on the measurement of Cx. The Cs2 has also no effect on the measurement of Cx because the feedback point of op-amp is kept at virtual earth and there is no potential difference across Cs2. Therefore, this capacitance measuring circuit is inherently stray-immune.

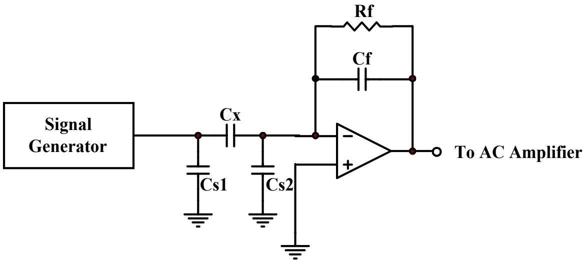

Fig.3 Detector circuit

The charge developed by the capacitance Cx is transferred to the feedback capacitor Cf and a feedback resistance Rf. Then a.c. voltage Vo is developed as given by eq. (1);

$$Vo = -\frac{j\omega CxRf}{j\omega CfRf + 1} Vi \tag{1}$$

where ω is the angular frequency of the excitation voltage.

When capacitance feedback is selected to be dominant, i.e. 1/ωCf << Rf the eq. (1) becomes;

$$Vo = -\frac{Cx}{Cf} Vi \tag{2}$$

This voltage is amplified by an a.c. amplifier constructed from, a wide bandwidth, operational amplifier (AD818) which provides selectable gains of 10 and 100. Signal from the amplifier is sent to band-pass filter (center frequency around 500KHz) for interference rejection before sending to the demodulator.

2.3 Demodulator Circuit

Demodulator circuit for capacitance measuring circuit are shown in Fig. 4.

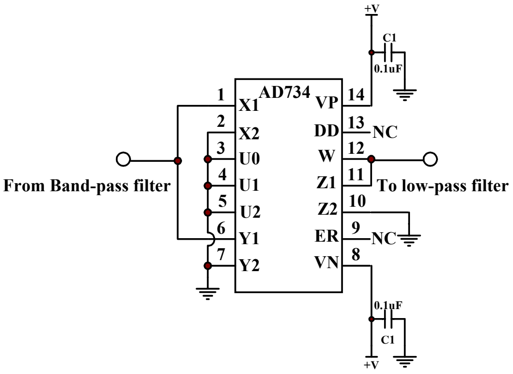

Fig.4 The demodulator (multiplier) circuit

The circuit is based on square law detection. The a.c. signals from band-pass filter are sent to an analogue multiplier circuit (AD734) to produce the square of signals. The squarer performs demodulation as follows;

$$Vd = \frac{1}{S}(A\sin(\omega t))(A\sin(\omega t)) \tag{3}$$

$$= \frac{A^2}{S}(\sin(\omega t))^2$$

$$= \frac{A^2}{S}\left[\frac{1}{2} - \frac{1}{2}\cos(2\omega t)\right]$$

$$\therefore\ Vd = \frac{A^2}{2S} - \frac{A^2}{2S}\cos(2\omega t) \tag{4}$$

The output signal from the multiplier circuit consists of d.c. and 1 MHz sine-wave components. A 2^{rd} orders low-pass filter with cut-off frequency of 10 KHz, is used for rejecting the 1 MHz components before sent to a square rooter circuit (AD633) as shown in Fig. 5. The square root signal performs as follow;

From the eq. (4); the output Vd after low-pass filter circuit;

$$Vd(LPF) = \frac{A^2}{2S} \tag{5}$$

The output Vd after square rooter circuit;

$$Voutput = \frac{A}{\sqrt{2S}} \tag{6}$$

The resultant d.c. signal represents the capacitance measurement.

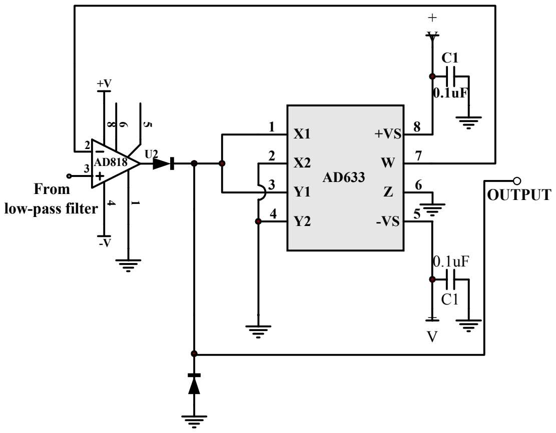

Fig. 5 Square rooter circuit

3.EXPERIMENTS WITH CAPACITIVE SENSORS

Because of the difficulty of obtaining suitably small capacitors for testing the proposed circuit (capacitance < 1pF), a box with two opposite electrodes (see Fig.6) containing vegetable oil ($\varepsilon_r = 3$) was used in the experiments. Level of vegetable oil had been changed then the capacitance was measured.

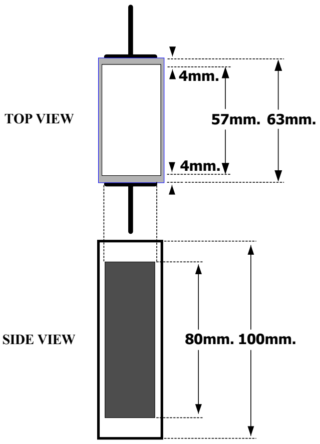

Fig. 6 Capacitve sensors

The proposed circuit has been simply constructed on a printed circuit as shown in Fig. 7 for using in the experiments. Characteristics of the board are illustated in the table.1.

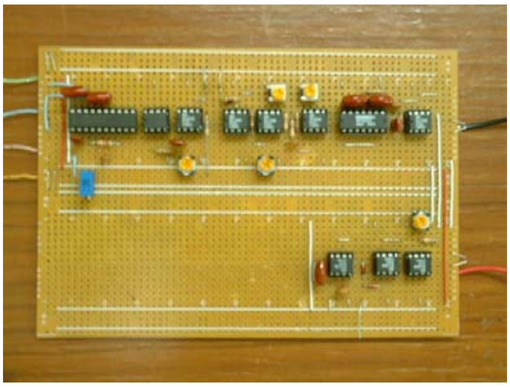

Fig.7 Implementation of the circuit

Table 1 Characteristics of the circuit

Circuit parameters	
Parameters	Value
Excitation voltage	20 Vp-p
Excitation frequency	500 KHz
Amplifier gain	10/100
Scale factor of multiplier circuit	10
Sensitivity	0.4 V/F at gain=10 4 V/F at gain = 100
Resolution	0.0025 pF at gain=10 0.00025 pF at gain=100
Scale factor of square rooter circuit	10

In the experiments we changed vegetable oil level from 1, 2,….,7 ,8 centimeters from the bottom and measured voltage output by a digital multimeter (HP 34401A) as shown in Fig 9.

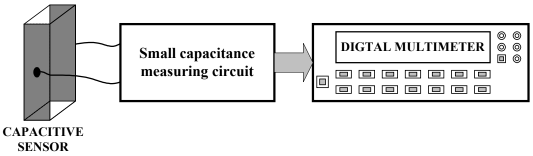

Fig. 8 Measuring circuit

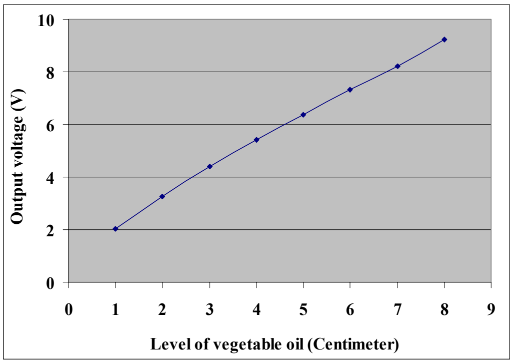

Fig. 9 Voltage measurement output

The corresponding measured capacitive values are calibrated by the HP4284A precision LCR meter and shown in Fig. 10.

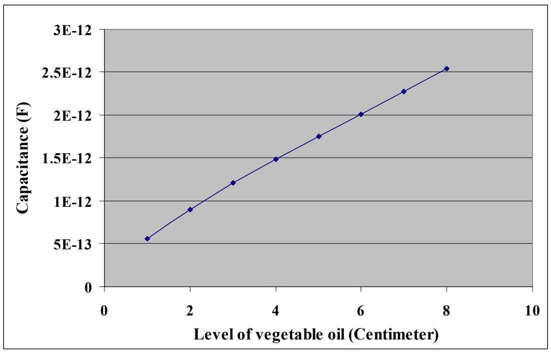

Fig. 10 Corresponding capacitive values of the box

4. TEST STABILITY OF THE CIRCUIT

To test stability of the proposed capacitance measuring circuit, we use a GPIB system for measure voltage output from the circuit. The system and flow diagram for stability testing of capacitance measuring circuit are shown respectively in Fig. 11 and Fig. 12.

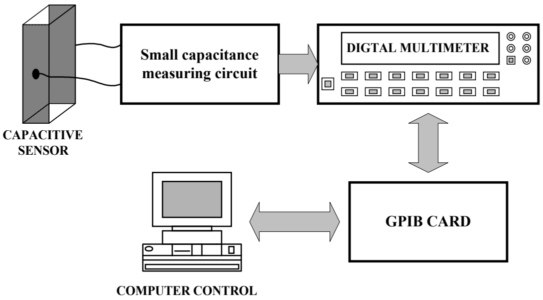

Fig. 11 System of stability testing

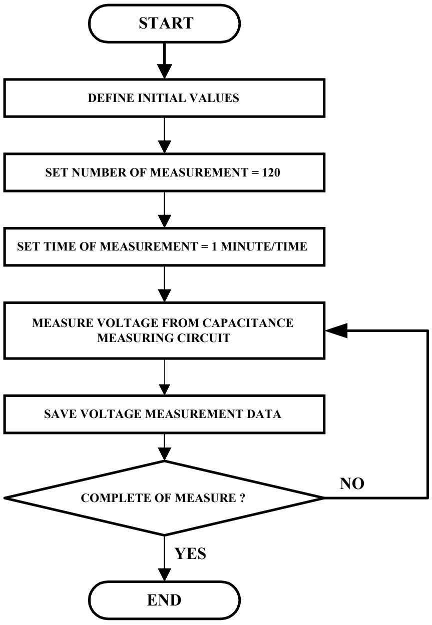

Fig. 12 Flow diagram for stability testing

Output voltages of the circuit had been measured every one minutes during 2 hours. So 120 data points were totally obtained. The results are shown in Fig. 13.

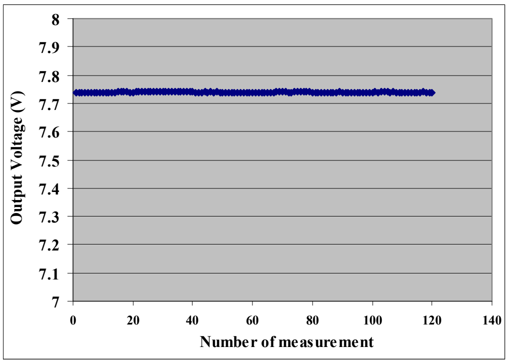

Fig.13 Output of the circuit during 2 hours of operation.

From the data shown in Fig. 13, Signal-to-noise ratio (SNR) of the system is calculated by using eq. 7 [8].

$$SNR = 10\log\left\{\frac{\sum_{n=1}^{N} V_n^2}{\sum_{n=1}^{N}\left(V_n - \overline{V}\right)^2}\right\} \qquad (7)$$

Where V_n is the signal value of sample n.

$\overline{V}$ is the average value of the samples.

From eq. 7

$$SNR = 10\log\left\{\frac{\sum_{n=1}^{N} V_n^2}{\sum_{n=1}^{N}\left(V_n - \overline{V}\right)^2}\right\} = 10\log\left\{\frac{7187.48}{0.00022106}\right\}$$

$$SNR = 10\log 32513706.69 = 75.12066484 \approx 75dB$$

$\therefore$ Signal-to-noise ratio (SNR) of system $\approx$ 75 dB.

5.CONCLUSIONS

A small capacitance measuring circuit has been detailed in the paper. Results of some experiments with a capacitive sensor filled by a vegetable oil at various levels have been shown satisfy sensitivities, linearity, resolution and stability of the proposed circuit.

The proposed small capacitance measurement circuit is suitable for capacitive sensors or industrial capacitance transducer.

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