ECE 167 Sensing and Sensor Technologies

Lab #1: Flex, Piezo, and Analog Filters

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I. Overview

This lab served as an introduction to resistive sensors. It focused on the flex sensor and the piezoelectric sensor. The flex sensor measures resistance changes based on bending, while the piezoelectric sensor generates voltages upon deflection or vibration. The goal was to create a musical instrument using both sensors, one to select the frequency and the other as a trigger to play the tone. Additionally, the lab also aimed to experimentally validate simple analog filtering techniques like a high-pass filter, a low-pass filter, and a bandpass filter.

Parts Used:

- Speaker: COM-11089
- Audio Amplifier: TPA2005D1 Mono Audio Amp Breakout
- Nucleo-64 + IO shield
- Flex Sensor and Mount
- Piezo Vibration Sensor
- Breadboard
- Resistors: 1MΩ, 47kΩ, 6.8 kΩ
- Capacitors: 100 pF, 47 nF, 22 µF

II. Wiring and Diagrams

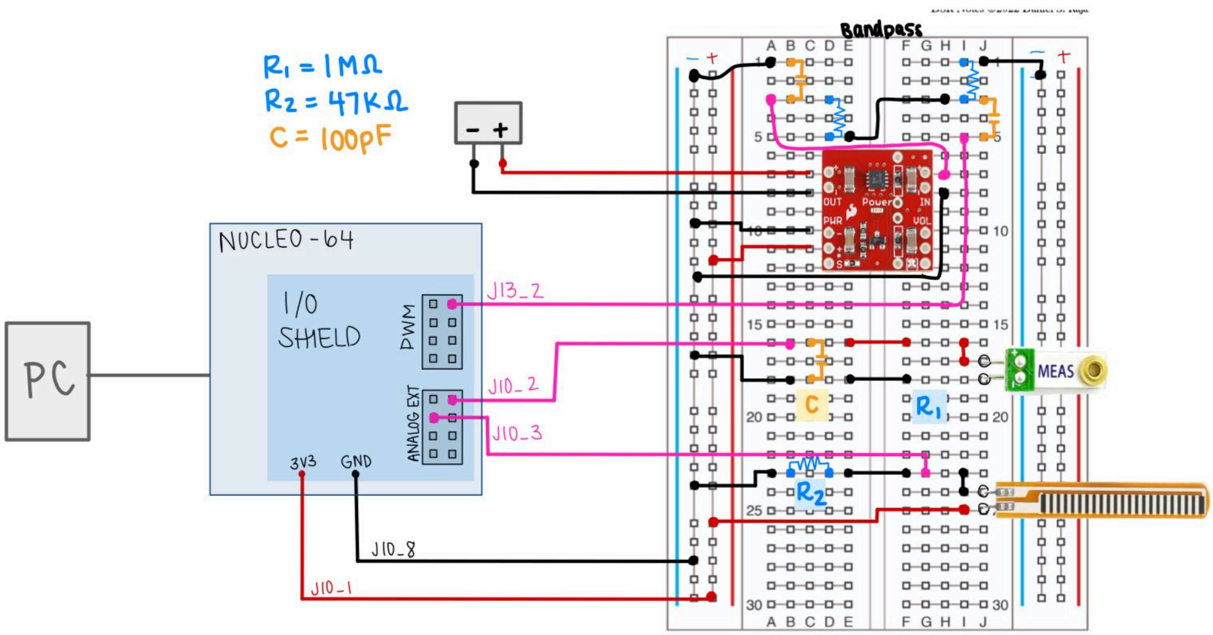


Figure 1. Breadboard circuit

III. Project Design

Part 1: Flex

1.2 Flex Sensor Regression Model

A regression model was created by mapping the bend angle in the flex sensor to the resulting output mapped into resistance. Multiple data points were collected and analyzed using spreadsheet software that generated the second degree polynomial regression trendline, Eq. 1 and the trendline in Fig. 2.

$$y = -\ 2 * 10^{-08}x^{2} + 0.0035x - 42.53 \qquad (1)$$

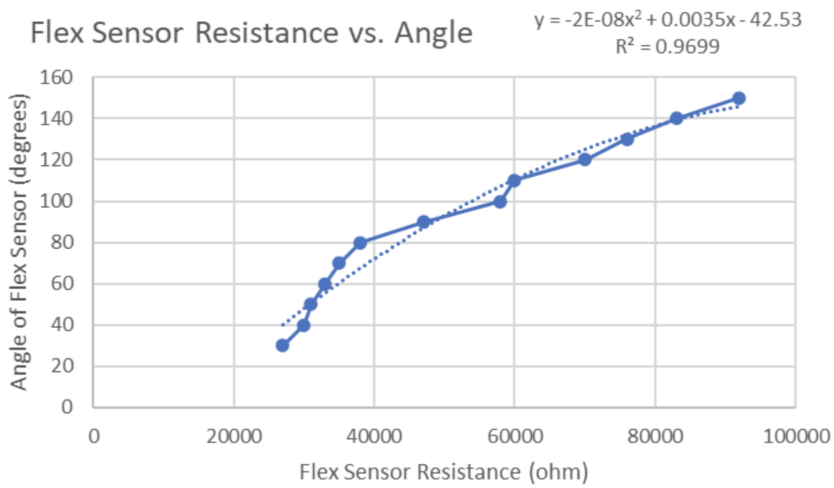


Figure 2. Flex Sensor Resistance vs. Angle

1.3 Speaker Based on Flex

The values measured from the ADC for the flex sensor ranged from 1000 to 2700. They are withing the range for the frequency input of the PMW.h funtion `PWM_SetFrequency(frequency)` so they can be used directly as the value for the frequency. To improve upon that, I first mapped the ADC output values to the resistance of the flex sensor. This was done by taking the ADC output and making it into a percentage of the total possible reading and then scaling that to a value within the range of the flex resistance. This was done using the mapping in Fig. 3.

```
int R_offset = ((Flex_reading - MIN_ADC) / ADC_RANGE) * R_RANGE;
int ADC_to_R = MIN_R + R_offset; // values of MIN_R to MAX_R
```

Figure 3. Mapping ADC output values to resistance range

The next mapping was the resistance to the range of the angle of the flex sensor (Fig. 4). This was done by passing the resistance values through the linear regresion Eq. (1). The angle output was used as an offset to the minimum possible angle.

```
ANG_offset = ((-2E-08 * pow(ADC_to_R, 2)) + (0.0035 * ADC_to_R) - 42.53);
R_to_ANG = ANG_offset - MIN_ANG;
```

Figure 4. Mapping resistance to angle range

The last mapping was to the frequency to be set on the speaker. This mapping, Fig. 5, was done with the same algorithm as the first mapping.

```
FREQ_offset = (R_to_ANG - MIN_ANG / ANG_RANGE) * FREQ_RANGE;
ANG_to_FREQ = MIN_FREQ + FREQ_offset;
```

Figure 5. Mapping angle range to desired frequency range

Part 2: Piezoelectric Sensor

2.1 Capture the taps (analog/digital)

The output voltage of the piezo sensor was larger than our microcontroller could handle so there needs to be snubbing. This was done with a 1MΩ resistor in parallel as shown. Since this did not meet the requirements of the input voltage I redesigned the circuit to have a capacitor in parallel. This would short-circuit high-frequency components, allowing them to pass through and reducing their amplitude across the resistor. As a result, the peak-to-peak voltage spikes observed on the oscilloscope were attenuated. Now the piezo could be connected to the STM32 without killing the input pin of the MCU.

Part 3: Musical Instrument Redux

Creating a musical instrument involved combining the previous measurements and mapping. The algorithm would continuously take a sample of the piezo sensor and then check if the reading was larger than the trigger value. The trigger value is high enough so that it would not consider lower disturbance values. It was chosen after observing the average reading of the piezo after a large disturbance.

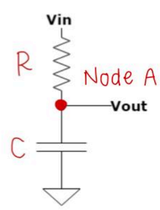
If the ADC read a value greater than the trigger value then a tone would be played. The frequency of the tone was selected based on the current reading of the flex sensor. The mapping of the ADC reading of the flex sensor to the frequency was used to get a frequency within a desired range. The tone would stop playing after reaching a "play time" duration. If while the tone was being played, there was another disturbance detected, the new selected tone would start playing, interrupting the current tone being played. This logic was done using a counter for keeping track of the time played that also checked for any large ADC readings which would mean a piezo disturbance.

The function in charge of keeping time being played would exit and return the status of the tone. If it returned TRUE, then the tone was played successfully without interruptions, else it returned FALSE which would indicate a disruption. Once the boolean value was detected, if there was a disruption a new frequency would be set based on the flex sensor and the tone playing counter would restart until it reached the "play time" duration. Once the duration was reached the duty cycle was set to 0 to turn off the signal.

Part 4: Simple Analog Filter Analysis

Initially, I picked a general value of 100-600 for the frequency value. This value was further defined based on the materials available in class. The final range was 150-500, and was not strict.

4.1 Low-Pass Filter



Nodal Analysis A

$$\frac{V_{out}-V_{in}}{R} + \frac{V_{out}-0}{Z_c} = 0$$

$$\frac{V_{out}}{R} - \frac{V_{in}}{R} + \frac{V_{out}}{Z_c} = 0$$

$$R\left[\frac{V_{out}}{R} + \frac{V_{out}}{Z_c}\right] = \frac{V_{in}}{R} \cdot R$$

$$V_{out} + \frac{RV_{out}}{Z_c} = V_{in}$$

$$V_{out}\left(1 + \frac{R}{Z_c}\right) = V_{in}$$

$$\frac{V_{out}}{V_{in}} = \left[\frac{1}{1+\frac{R}{Z_c}}\right] \cdot \frac{Z_c}{Z_c} = \frac{Z_c}{Z_c + R}$$

Figure 6. Nodal Analysis of Low-Pass Filter

Using complex impedances for the capacitor and KCL at Node A in Fig. 6 we obtain the transfer function for the low-pass filter to be Eq. 2.

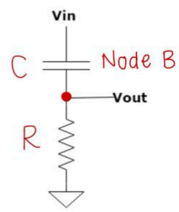
$$H(s) = \frac{V_{in}}{V_{out}} = \frac{Z_C}{R+Z_C} = \frac{\frac{1}{sC}}{R+\frac{1}{sC}} = \frac{1}{RsC+1} \qquad (2)$$

To design the low-pass filter with a desired corner frequency of 600, I used a 6.8 kΩ resistor and a 47 nF capacitor which would make the transfer function Eq. 3.

$$H(s) = \frac{1}{RsC+1} = \frac{1}{(6.8 \cdot 10^{3}\Omega)(47 \cdot 10^{-9}F) \cdot s} = \frac{1}{1+ 0.3196 \cdot 10^{-3}s} \qquad (3)$$

4.2 High-Pass Filter

Nodal Analysis B



$$\frac{V_{out}-V_{in}}{Z_c} + \frac{V_{out}-0}{R} = 0$$

$$\frac{V_{out}}{Z_c} - \frac{V_{in}}{Z_c} + \frac{V_{out}}{R} = 0$$

$$Z_c \cdot \left[\frac{V_{out}}{Z_c} + \frac{V_{out}}{R}\right] = \frac{V_{in}}{Z_c} \cdot Z_c$$

$$V_{out} + \frac{Z_c V_{out}}{R} = V_{in}$$

$$V_{out}\left(1 + \frac{Z_c}{R}\right) = V_{in}$$

$$\frac{V_{out}}{V_{in}} = \left[\frac{1}{1+\frac{Z_c}{R}}\right] \cdot \frac{R}{R} = \frac{R}{R+Z_c}$$

Figure 7. Nodal Analysis of High-Pass Filter

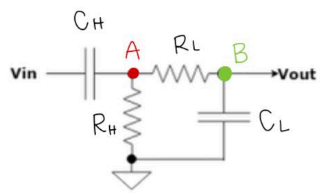
Using complex impedances for the capacitor and KCL at Node B in Fig. 7 we obtain the transfer function for the high-pass filter to be Eq. 4

$$H(s) = \frac{V_{in}}{V_{out}} = \frac{R}{R+Z_{C_1}} = \frac{R}{R+\frac{1}{sC}} = \frac{RsC}{1+RsC} \qquad (4)$$

To design the high-pass filter with a desired corner frequency of 100, I used a 47 Ω resistor and a 22 µF capacitor which would make the transfer function Eq. 5.

$$H(s) = \frac{RsC}{RsC+1} = \frac{(47\Omega)(22 \cdot 10^{-6}F) \cdot s}{(47\Omega)(22 \cdot 10^{-6}F) \cdot s + 1} = \frac{1.034 \cdot 10^{-3}s}{1+ 1.034 \cdot 10^{-3}s} \qquad (5)$$

4.3 Band-Pass Filter



@ NODE A

$$\frac{V_A - V_{in}}{Z_{CH}} + \frac{V_A - 0}{R_H} + \frac{V_A - V_{out}}{R_L} = 0$$

$$\frac{V_A}{Z_{CH}} - \frac{V_{in}}{Z_{CH}} + \frac{V_A}{R_H} + \frac{V_A}{R_L} - \frac{V_{out}}{R_L} = 0$$

$$\frac{V_A}{Z_{CH}} + \frac{V_A}{R_H} + \frac{V_A}{R_L} = \frac{V_{out}}{R_L} + \frac{V_{in}}{Z_{CH}}$$

$$V_A\left(\frac{1}{Z_{CH}} + \frac{1}{R_H} + \frac{1}{R_L}\right) = \frac{V_{out}}{R_L} + \frac{V_{in}}{Z_{CH}}$$

$$V_A = \left[\frac{\frac{V_{out}}{R_L} + \frac{V_{in}}{Z_{CH}}}{\frac{1}{Z_{CH}} + \frac{1}{R_H} + \frac{1}{R_L}}\right] \cdot \frac{R_L Z_{CH}}{R_L Z_{CH}}$$

$$V_A = \frac{V_{out} \cdot Z_{CH} + V_{in} R_L}{R_L + \frac{R_L Z_{CH}}{R_H} + Z_{CH}}$$

@ Node B

$$\frac{V_{out} - 0}{Z_{CL}} + \frac{V_{out} - V_A}{R_L} = 0$$

$$\frac{V_{out}}{Z_{CL}} + \frac{V_{out}}{R_L} - \frac{V_A}{R_L} = 0$$

$$V_{out}\left(\frac{1}{Z_{CL}} + \frac{1}{R_L}\right) = \frac{V_A}{R_L}$$

$$V_{out}\left(\frac{R_L}{Z_{CL}} + 1\right) = V_A$$

$$V_{out}\left(\frac{R_L}{Z_{CL}} + 1\right) = \frac{V_{out} \cdot Z_{CH} + V_{in} R_L}{R_L + \frac{R_L Z_{CH}}{R_H} + Z_{CH}}$$

$$\left(R_L + \frac{R_L Z_{CH}}{R_H} + Z_{CH}\right) V_{out}\left(\frac{R_L}{Z_{CL}} + 1\right) = V_{out} Z_{CH} + V_{in} R_L$$

$$\left(\frac{R_L^2}{Z_{CL}} + R_L + \frac{R_L^2 Z_{CH}}{R_H Z_{CL}} + \frac{R_L Z_{CH}}{R_H} + \frac{Z_{CH} R_L}{Z_{CL}} + Z_{CH}\right) V_{out} = V_{out} Z_{CH} + V_{in} R_L$$

$$\frac{V_{out}}{V_{in}} = \frac{R_L}{\left(\frac{R_L^2}{Z_{CL}} + R_L + \frac{R_L^2 Z_{CH}}{R_H Z_{CL}} + \frac{R_L Z_{CH}}{R_H} + \frac{Z_{CH} R_L}{Z_{CL}} + Z_{CH}\right) - Z_{CH}}$$

Figure 7. Nodal analysis for Band-Pass Filter

IV. Testing and Results

Part 1: Flex

1.2 Flex Sensor Regression Model

This will involve creating a list of input and corresponding outputs, and using a regression to find the relation between the two. The result is Eq. 1.

1.3 Speaker Based on Flex

To make testing easier, the algorithm that performs the mapping exists as a function outside the main call. It is controlled by macros that can be redefined as shown in Fig. 8. This made fine tuning the smoothness and frequency range easier.

```
// MAPPING CONTROLS
// Change values for various ranges
#define MAX_ADC 2700.0
#define MIN_ADC 1000.0
#define ADC_RANGE (MAX_ADC - MIN_ADC)

#define MAX_R 92000.0
#define MIN_R 27000.0
#define R_RANGE (MAX_R - MIN_R)

#define MAX_ANG 150.0
#define MIN_ANG 10.0
#define ANG_RANGE (MAX_ANG - MIN_ANG)

#define MAX_FREQ 600.0
#define MIN_FREQ 100.0
#define FREQ_RANGE (MAX_FREQ - MIN_FREQ)
```

Figure 8. Macros to control mapping

Part 2: Piezoelectric Sensor

2.1 Capture the taps (analog/digital)

First I measured the peak-to-peak voltage spikes of the piezo vibration sensor using an oscilloscope as seen in Table 1 along with the minimum, maximum and average voltage spikes.

Peak to Peak (V)	Results

1.55	Minimum spike: 1.03V Maximum spike 46 V Average spike: 19.4 V
1.03	
1.15	
1.11	
13.1	
14.5	
15.7	
16.1	
18.1	
42	
46	
45	
44	
12.5	

Table 1. Peak-to-Peak measurements of piezo

From the STM32 reference manual the maximum external input voltage can be 3.6 V. A disturbance to the piezo vibration sensor causes an average voltage spike of about 20 V while its minimum was 1V and its maximum was around 50V. These values surpassed the maximum input voltage allowed by the STM32. To improve this a resistor and capacitor in parallel with each other and the sensor were added to snub the high voltage.

Now that the voltage was snubbed, the average voltage spike would always be lower than the maximum external input voltage. The snubbed piezo would read lower peak-to-peak voltage samples as seen in Table 2, where the average is 2.25 V

Peak to Peak	Results
2.13	Minimum spike: 2.01V Maximum spike: 2.56 V Average spike: 2.25 V
2.01	
2.21	
2.29	
2.56	
2.29	
2.25	

Table 2. Peak-to-Peak measurements of piezo after snub

Part 3: Musical Instrument Redux

The implementation of the musical instrument was tested by printing the values of the sensors to determine how sensitive to make the trigger values that would activate the tone. Print statements were the main source of information analysis I implemented.

Part 4: Simple Analog Filter Analysis

4.1 Low-Pass Filter

For the low-pass filter transfer function Eq. 3, the theoretical magnitude vs. frequency curve is in Fig. 9.

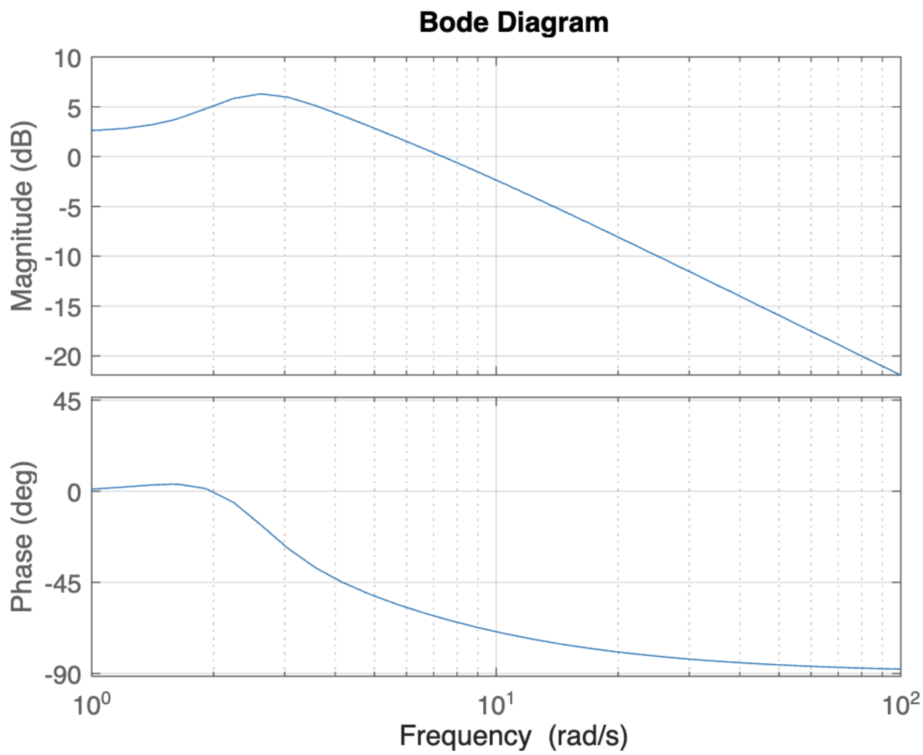


Figure 9. Magnitude and Phase vs Frequency of Eq. 3

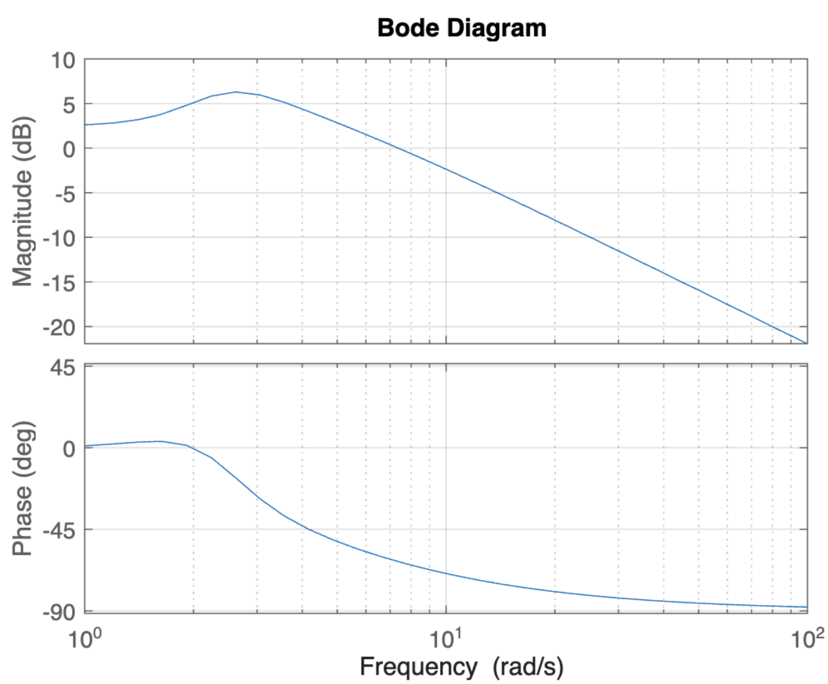


Figure 10. Magnitude and Phase vs Frequency of Eq. 5

4.2 High-Pass Filter

For the High-Pass filter transfer function Eq. 5, the theoretical magnitude vs. frequency curve is in Fig. 10.

V. Conclusion

In conclusion, this lab assignment provided a comprehensive introduction to resistive sensors, focusing on flex and piezoelectric sensors. The primary goal was to design a musical instrument where the flex sensor controlled the instrument's frequency, and tapping on the piezo played a note. By mapping the bend angle to the resulting output, I successfully generated a second-degree polynomial regression trendline using spreadsheet software. This model allowed me to understand and predict the sensor's behavior as it underwent different levels of flex. The integration of the piezoelectric sensor required capturing voltage spikes using an oscilloscope.

The final portion of the lab involved the flex and piezo sensors. Selecting tones based on the flex sensor and activating tones with a tap on the piezo sensor added a dynamic and interactive element to the instrument.

The exploration of simple analog filtering through low-pass, high-pass, and band-pass filters contributed to a deeper understanding of signal processing. The theoretical analysis and experimental validation provided valuable insights into the practical aspects of implementing filtering in electronic circuits.