Indian Institute of Space Science and Technology

Single Element Resistive Sensor using Microcontroller Approach

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1 Aim of the experiment

To analyse the working and implementation of Resistance to Digital Converter using Microcontroller Approach.

2 Resistance to Digital Converter

This resistance to digital converter is using microcontroller approach for single element resistive sensors.
We want to find the resistance value of the resistor R_x for that we need the discharging time of the capacitor C in two cases:

1. Discharging via PIN_{10}
2. Discharging via PIN_9

Let the time taken by the capacitor to discharge via PIN_{10} as T_{11} and via PIN_9 as T_{22} the the value of resistance R_x is given as:

$$R_x = \left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right]$$

where, R is a resistor with resistance 150Ω

2.1 Equipment Required

- Microcontroller i.e. Arduino Due
- Capacitor
- Resistors
- Connecting Wires
- Personal Computer
- Decade Resistance Box
- Oscilloscope
- USB connector

2.2 Theory

We are using Direct Microcontroller Approach for Single-Element Resistive Sensors. The microcontroller consists of many pins mainly digital and analog pins. In this experiment, we are using digital pins and connecting our passive components like resistors and capacitor to these digital pins as shown in Figure1. We can control the voltage of the pins by writing a simple Arduino Code on Arduino IDE and then uploading it on the Microcontroller. We can control the time, Voltage, on-off state, input-output state etc. of the digital pins.

We are dividing the whole process into **4 phases** namely A, B, C and D out of which phase A and C are charging phase of capacitor and phase B and D are discharging phase of the capacitor. Let's see each of these phases one by one.

1. **Phase-A**
   In this phase, PIN $_4$ is in On state or Low Impedance state with voltage V $_{dd}$ = 3.3V, PIN $_9$ and PIN $_{10}$ are in Off or High Impedance state.
   The PIN_9 and PIN_{10} will act as Open circuit and the capacitor C will get charged from PIN $_4$ via the path shown in Figure 1.

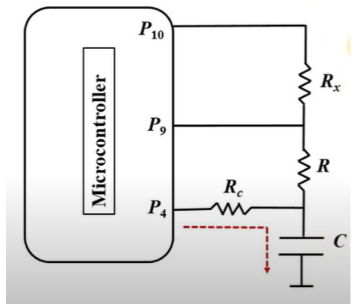

Figure 1: Charging of Capacitor Via PIN_4

The capacitor will get charged upto 3.3V with a time constant of:

$$\tau = R_c C$$

The capacitor will get charged in almost 5 time constants or in 5τ. When the time of operation exceeds the specified time the microcontroller will change the state of PIN_4 from On to Off state and make PIN $_{10}$ as On and hence, we will enter in **Phase-B** of the process.

2. **Phase-B**
   Now, PIN_4 will act as an Open circuit and the capacitor gets discharged via PIN_{10} as shown in the Figure 2

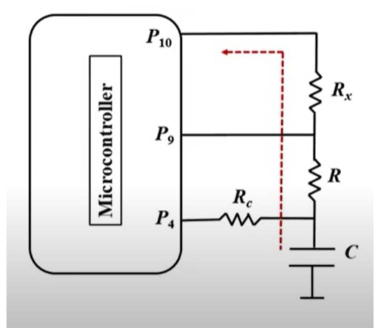

Figure 2: Discharging of Capacitor Via PIN_{10}

with a time constant of:

$$\tau_1 = R_{eq1} C$$

Where, $R_{eq1} = R + R_x$

We will measure the time at which the capacitor starts discharging from V_{dd} =V_c=3.3V upto V_{th}=V_c=1.2V.
Where, $V_{th}$is the threshold voltage of pin and V_c is the capacitor voltage.

The discharging of the capacitor is govern by the equation:

$$V_c(t) = V_c(0)e^{-T_1/R_{eq1}C}$$

By substituting the values of $V_c(t)$ at specified time and taking log we get T_{11} as:

$$T_{11} = R_{eq1}K_m, K_m = Cln(V_{dd}/V_{th})$$

Where, $R_{eq1} = R + R_x$

The plot or waveform that we obtain till phase-B is shown in Figure 3.

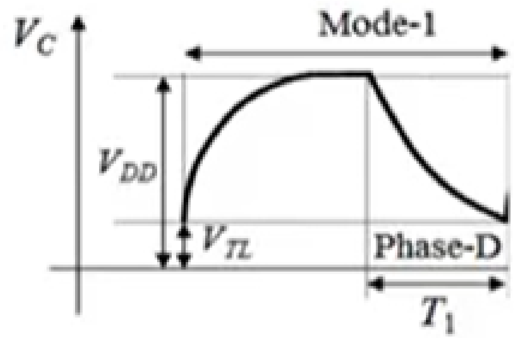

Figure 3: Waveform of Capacitor Voltage till Phase-B

When the capacitor voltage reaches the threshold voltage of the digital PIN $_4$ the microcontroller will make the state of PIN $_4$ as On and of PIN$_{10}$ as Off and hence, we will enter in **Phase-C** of the process.

3. **Phase-C**
Now as PIN $_4$ is in On state or Low Impedance state with voltage V $_{dd}$ = 3.3V, PIN $_9$ and PIN $_{10}$ are in Off or High Impedance state.
The PIN $_9$ and PIN $_{10}$ will act as Open circuit and the capacitor C will get charged from PIN $_4$ via the path shown in figure2. The capacitor will get charged upto 3.3V with a time constant of:

$$\tau = R_c C$$

The capacitor will get charged in almost 5 time constants or in 5τ. When the time of operation exceeds the specified time the microcontroller will change the state of PIN $_4$ from On to Off state and make PIN $_9$ as On and hence, we will enter in **Phase-D** of the process.

4. **Phase-D**
Now, PIN $_4$ will act as an Open circuit and the capacitor gets discharged via PIN $_9$ as shown in the Figure 4
with a time constant of:

$$\tau_1 = R_{eq2}C$$

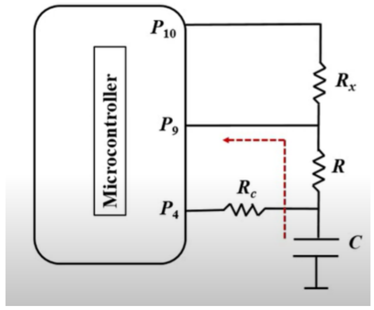

Figure 4: Discharging of Capacitor Via PIN_9

Where, $R_{eq2} = R$

We will measure the time at which the capacitor starts discharging from $V_{dd} = V_c = 3.3V$ upto $V_{th} = V_c = 1.2V$.

Where, V_{th}*is the threshold voltage of pin and* V_c *is the capacitor voltage.*

The discharging of the capacitor is govern by the equation:

$$V_c(t) = V_c(0)e^{-T_2/R_{eq2}C}$$

By substituting the values of $V_c(t)$ at specified time and taking log we get T_{22} as:

$$T_{22} = R_{eq2}K_m, K_m = Cln(V_{dd}/V_{th})$$

Where, $R_{eq2} = R$

The plot or waveform that we obtain till phase-D is shown in Figure 5.

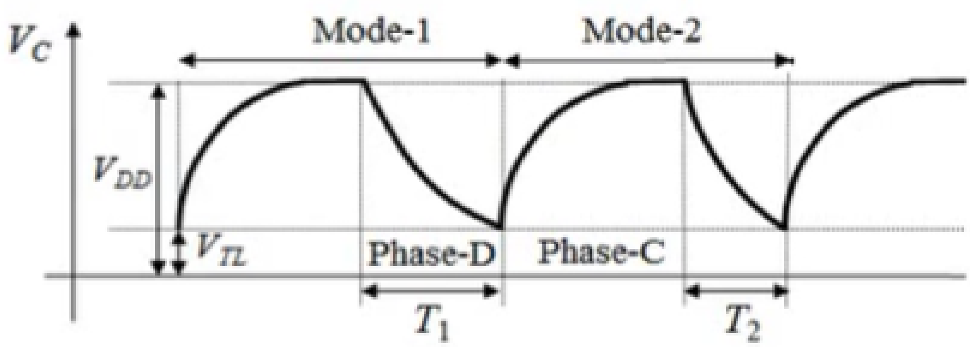

Figure 5: Waveform of Capacitor Voltage till Phase-D

When the capacitor voltage reaches the threshold voltage of the digital PIN $_4$ the microcontroller will delay the further process for 500seconds and after that the process will again starts from Pahse-A till Phase-D.

From the above process, we obtain discharging times T_{11} and T_{22} and from these values we can calculate the resistance R_x as:

$$\left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right] = \left[\frac{(R_{eq1} - R_{eq2})\cancel{K_m}}{R_{eq2}\cancel{K_m}} \times R\right] = R_x$$

Where, $R_{eq1} = R + R_x$ *and* $R_{eq2} = R$

2.2.1 Error analysis

The above discussed case and formulas are for Ideal Case in which we are considering the pin resistance of microcontroller as negligible but in practical or real scenario the pins will have some resistance of thier own and maybe some offset between them too.
The pin resistances are shown in the Figure 6 below.

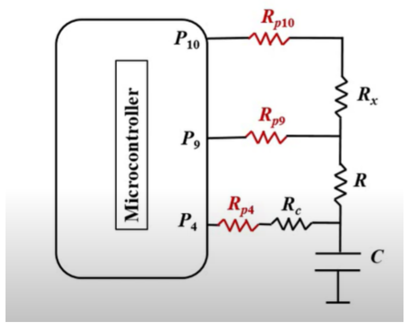

Figure 6: Microcontroller with Pin resistance

Considering the effect of Pin resistance in our calculations we get,

$R_{eq1} = R + R_x + R_{p10}$ *and* $R_{eq2} = R + R_{p9}$

$$\left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right] = \left[\frac{(R_{eq1} - R_{eq2})\cancel{K_m}}{R_{eq2}\cancel{K_m}} \times R\right]$$

$$\Rightarrow \left[\frac{T_{11} - T_{22}}{T_{22}} \times R\right] = \left[\frac{R_x + (R_{p10} - R_{p9})}{R + R_{p9}} \times R\right] \neq R_x$$

which is not exactly equal to R_x and hence we will get some error or non-linearity in the measurement.

2.3 Procedure

1. First, we will connect all the passive components on the breadboard and connect it to the desired digital pins of Microcontroller.

2. Next, we will write an arduino code based on the above theory and then upload it on the microcontroller.

3. Setting up the resistance value on the decade resistance box and checking the connections.

4. We will begin the Experiment by running the code and microcontroller will print the resistance values on our computer.

5. Analyzing the output waveform on the oscilloscope and the resistance value obtained we can compare the measured value with the true value.

2.4 Inferences

1. The resistance value that we obtained in the lab were less than that of the actual value of R_x.

2. The non-linearity in the result are due to the pin resistances that we didn't take into account.

3. The tolerance of the resistance and the non idealities of the capacitor can also contribute to the non-linearities.

4. The arduino duo uses a default timer 0 and it has a time resolution of $2\mu s$ because of this it shows some error if the time duration is lesser than $2\mu s$ for that we take the average of multiple readings.

3 Simulations

3.1 Simulating Microcontroller using $L_T Spice$

The $L_T Spice$ does not have its own arduino box therefore, we used **Switches, Comparator, Monostable Multivibrator, D-flip flop and Pulse Signals** to mimic the function and working of arduino pins. We used **Voltage Contolled Switch** and give voltage to it in the form of pulse to make it on or off. The T_{ON} and T_{OFF} are selected in such a way that they give sufficient time to the capacitor to get charged and discharged. These values of T_{ON} and T_{OFF} are dependent on Capacitor Voltage and are fed to switches using logic.
For measuring the time we used the **.meas** command to measure the time at which the voltage falls from 3.3V and recahes the 1.2V mark. We done the whole process from **Phase-A** to **Phase-D** in a single run by using the **transient analysis** of $L_T Spice$. We calculated the value of resistance from the discharging time by again using the .meas command in the $L_T Spice$ itself.

3.1.1 Circuit Diagram

The circuit diagram for the single element resistive sensor using Microcontroller approach is shown in Figure 7 . In the circuit we use 3 **Voltage controlled Switches** to mimic the arduino pins. We add a Voltage source of 3.3V at the end of the switch to replicate the V_{dd} of arduino pins.We used 1 pulse signal to control the charging of the capacitor and use a comparator that generates a trigger signal which activates a Monostable MultiVibrator that closes the switch at PIN_4 which in turn is fed along with the charging pulse to a D flip flop that generates signals that controls the PIN_9 and PIN_{10} . The opening and closing of the switches is heavily based on the theory and the logic that we used in the arduino code.
For measuring T_1, T_2, T_3 and T_4 we used **.meas** command.While measuring the time we face some problems such as getting the time of rise instead of fall, not getting the exact time when it reaches 1.2V etc.
We overcome this problem by using **fall** keyword which represent the falling part of the waveform and will strict the measurement done by the .meas command in the falling region of waveform only. We used **fall = last, secondlast, 1 and 2** where **last** represent the last fall or part of the waveform after the last peak, **secondlast** represent the part of the waveform after the second last peak and search for the time where our desired condition first met. Similarly 1 and 2 represent the 1st and 2nd fall. We used the keyword fall to restrict the measuring region of **.meas** command as

there are multiple point where V_C is either 3.3V or 1.2V.
We use the **.step** command to change the values of resistance R_x as asked in the question. We start from the value of 1000Ω to 10000Ω with an increase of 500Ω so that we can get all the desired values in one run.

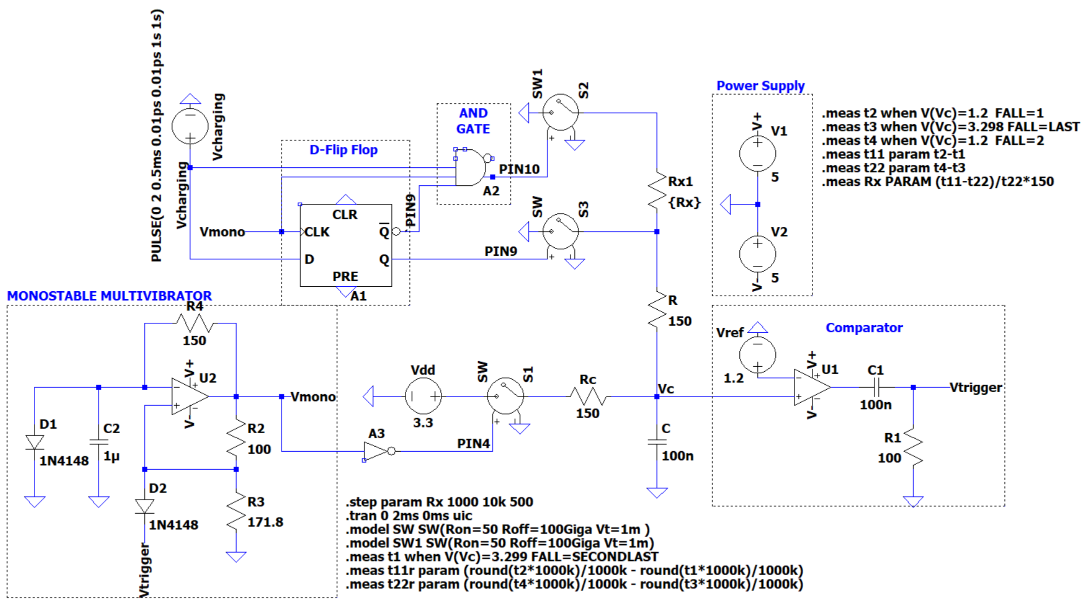

Figure 7: $L_T Spice$ Circuit Diagram

We use the **.model** command to model the switch with R_{ON} = 50Ω and R_{OFF} = 100GigaΩ which reprsents that when the switch is Off it will act as open circuit.
We used **round** function to round-off the values upto the desired decimal places.
We used **uic** condition along with .tran to skip the initial condition of the Opamp and we will get a non-fuzzy plot.
We used **.meas** command to measured the **difference** between T_1, $T_2$and T_3 ,T_4.

3.1.2 Switching Logic

The opening and closing of the switches are controlled by voltage signals that are tuned and timed depending on the time constant. The charging constant of the circuit is given as:

$$\tau = R_c C = 150\Omega \times 100nF = 15\mu s$$

The value of $5\tau = 75\mu s$ therefore, we choose the value of $t_{charging}$ = 0.5ms of the voltage signal $V_{charging}$ which is sufficient for the circuit to get charged as shown in Figure 8.

In the Figure 8 we can see that, PIN_4 is active when other PINs are inactive which charges the capacitor and when the PIN_4 is in inactive state the others are in active depending on the PIN that is going through discharging.
The pin voltages shown in Figure 8 are dependent on different components like Monostable MultiVibrator, Comparator, D - Flip FLop, AND gate and voltage signal these work at different time instances or previously defined time states or phases.

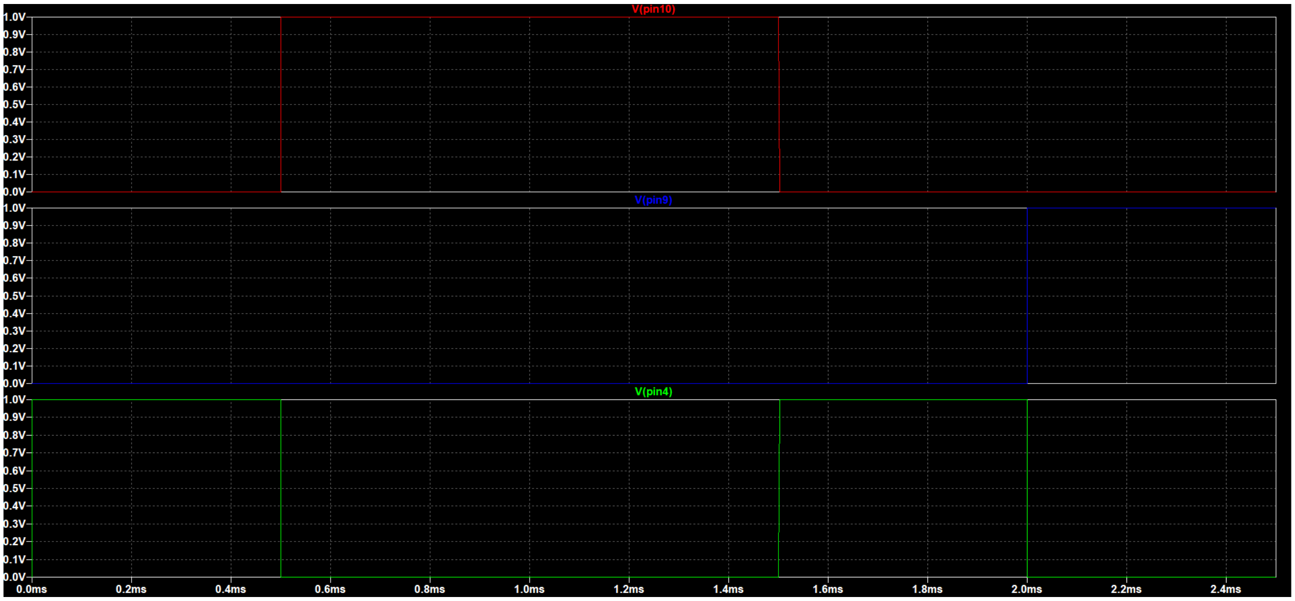

Figure 8: Switching Logic

3.1.3 PIN$_4$

Here, the input logic given to PIN$_4$ is the output of **Monostable Multivibrator** given through a **Inverter** which inverts the signal and polishes the roughness of the signal due to the triggering voltage.We invert the signal so that it will work in the negative peak of the Monostable Multivibrator as we want our circuit to charge initially. When the capacitor is fully charged the charging switch opens and the discharging switch closes which discharges the circuit and when the capacitor voltage reaches 1.2 V the **Comparator** gives a triggering signal to the Monostable Multivibrator which again closes the PIN$_4$ and the capacitor charges. The output of Monostable Mulivibrator, Inverter and trigger are shown in Figure 9.

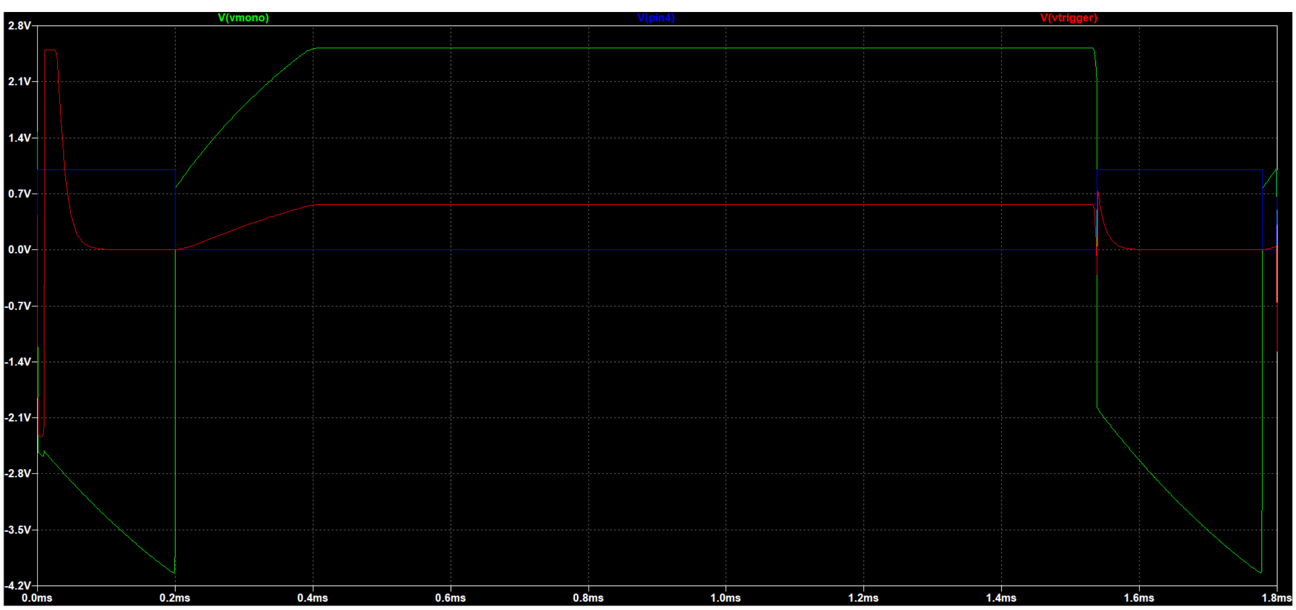

Figure 9: Switching Logic - PIN$_4$

The Multivibrator is designed using the equation

$$T_E = R_4\ C_2\ ln\left[1 + \frac{R_1}{R_2}\right]$$

and the triggering signal is given by R_1C_1. We want a T_E of $150\mu s$ and for that we choose $ln\left[1 + \frac{R_1}{R_2}\right] = 1$, $R_4 = 150\Omega$ and $C_2 = 1\mu F$.

3.1.4 PIN$_9$

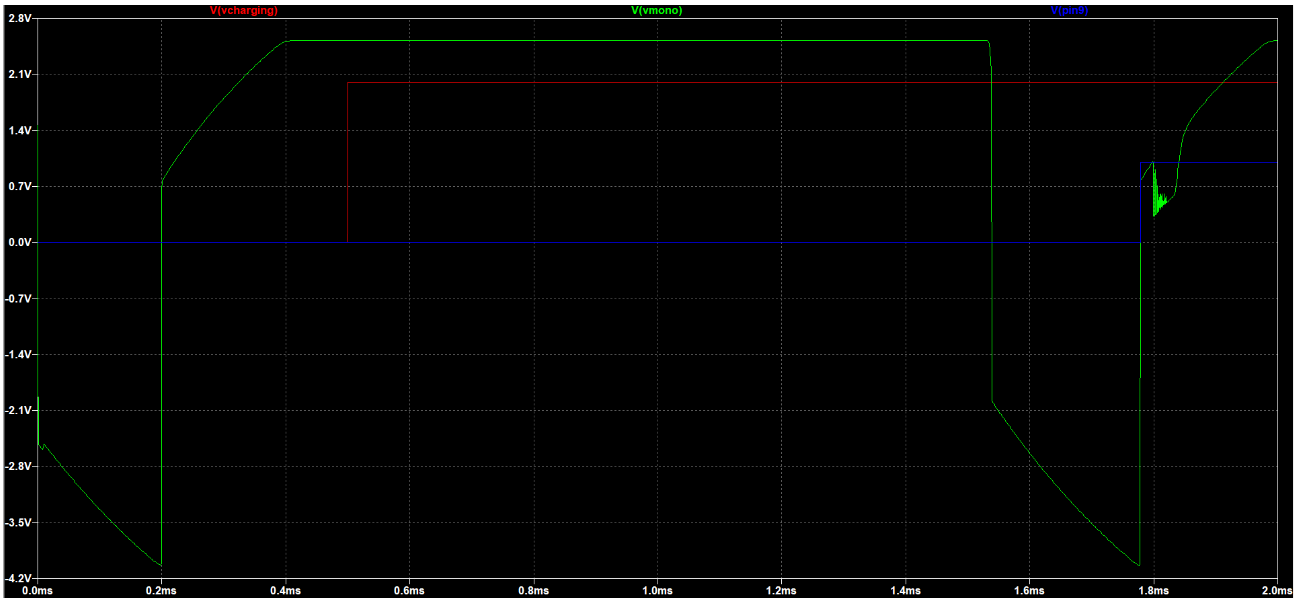

Figure 10: Switching Logic - PIN$_9$

For, choosing the operating signal for PIN$_9$ we use a **D-Flip Flop**. We give the Vmono as the clock for the D-Flip Flop and Vcharging as D or the input of the D-flipflop as the D-flipflop gives the same next or future state depending on it's current value and as it operates only when clock changes to positive side or at the **positive edge** of the clock. We take the signal for PIN$_9$ as the next state of the D-flipflop. Initially, the clock signal or Vmono is in negative state and hence, the flip flop is in Off state when the Vmono transits from negative to positive the Voltage of the input or the Vcharging will determine the next state of the Flip Flop or here that is PIN$_9$. We select the D- Flip Flop from the digital folder of L_TSpice.

3.1.5 PIN$_{10}$

Here, as we need the PIN$_{10}$ to work when other PINs are in inactive state for that we take the **AND** of the signals Vcharging, Vmono and Vpin'.These signals are responsible for the working of the other pins and therefore, these all will together decide the time where, the PIN$_{10}$ will work that we can see in Figure 11. We select the AND from the digital folder of L_TSpice which is used to convert different inputs into single output.

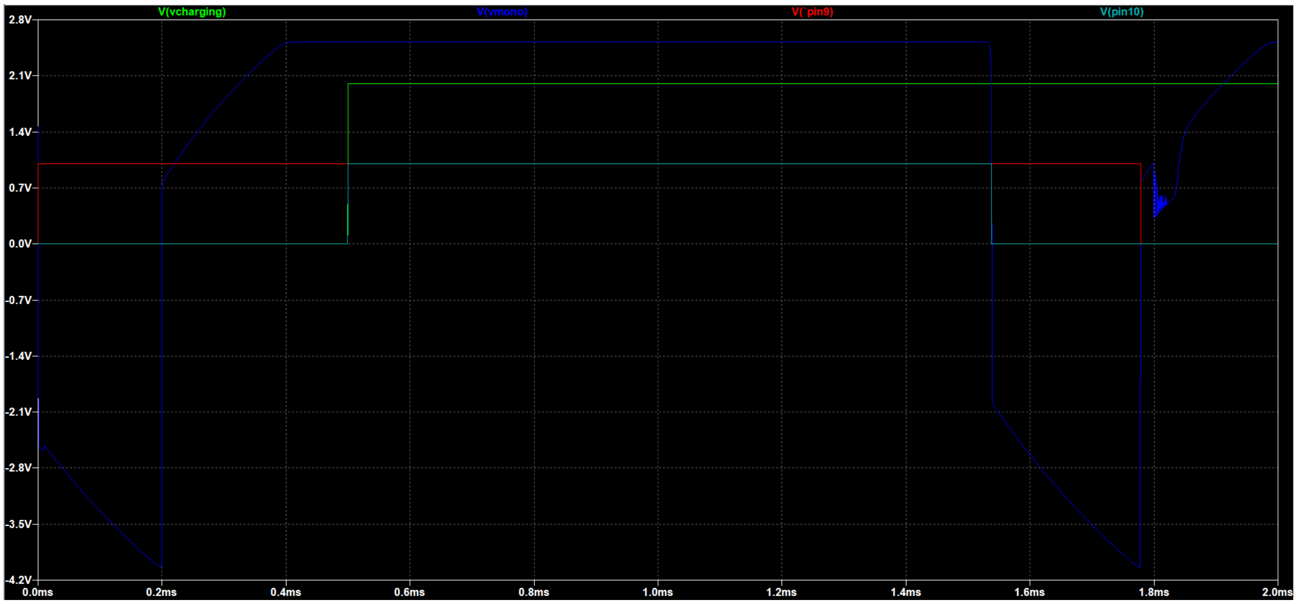

Figure 11: Switching Logic - PIN_{10}

3.1.6 Charging and Discharging Waveform

Initially, the charge on the capacitor was 0 and to invoke the condition we used **.IC** command which sets the initial value of the capacitor as 0 V. The charging and discharging of the capacitor is shown in Figure 12 after we apply the above **switching logic** into the circuit show in Figure 7.

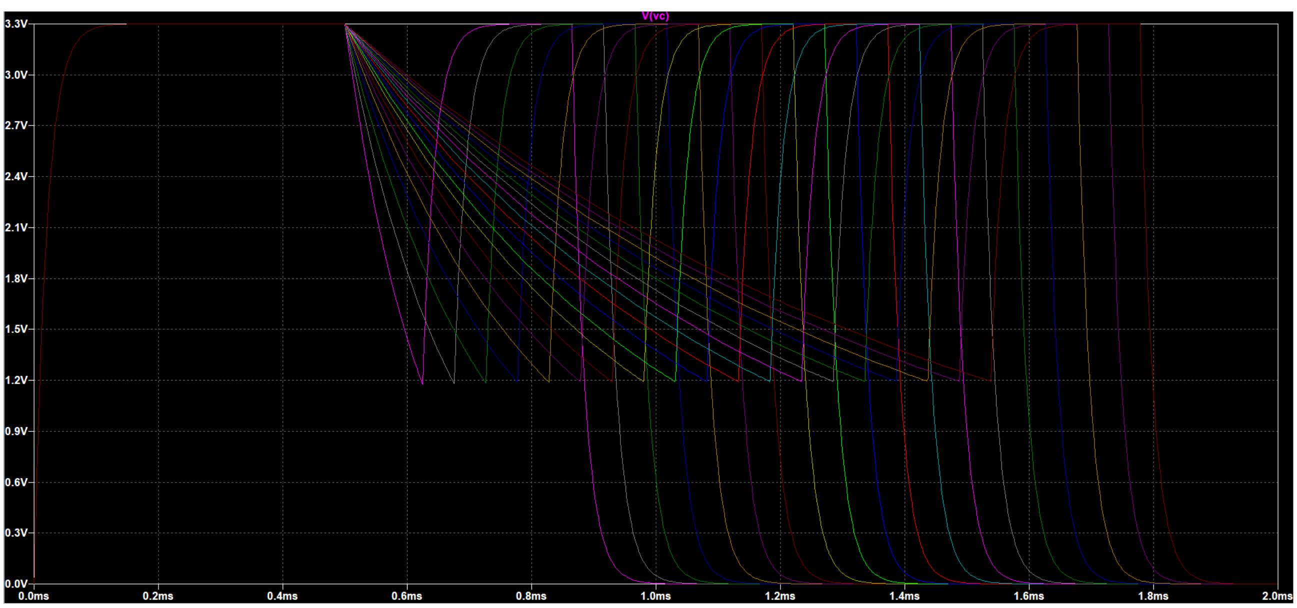

Figure 12: Charging and Discharging Curve

The discharging of the capacitor is govern by the equation:

$$V_c(t) = V_c(0)e^{-T/R_{eq2}C}$$

and from the above equation we can see that the discharging of the capacitor is exponential in nature and so it's charging.
From the Figure 12 we can see or rather observe that the plot that we obtained from the simulation is similar to the one shown in Figure 5. We can see in the plot that the voltage of the capacitor first increases exponentially and reaches 3.3 V and then it decreases till it reaches 1.2 V. We can also observe that the charging time of the capacitor is less than that of the discharging time because of the different capacitor values.

3.1.7 Calculation of % Non-Linearity

After the simulation we press Ctrl + L to view the **error log** in the $L_T Spice$ and then exporting the measured values by .meas command into a text file. We then **load the data** into **MSexcel** for the calculation of measured values and to find the standard error and % Non-Linearity.
We used the **Data Analysis package** available in MSexcel to find the Linear Regression, predicted value of resistance, plots, Standard Error and % Non-Linearity below are the formlaes used in the calcualtion: We calculated the measured $\mathrm{R_x}$ by using the formulae:

$$R_x = \frac{T_{11} - T_{22}}{T_{22}} \times R$$

The predicted value is calculated using **Linear Regression** or **Least Square Fitting Method** and from there we calculated the residual as

$$Residual = y - \widehat{y}$$

and finally we calculated the % Non-Linearity by using

$$\%Non\ Linearity = \frac{Residual}{Output\ Span} \times 100 = \frac{y - \widehat{y}}{OutputR_{\mathrm{x}}|_{\mathrm{MAX}} - OutputR_{\mathrm{x}}|_{\mathrm{MIN}}}$$

where, $OutputSpan = OutputR_x|_{MAX} - OutputR_x|_{MIN}$
All the calculations are performed in MS Excel.

3.2 Outputs

After running the simulation of the above circuit and all the commands we obtain the values of discharing times of the capacitor via PIN_{10} and PIN_9 that are used to calculate the values needed to answer the following questions that are asked in the assignment.

The following common measurements need to be done for the circuit shown in the above figure. Consider the resistor Rc and R is 150Ω , charging time of 5 ms, VDD = 3.3 volts, and VTL = 1.2 volts. The inferences observed from the simulation studies should present in the assignment.

(a) Find the % Nonlinearity between input Rx and measured Rx without rounding the discharge times to microseconds. Assume there is no mismatch in microcontroller pin-resistance and the pin resistance is 50Ω .
Assuming no mismatch between the pin resistances and without rounding off the discharge time to microseconds then calculating the values using above specified methods all the results are shown in the tables subsection 3.2 and Table 2.

Input Rx	**T11**	**T22**	***Measure Rx***
1000	0.000121351	2.02187E-05	750.288
1500	0.000171916	2.02161E-05	1125.59
2000	0.000222479	2.02301E-05	1499.62
2500	0.000273043	2.02178E-05	1875.77
3000	0.000323607	2.02269E-05	2249.83
3500	0.00037417	2.02214E-05	2625.55
4000	0.000424733	2.02278E-05	2999.63
4500	0.000475297	2.02163E-05	3376.58
5000	0.00052586	2.02496E-05	3745.34
5500	0.000576423	2.02165E-05	4126.87
6000	0.000626985	2.02385E-05	4496.99
6500	0.000677548	2.02328E-05	4873.14
7000	0.000728111	2.02139E-05	5253.05
7500	0.000778673	2.02424E-05	5620.11
8000	0.000829236	2.02193E-05	6001.83
8500	0.000879798	2.02199E-05	6376.74
9000	0.00093036	2.02427E-05	6744.04
9500	0.000980922	2.02198E-05	7126.95
10000	0.00103148	2.02204E-05	7501.82

Table 1: Simulation Values

The simulation values obtained are shown in the subsection 3.2.

The Non-lineartity calculated is shown in the Table 2 along with the residual values and predicted Resistance. The least square fitted line is also shown in the Figure 13 .

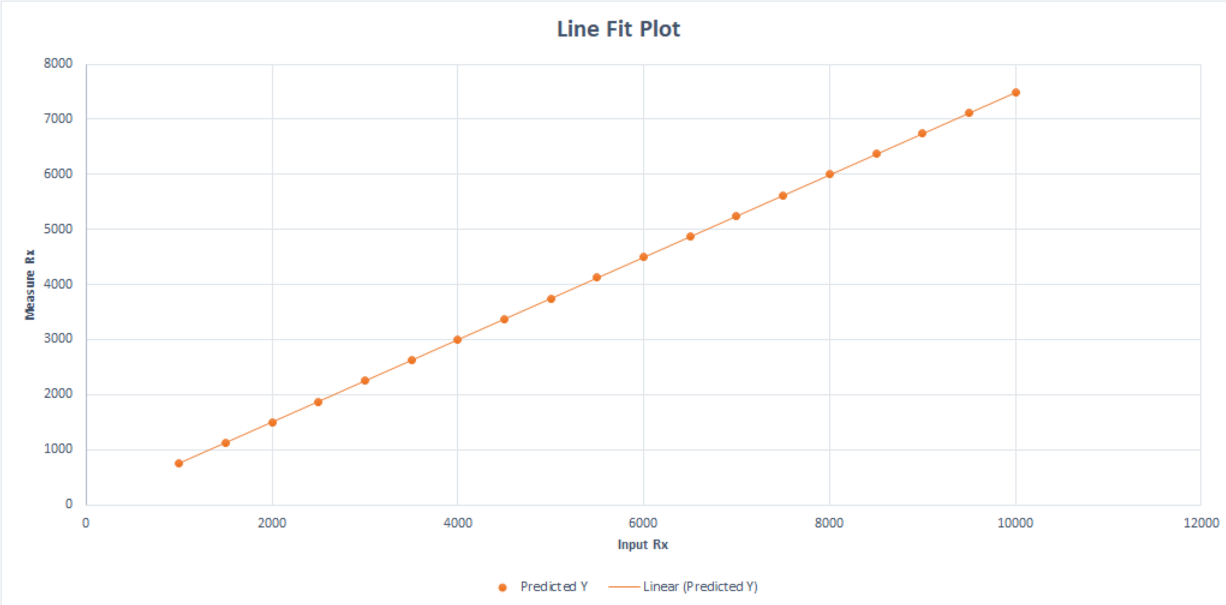

Figure 13: Line Fit Plot

Measure Rx	Predicted Rx	*Residuals*	% Non - Linearity
750.288	749.9646632	0.323336842	0.004789088
1125.59	1124.937818	0.652182456	0.00965977
1499.62	1499.910972	-0.29097193	-0.004309717
1875.77	1874.884126	0.885873684	0.013121077
2249.83	2249.857281	-0.027280702	-0.000404067
2625.55	2624.830435	0.719564912	0.010657802
2999.63	2999.803589	-0.173589474	-0.002571112
3376.58	3374.776744	1.80325614	0.026708844
3745.34	3749.749898	-4.409898246	-0.065317001
4126.87	4124.723053	2.146947368	0.03179941
4496.99	4499.696207	-2.706207018	-0.040082858
4873.14	4874.669361	-1.529361404	-0.022652065
5253.05	5249.642516	3.407484211	0.050469793
5620.11	5624.61567	-4.505670175	-0.066735523
6001.83	5999.588825	2.241175439	0.033195065
6376.74	6374.561979	2.178021053	0.032259657
6744.04	6749.535133	-5.495133333	-0.08139091
7126.95	7124.508288	2.441712281	0.036165307
7501.82	7499.481442	2.338557895	0.034637441

Table 2: Non-Linearity Table

The **Overall Non-Linearity** of the sensor is the **Max. absolute individual Non-linearity** and for the above case it is **0.08139091%**.

(b) Find the % Nonlinearity between input Rx and measured Rx after rounding the discharge times to microseconds. Assume there is no mismatch in microcontroller pin-resistance and the pin resistance is 50 Ω .

Assuming no mismatch between the pin resistances and after rounding off the discharge time to microseconds then calculating the values using above specified methods all the results are shown in the tables Table 3.2 and Table 4.

Input Rx	**T22_Rounded**	***T11_Rounded***	**Resistance_Rounded**
1000	0.00002	0.000121	757.5
1500	0.00002	0.000172	1140
2000	0.000021	0.000223	1442.86
2500	0.000021	0.000273	1800
3000	0.00002	0.000324	2280
3500	0.00002	0.000374	2655
4000	0.00002	0.000425	3037.5
4500	0.000021	0.000475	3242.86
5000	0.00002	0.000526	3795
5500	0.00002	0.000577	4177.5
6000	0.000021	0.000627	4328.57
6500	0.000021	0.000678	4692.86
7000	0.00002	0.000728	5310
7500	0.00002	0.000779	5692.5
8000	0.00002	0.000829	6067.5
8500	0.00002	0.00088	6450
9000	0.00002	0.000931	6832.5
9500	0.00002	0.000981	7207.5
10000	0.000021	0.001032	7221.43

Table 3: Simulation Values

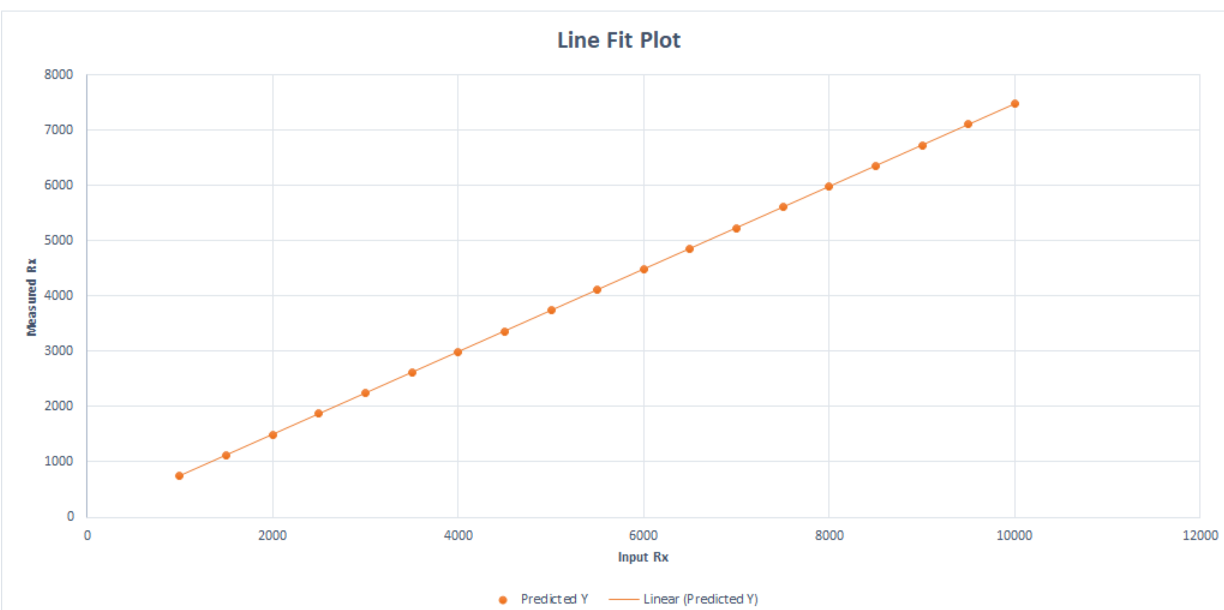

Figure 14: Line Fit Plot

The simulation values obtained are shown in the Table 3.2.

The Non-lineartity calculated is shown in the Table 4 along with the residual values and predicted Resistance. The least square fitted line is also shown in the Figure 14 .

Resistance_Rounded	***Predicted Rx_rounded***	***Residuals***	**% Non - Linearity**
757.5	738.2449474	19.25505263	0.297884609
1140	1113.124632	26.87536842	0.415774435
1442.86	1488.004316	-45.14431579	-0.698403538
1800	1862.884	-62.884	-0.972844694
2280	2237.763684	42.23631579	0.653415427
2655	2612.643368	42.35663158	0.655276768
3037.5	2987.523053	49.97694737	0.773166593
3242.86	3362.402737	-119.5427368	-1.849381674
3795	3737.282421	57.71757895	0.89291776
4177.5	4112.162105	65.33789474	1.010807585
4328.57	4487.041789	-158.4717895	-2.451632203
4692.86	4861.921474	-169.0614737	-2.615459538
5310	5236.801158	73.19884211	1.132420093
5692.5	5611.680842	80.81915789	1.250309918
6067.5	5986.560526	80.93947368	1.252171259
6450	6361.440211	88.55978947	1.370061085
6832.5	6736.319895	96.18010526	1.48795091
7207.5	7111.199579	96.30042105	1.489812251
7221.43	7286.079263	-65.64926316	-1.015624599

Table 4: Non-Linearity Tables

The **Overall Non-Linearity** of the sensor is the **Max. absolute individual Non-linearity** and for the above case it is **2.615459538%**.

(c) Find the % Nonlinearity between input Rx and measured Rx without rounding the discharge times to microseconds. Assume the mismatch between the microcontroller pin-resistance is 10Ω .

The mismatch between the arduino pins is 10Ω that means the relation between PIN_{10} and PIN_9 is given as:

$$R_{p9} = R_{p10} \pm 10\Omega$$

Assuming $R_{p9} = 50\Omega$ we get,$R_{p10} = 40\Omega, 60\Omega$ and if we assume $R_{p10} = 50$ we get,$R_{p9} = 40\Omega, 60\Omega$ So here we get **4 different cases** out of which we analyze the case where $R_{p10} = 60\Omega$ and $R_{p9} = 50\Omega$. A slight change in the resistance values will effect the dicharge time of Phase-D significatly due to the small value of R which is 150Ω .

The time constant of the discharging in Phase-D will become

$$\tau = (R + R_{p10} \pm 10)C$$

We will take one case: **Case:** $R_{p10} = 60\Omega \textit{ and } R_{p9} = 50\Omega$

The value of resistances that we obtained in the above cases are shown in the Table 5.

Input Rx	T11	T22	Measured Rx
1000	0.000122363	2.02143E-05	757.991
1500	0.000172927	2.02146E-05	1133.18
2000	0.000223491	2.02237E-05	1507.64
2500	0.000274055	2.02221E-05	1882.84
3000	0.000324618	2.02184E-05	2258.34
3500	0.000375181	0.000020225	2632.56
4000	0.000425745	2.02129E-05	3009.45
4500	0.000476308	2.02099E-05	3385.21
5000	0.000526871	0.000020209	3760.66
5500	0.000577434	2.02496E-05	4127.37
6000	0.000627997	2.02217E-05	4508.33
6500	0.000678559	2.02342E-05	4880.3
7000	0.000729122	2.02129E-05	5260.81
7500	0.000779684	2.02328E-05	5630.34
8000	0.000830247	2.02161E-05	6010.28
8500	0.000880809	2.02394E-05	6377.92
9000	0.000931372	2.02441E-05	6751.05
9500	0.000981934	2.02269E-05	7131.89
10000	0.0010325	2.02233E-05	7508.21

Table 5: Comparison between T_{22} and Resistance values keeping $R_{p10} = 60\ \Omega$

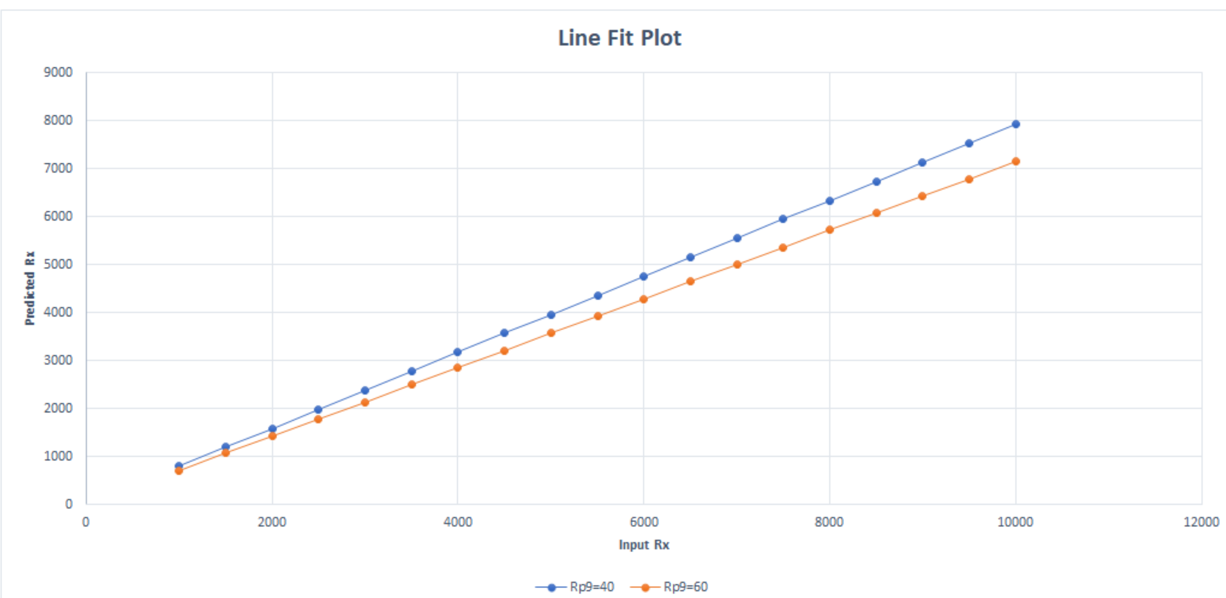

Figure 15: Line Fit Plot for two cases of earlier simulations

The plot between the least square fitted lines in both the cases are show in Figure 15 and compared values are shown in Table 6.
We observed that when the values of R is decreased or say when R_{p9}=40 the value of measured R_x is increased as compared to original case and when R_{p9}=60 the value decreases. This is because as

R decreases the value of T_{22} also decreases and hence R_x increases. Similarly when thae value of R increases and hence R_x decreases. This is because in the measurement formula of R_x T_{22} comes in denominator or it has a inverse relation with R_x .

Measured Rx	Predicted Rx	Residuals	% Non-Linearity
757.991	758.7760895	-0.785089474	-0.011630578
1133.18	1133.616004	-0.436003509	-0.006459102
1507.64	1508.455918	-0.815917544	-0.012087275
1882.84	1883.295832	-0.455831579	-0.006752841
2258.34	2258.135746	0.204254386	0.003025893
2632.56	2632.97566	-0.415659649	-0.006157721
3009.45	3007.815574	1.634426316	0.024212938
3385.21	3382.655488	2.554512281	0.037843399
3760.66	3757.495402	3.164598246	0.046881416
4127.37	4132.335316	-4.965315789	-0.073557847
4508.33	4507.17523	1.154770175	0.017107151
4880.3	4882.015144	-1.71514386	-0.025408714
5260.81	5256.855058	3.954942105	0.058589834
5630.34	5631.694972	-1.35497193	-0.020073007
6010.28	6006.534886	3.745114035	0.055481371
6377.92	6381.3748	-3.4548	-0.051180562
6751.05	6756.214714	-5.164714035	-0.0765118
7131.89	7131.054628	0.83537193	0.012375479
7508.21	7505.894542	2.315457895	0.034301967

Table 6: Comparison between Predicted and % Non-Linearity values keeping R_{p10}=60 Ω

The **Overall Non-Linearity** of the sensor is the **Max. absolute individual Non-linearity** that for the above case is **0.073557847%**.

(d) Find the % Nonlinearity between input Rx and measured Rx after rounding the discharge times to microseconds. Assume the mismatch between the microcontroller pin-resistance is 10Ω .

The values obtained are rounded and then the non linearity, resistance, residuals and other parameters are calculated below are the tables that show the comparison of the values. The plot between the rounded least square fitted lines in both the cases are show in Figure 15 and compared values are shown in Table 8.

We observed that when the values of R is decreased or say when R_{p9}=40 the value of measured R_x is increased as compared to original case and when R_{p9}=60 the value decreases. This is because as R decreases the value of T_{22} also decreases and hence R_x increases. Similarly when thae value of R increases and hence R_x decreases. This is because in the measurement formula of R_x T_{22} comes in denominator or it has a inverse relation with R_x and these values are a bit shifted as compared to non-rounded values.

Input Rx	T11_Rounded	T22_Rounded	Resistance_Rounded
1000	0.000122	0.00002	765
1500	0.000173	0.00002	1147.5
2000	0.000224	0.000021	1450
2500	0.000274	0.00002	1905
3000	0.000325	0.00002	2287.5
3500	0.000375	0.00002	2662.5
4000	0.000426	0.00002	3045
4500	0.000476	0.000021	3250
5000	0.000527	0.00002	3802.5
5500	0.000578	0.00002	4185
6000	0.000628	0.00002	4560
6500	0.000679	0.000021	4700
7000	0.000729	0.00002	5317.5
7500	0.00078	0.00002	5700
8000	0.00083	0.00002	6075
8500	0.000881	0.00002	6457.5
9000	0.000932	0.00002	6840
9500	0.000982	0.00002	7215
10000	0.001033	0.000021	7567.57

Table 7: Comparison between the rounded values of T_{22} and Resistance values keeping R_{p10}=60 Ω

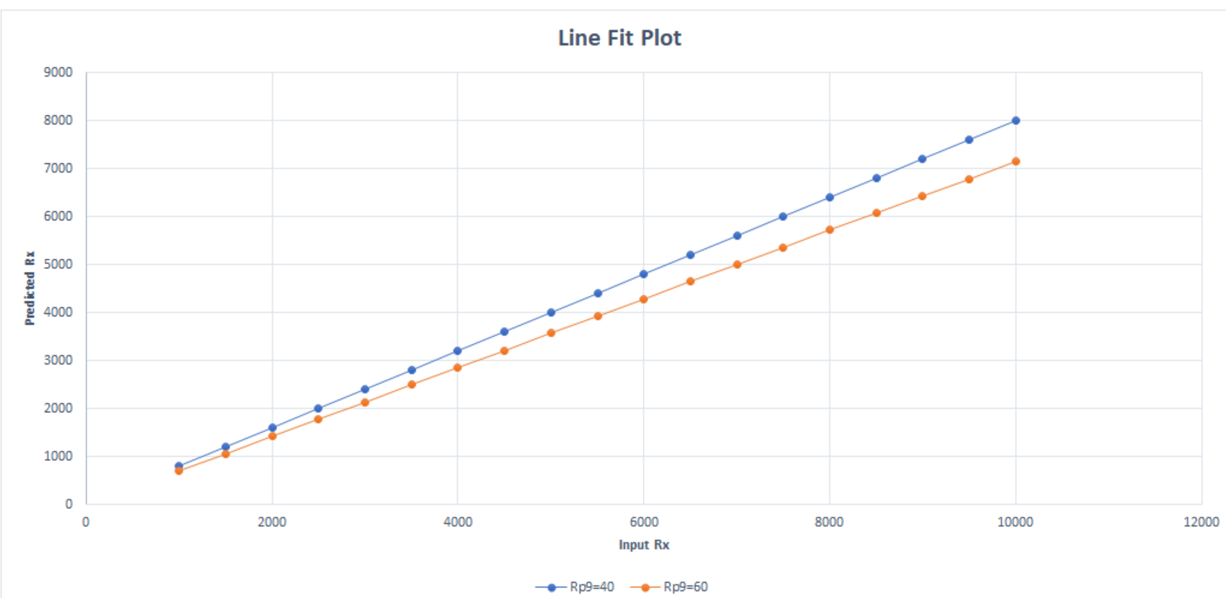

Figure 16: Line Fit Plot for two cases of earlier simulations

Resistance_Rounded	**Predicted Rx_rounded**	***Residuals***	**% Non-Linearity**
765	768.299	-3.299	-0.051025695
1147.5	1142.543965	4.956035088	0.076655088
1450	1516.78893	-66.78892982	-1.03302564
1905	1891.033895	13.96610526	0.216014014
2287.5	2265.27886	22.22114035	0.343694798
2662.5	2639.523825	22.97617544	0.35537294
3045	3013.768789	31.23121053	0.483053724
3250	3388.013754	-138.0137544	-2.134661348
3802.5	3762.258719	40.2412807	0.622412649
4185	4136.503684	48.49631579	0.750093433
4560	4510.748649	49.25135088	0.761771575
4700	4884.993614	-184.993614	-2.861299725
5317.5	5259.238579	58.26142105	0.901130501
5700	5633.483544	66.51645614	1.028811284
6075	6007.728509	67.27149123	1.040489426
6457.5	6381.973474	75.52652632	1.16817021
6840	6756.218439	83.7815614	1.295850994
7215	7130.463404	84.53659649	1.307529136
7567.57	7504.708368	-276.1383684	0.871037364

Table 8: Comparison between Rounded Predicted and % Non-Linearity values keeping $R_{p10} = 60$ Ω

The **Overall Non-Linearity** of the sensor is the **Max. absolute individual Non-linearity** and the values for the above case is **2.861299725%.**

3.3 Observations

1. The value of rise time and fall time of Voltage pulse contributes significantly to the Capacitor saturation Voltage.
2. On and Off resistances of the switch also effects capacitor voltage if we keep the Off resistance of switch low than a significant amount of current passes through the switch and causes error.
3. The time of discharging for Phase-B is very large as compared to phase-D.
4. Discharging time (T_{22}) of Phase-D remains constant for every value of input Resistance R_x
5. There is a change in the measure Resistance value when the discharging times are rounded and when there are not.
6. The value of T_{11} remains same for Case a and c at a fixed input resistance.
7. The % Non-Linearity is very low less than 1%.
8. The % Non-Linearity remains almost same for the 3 cases even after changing the value of R_{p9} in those 3 cases.

9. The value of resistances varied with significant amount when the value of R_{p9} is varied as compared to R_{p10}.

10. The slope of Least Square fit line is greater when R_{p9} is low in value.

11. As R_{p9} increases the value of measured resistance decreased significantly keeping R_{p10} constant.

12. The results that we obtained using Voltage sources are much more accurate as compared to the case when we used Comparator and Multivibrator.

3.4 Inferences

1. The rise time and fall time of the pulse causes the switch delay and when the rise time is of the order of time constant of capacitor charging and discharging which is in microseconds in the above cases we get some error. To rectify it we choose the rise and fall time of the pulse in nanoseconds.

2. When the Roff of the Switch is low a significant amount of current passes through it and charges the capacitor when it is in discharge mode. To avoid that we choose the Roff value to be in Giga Ω.

3. The time constant of Phase-B is large as compared to Phase-D because the effective resistance at PIN_{10} (R_x) is of the order of thousands of Ohms while the resistance at PIN_9 (R) is only 150 Ohm.

4. The value of R remains constant throughout the analysis while R_x changes at every iteration of $L_T Spice$ that's why T_{22} remains constant .

5. As the values of T_{22} and T_{11} are of the order of nanoseconds therefore, a slight change in their values cause a significant impact at the output.

6. The Resistance of PIN_{10} is same for the case a and c therefore, T_{11} also remains the same.

7. We tuned the circuit after so many simulations in such a way that it shows minimum or no error that's why the % Non-Linearity is very less because the Measured R_x value is very close to the Real one.

8. Changing the value of R_{p9} also causes a change in measured Rx and hence, changes the residual value. The output span also changes and the ratio of residual and output span remains almost the same.

9. As the value of Resistance at PIN_9 (R) is 150 ohm so a slight change say 10 Ohms causes a large change in the calculations as compared to change in the value of resistance of PIN_{10} because it has R_x connected in series which is about 1000 to 10000 Ohms.

10. The values of resistance is increases when the value of R_{p9} decreases and hence slope also increases.

11. When we increase the value of R_{p9} keeping R_{p10} constant the value of T_{22} increases but T_{11} remains the same and as T_{22} is inversely related to R_x we see a decrease in the measured resistance value.

12. Comparator and Multivibrator uses Opamp which has its own Non-Idealities like slew rate, input resistance, output resistance, Offset Voltage, bias currents and many more that causes some shift in the measured values as compared to expected values. We can overcome the problem by choosing the right Opamp which meets the specifications of our application.

3.5 Result

We simulated the single element resistive sensor using Microcontroller approach using $L_T Spice$ the questions asked in the lab assignment are answer in the **Subsection- Lab Exercise**. The values and simulation results obtained in the simulation are clearly mentioned in the above Tables and plots of linear regression are also present. All the methods, approach and logic used in evaluating, simulating and calculating the final answer is mentioned in the **Subsection-Simulating Microcontroller using** $L_T Spice$.