Optimal Charging Time Interval in Direct Sensor to Microcontroller Interface

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***Abstract* – The resistive and capacitive modulating sensors can be directly measured with microcontroller by measuring the charging or discharging time of RC circuit. The measurement contains two phases: charging and discharging phase. In the first phase the charging/discharging time interval should be short enough to ensure high speed measurements and in the same time to be long enough to ensure high resolution. Therefore, the optimal charging/discharging time interval that gives the best speed/resolution trade-off has to be determined. In this paper theoretical and experimental analysis for the optimal charging/discharging time interval are presented.**

***Keywords* – Direct sensor-microcontroller interface, Optimal charging time interval, Measurement**

I. INTRODUCTION

Direct sensor to microcontroller interface is an alternative approach for conditioning of modulating resistive and capacitive sensors without the use of an A/D converter. The microcontroller uses the built in timer to measure the charging or discharging time of RC circuit formed by the sensor and reference resistor/capacitor. In this way, the microcontroller and the sensor form a relaxation oscillator causing the modulating sensor to act like a quasi-digital sensor.

Two measurement methods are proposed: a method based on charging [1] or discharging time [2] of the RC circuit. The two methods differentiate by the crossing of the upper or the lower threshold voltage (V_{th} or V_{tl}) of the Schmitt trigger port to create an interrupt. The method based on discharging time gives better measurement results [3] because the lower threshold voltage V_{tl} has better rejection of the power supply interference and because usually the microcontroller ports can sink more current than they can source. In this paper the analysis are restricted to the interfaces based on the measurement of the discharging time but the same methodology can be applied to the interfaces based on the measurement of the charging time.

II. INTERFACE BASED ON DISCHARGING TIME

The most basic direct sensor to microcontroller interface can be realized by using two microcontroller pins, one output and one input pin. Simplified electrical circuit of the direct sensor -microcontroller interface based on measurement of discharging time is shown in Fig. 1.

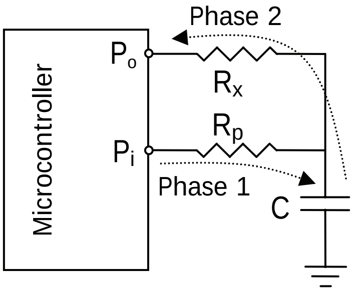

Fig. 1. Direct sensor–microcontroller interface based on measurement of discharging time

The measurement contains two phases: charging phase and discharging phase. The wave shape of the capacitor voltage in the two phases is shown in Fig.2.

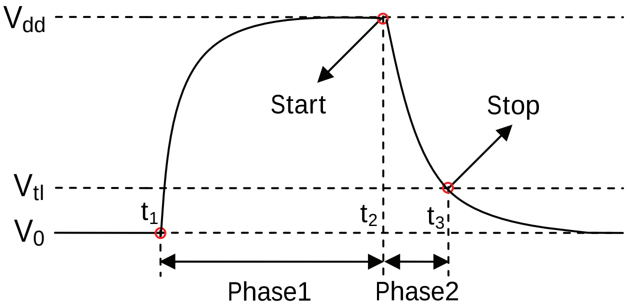

Fig. 2. Wave shape of the capacitor voltage in the two measurement phases

At the beginning the pin P_i is set as output with logical state "1" and the pin P_o is set as input (high impedance state). The capacitor charges through R_p to V_{dd} in a period $t_1 \div t_2$. In the next step the pin P_o is set as output with logical state "0", the timer starts and the pin P_i is set to high impedance state. This time the capacitor discharges through R_x until the voltage reaches the lower threshold voltage V_{tl}. Crossing of the threshold voltage V_{tl} initiates interrupt that stops the timer.

The capacitor voltage in the second (discharging) phase (Fig.2) can be expressed as

$$V_c(t) = V_0 + (V_{dd} - V_0)e^{-\frac{t}{\tau}} \tag{1}$$

where $\tau = R_x C$ is the discharging time constant. Here, the time needed for the capacitor to discharge from V_{dd} to V_0 is

$$t_x = (t_3 - t_2) = \tau \ln\left(\frac{V_0 - V_{dd}}{V_0 - V_{tl}}\right) \tag{2}$$

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Having in mind that V_0, V_{dd}, V_{tl} and C are constant, from (2) can be seen that the time interval t_x is proportional to the measuring resistance R_x. This time interval (t_x) is measured with the built in timer in the microcontroller. The result of the time to digital conversion can be expressed as

$$N = kR_x \tag{3}$$

where k is constant dependent on V_0, V_{dd}, V_{tl}, C and the time base of the timer. In practice the input/output resistances and leakage currents of the microcontroller ports cause gain, offset and nonlinearity errors [4]. Additionally the constant (k) in the equation (3) is not very stabile. Therefore, in practice direct sensor-microcontroller interface is realized by using some calibration technique [5] that cancels the contribution of V_0, V_{dd}, V_{tl} and C.

III. OPTIMAL CHARGING TIME INTERVAL

The charging time interval in the first phase (phase1) in Fig.2 can be expressed with the equation

$$V_c(t) = V_{dd} + \left(V_0 - V_{dd}\right)e^{-\frac{t}{\tau}} \tag{4}$$

where $\tau = R_pC$ is the charging time constant. From (4) it can be seen that theoretically the capacitor voltage will reach V_{dd} in infinity. If we take a finite value for the charging time interval in phase1 (Fig.2), than we introduce error in the equation (1) taking $V_c(t_2)=V_{dd}$. This error is smaller for longer charging time intervals, but also longer charging time intervals decrease the speed of the measurement. One possible solution for increasing of the speed of measurement is reduction of the resistance R_p. However this resistance is limited by the maximal current that the microcontroller can source. Also higher value of R_p improves the power supply noise rejection ratio of the measuring system [6].

Very often in the literature that deals with the direct sensor -microcontroller interface, charging time interval higher than 5τ is recommended. However this is not always true and the charging time interval must be chosen depending on the desired resolution. The error of the time interval measurement must be smaller than half of the least significant bit (LSB) for the desired resolution. Therefore the optimal charging interval that gives best speed/resolution trade-off has to be determined.

The relative error of the capacitor voltage in phase1 is expressed with the equation

$$\Delta V_c\left(t_2\right) = \frac{V_c(t) - V_c(\infty)}{V_c(\infty)} 100[\%] \tag{5}$$

Considering the Eq. (4) and if we take $V_c(\infty)=V_{dd}$, the Eq. (5) becomes

$$\Delta V_c\left(t_2\right) = 100\left(\frac{V_0}{V_{dd}} - 1\right)e^{-\frac{t}{\tau}}[\%] \tag{6}$$

Similarly, considering the Eq. (2) the relative error for the measured time interval is

$$\Delta t_x = \frac{\ln\dfrac{V_0 - V_c(t_2)}{V_0 - V_{dd}}}{\ln\dfrac{V_0 - V_{dd}}{V_0 - V_{tl}}} 100[\%] \tag{7}$$

The relative errors of the capacitor voltage (6) and the time interval measurements (7) for charging time intervals of 1÷10τ are given in Table I.

TABLE I
RELATIVE ERRORS OF THE CAPACITOR VOLTAGE AND TIME INTERVAL

t/τ	$V_c(t_2)$[V]	ΔV_c[%]	Δt_x[%]
1	3.22	35.3	/
2	4.33	12.9	10.5
3	4.74	4.7	3.6
4	4.89	1.7	1.3
5	4.94	0.64	0.4
6	4.96	0.23	0.17
7	4.97	0.08	0.06
8	4.97	0.03	0.02
9	4.97	0.01	0.008
10	4.98	0.004	0.003

The relative errors in Table I are calculated by using V_0=0.02, V_{dd}=5V and V_{tl}=1.4V. The relative errors are shown on Fig.3.

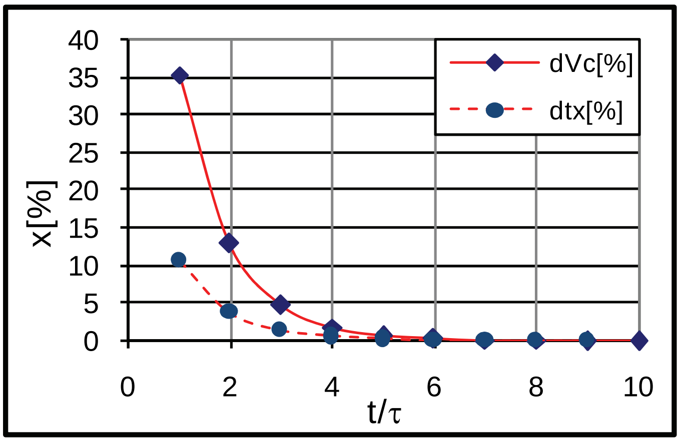

Fig. 3. Relative errors of the capacitor voltage and time interval

From the results reported in Table I and in Fig.3 it can be seen that for charging time interval of 1τ, the high threshold voltage V_{th}=3,6V cannot be reached. Therefore measurement with such charging time is impossible. For charging time interval 5τ, the capacitor voltage reaches 99.5% of the voltage V_{dd}. The relative error of the measured time interval in this case will be 0.4%. This relative error is lower than 0.5LSB for resolution of 6 bits. Therefore if we want to achieve higher resolution, the charging time interval must be proportionally increased. For example if the desired resolution is 12 bits, then the charging time interval must be longer than 9τ. Hence, the optimal charging time should always be determined with respect to the desired resolution. The relative error in that case should be lower than 0.5LSB.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The theoretical analyses in Section III are experimentally verified for charging time intervals 3τ÷10τ. The experiments are realized by using microcontroller PIC16F877 [7] with clock frequency of 8 MHz, effective instruction cycle speed 2MHz and period 0.5μs. The falling edge of the input signal was registered with the RB0/INT Schmitt trigger pin. This pin initiates interrupt that stops the 16-bit timer - Timer1.

The results of the measurements are sent to personal computer through the serial RS232 port. The MAX232 (TTL/RS232) level translator was supplied from separate power supply to prevent transients (about 170 kHz) from interfering with the power supply rails of the microcontroller. To reduce the noise effects affecting the voltage comparison between V_c and V_{tl} several design solutions were applied:

- Decupling capacitor of 100nF was placed as close as possible to the microcontroller pins as recommended from the manufacturer
- The board ground plane was carefully designed for low electromagnetic interference
- Only the microcontroller was supplied from the power supply to eliminate other interference effects
- The microcontroller didn't execute any other task while waiting for the interrupt
- The program algorithm was not changed while performing the experiments

The passive components were measured with measuring instrument with maximal error of ±0.1%+5 for resistance and ±1%+5 for capacitance measurement. The measured and the nominal values are given in Table II.

TABLE II
THE MEASURED AND THE NOMINAL VALUES OF THE PASSIVE COMPONENTS

$R_x[\Omega]$	4697.5
$R_p[\Omega]$	1190.9
$R_0[\Omega]$	75
C[μF]	2.284
τ[ms]	2.89

The output resistance of the port R_0 in Table II was measured indirectly by measuring the voltage drop of a resistive divider. The divider was formed by the output port resistance and resistor with nominal value of 470Ω. The time constant given in Table II was calculated as

$$\tau = (R_0 + R_p)C \tag{7}$$

The measurements of the time interval t_x were repeated 100 times for each charging time interval (3τ÷10τ). The standard deviation, the average and the relative error was then calculated for each set of the measurements. The average of the measurements with charging time 10τ was taken as a true value for calculation of the time interval relative error. The results are given in Table III.

TABLE III
STANDARD DEVIATION, AVERAGE AND RELATIVE ERROR OF THE TIME INTERVAL MEASUREMENTS

	σ[μs]	$t_{x\text{-}av}$[ms]	Δt_x[%]
3τ	0.8	12.58	3.6
4τ	0.6	12.88	1.3
5τ	0.9	12.99	0.5
6τ	0.8	13.03	0.1
7τ	0.5	13.05	0.04
8τ	0.9	13.06	0.002
9τ	0.4	13.06	0.0005
10τ	0.5	13.06	≈0

The averages of the time interval measurements for different charging time intervals are graphically shown in Fig.4.

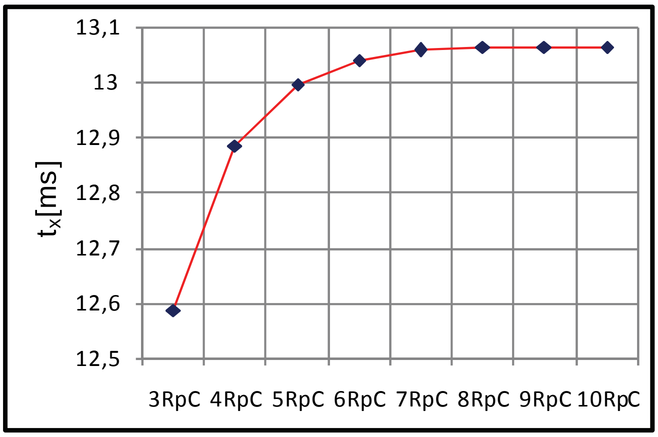

Fig. 4. Time interval average for different charging time

From the results reported in Table III it can be seen that the standard deviation of the measurements was nearly equal for all set of measurements. This was expected having in mind that the noise influence is the same in all measurements. To minimize the differences caused by program related errors, the program algorithm during the measurements was not changed.

The averages of the time interval measurements increased with increasing of the charging time interval. However, for charging interval higher than 8τ the average of the measurements was nearly constant (Fig.4). This is also confirmed with the relative error which is very low (0.002%) for charging time interval of 8τ. Having in mind that the maximal resolution that has been achieved with the direct sensor-microcontroller interface is around 13 bits [8] we can say that charging time interval of 10τ will be always satisfactory. However, for lower resolution and higher speed of the measurements lower charging time intervals should be used. In this way the best speed/resolution trade-off can be achieved.

The comparison of the theoretical (Table I) and the experimental (Table III) results for the relative error of the time interval measurements are shown on Fig.5.

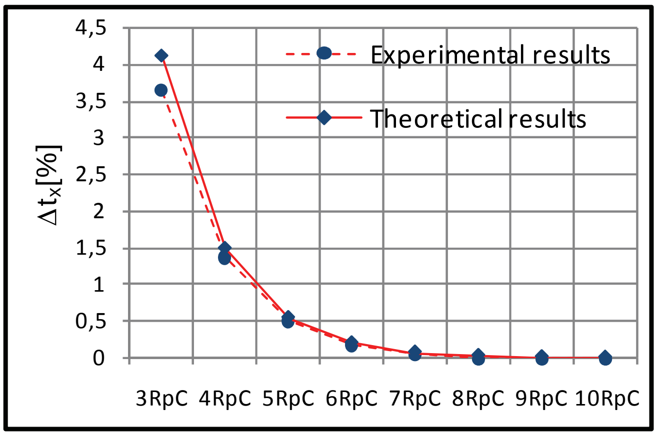

Fig. 5. Comparison of theoretical and experimental results

From the results reported in Fig.5 it can be seen that the theoretical and the experimental results fit very well. The small difference is due to deviations of the output resistance of the microcontroller pin. The applied measurement procedure for determination of this resistance is not very accurate.

The relative error of the time interval measurements with charging time interval 3τ was around 4%. This relative error is very high and such value for the charging time interval cannot be used. When charging interval 5τ was used, the relative error decreased to nearly 0.5%. This charging interval can be applied for measurements where the desired resolution is 6÷7 bits. The relative error of the measurements for charging time intervals over 9τ were very low and the average of the measurements were almost constant. Here, the capacitor voltage at the end of the phase1 (Fig.2) reach 99.99% of the voltage V_{dd}. Therefore charging time intervals higher than 9÷10τ carry no more benefit and should not be used.

V. CONCLUSION

The direct sensor-microcontroller interface can be used for simple and cost-effective measurements of the resistive and capacitive modulating sensors. The measurement contains two phases, charging and discharging phase. In this paper analysis for the optimal charging time interval that results in best speed/resolution trade-off were presented.

In the paper theoretical and experimental analysis for different charging time intervals from 3τ÷10τ were preformed. The experiments were realized by using PIC16F877 microcontroller. The falling edge of the input signal was registered with the RB0/INT Schmitt trigger pin. The discharging time was measured by using 16-bit timer - Timer1.

The theoretical and the experimental analysis fitted very well. The relative error of the time interval measurements with charging time interval of 3τ was very high and such value for the charging time interval cannot be used. The relative error of the measurements for charging time intervals over 9τ were very low and the average of the measurements remain almost constant. Therefore charging time intervals higher than 9÷10τ carry no more benefit and should not be used.

For measuring systems where the speed of the measurement is not very important, charging time interval of 10τ should be used. For higher speed measurements the optimal charging time interval depends on the desired resolution. The duration of this interval must not result in relative error of the measurements higher than 0.5LSB.

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