EE 616 Course Project

Clap Detector for Toy and Appliance Control

Submitted By

Prasad Trimukhe	(203076001)	<203076001@iitb.ac.in>
Lohit Penubaku	(204076009)	<204076009@iitb.ac.in>
Sagar Zoting	(203070064)	<203070064@iitb.ac.in>

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Under the guidance of

Prof. P.C. Pandey

Department of Electrical Engineering
Indian Institute of Technology, Bombay

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Contents

Abstract

The project aims to control toy and electrical appliances using the clap signal. There are different ways to detect the clap signal. In this project, clap is detected using discrete components against any other sound. Decay time and the peak of a clap signal are used to distinguish it from different similar sounds. The output of the microphone is amplified and then rectified. Envelopes of claps have a definite decay period. The time required for claps' value to decay from 60% to 10% of peak value is noted. If this recorded time is within the predefined interval, the clap is detected. When one clap is detected, the circuit is activated. If there are two successive claps detected, then the appliance is turned on. If there is one successive clap detected, then the appliance is turned off.

Introduction

The objective is to design a circuit for detecting clap from an analog signal captured by the microphone. This circuit is used to control toys and electrical appliances. All implemented circuits are discussed, along with their circuit diagrams. The results after the various phases are recorded by simulating on PSpice. A literature review was done to design the circuit.

The basic principle of an electret microphone is that changing the distance between the two plates of the capacitor changes the voltage across it while keeping the charge constant. Most electret microphones have an internal JFET which buffers the microphone capacitor. The voltage signal produced by sound modulates the gate voltage of the JFET, causing a change in the current flowing between the drain and source of the JFET (IMIC).

Clap-based appliance control requires an amplifier, rectifier, envelope, and peak detector implemented using the OPAMP device. The decay feature of the clap is extracted at the window comparator, which controls the control code generator circuitry.

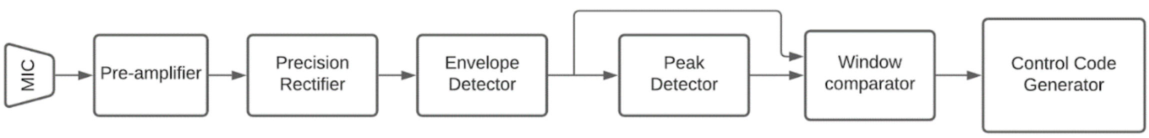

Figure 1: Block Diagram

The implementation of the project is broken down into three major stages, the pre-amplifier stage, the clap detection stage, and the control code stage.

Investigation

1. Clap Response

Based on a literature survey, the frequency of clap is between 750 Hz to 2.5 kHz, and in some cases between 4 kHz – 8 kHz. Clap audio recorded using three smartphones at a sampling rate of 44.1 kHz. Non-clap audio was observed and compared with a clap to understand the distinguishing features of clap audio. Rise time, fall time determined by MATLAB programming. The frequency range is determined by plotting FFT in the python platform. The recorded audio is made available on this link Audio Signals.

Table 1: Clap Response of Three Users

User	Clap Number	Rise Time (ms)	Fall Time (ms)	Frequency range (kHz)
User 1	1	4.85	74.27	1 to 2
	2	5.51	79.36	1 to 2
	3	5.11	76.54	0.75 to 1.5
User 2	1	2.25	59.94	0.75 to 1.25
	2	5.36	37.01	0.75 to 1.25
	3	1.08	58.36	0.75 to 1.4
User 3	1	2.25	66.08	0.9 to 1.3
	2	5.53	37.38	0.5 to 1.5
	3	1.08	67.63	0.9 to 1.3

Table 2: Different Audio profiles and Their Responses

Noise	Rise Time (ms)	Fall Time (ms)	Frequency (kHz)
Door knock	14.57	35.36	0.25 to 0.5
Steel Glass 1	5.94	131.85	4.25 to 4.75
Steel Glass 2	2.28	131.85	4.25 to 5
Butter Paper Crushing	59.75	44.71	3 to 4

2. Pre-amplifier

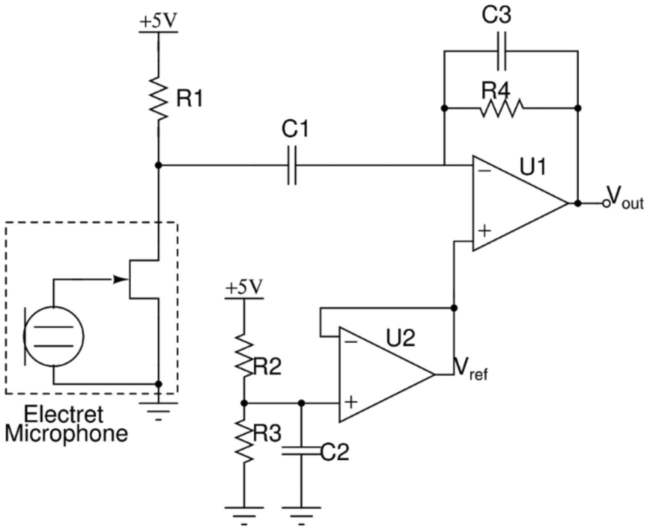

Figure 2: Microphone with Pre-amplifier Circuit

A basic schematic of the pre-amplifier is shown in the following figure. Microphone (I_{MIC}) has a dc component (I_{dc}) necessary to bias the internal JFET and an ac component (I_{ac}) caused by sound waves. [1] POM-3535P-R microphone selected for the design.

Microphone sensitivity is given as a dB value relative to 1V, measured at 94 dB SPL (1 Pascal). Therefore, the sensitivity of the microphone in volts per Pascal of air pressure is:

$$10^{\left(\frac{-35\ dB}{20}\right)} = 17.78\frac{mV}{Pa} \qquad \ldots(1)$$

As the pre-amplifier used in the reference is trans-impedance, the microphone's sensitivity converted to current per pascal of air pressure. [1] The impedance of the microphone is $2.2\ k\Omega$. Therefore, current per pascal of air pressure is:

$$\frac{\left(17.78\frac{mV}{Pa}\right)}{2.2\ k\Omega} = 8.083\frac{\mu A}{Pa} \qquad \ldots(2)$$

The gain calculation depends on the maximum sound pressure level expected. In this design $100\ dB$ SPL is expected, which is a map to typical audio levels (1.228Vrms). $100\ dB$ SPL is in air pressure of $2\ Pa$, giving output current:

$$8.083\frac{\mu A}{Pa} \times 2\ Pa = 16.166\ \mu A \qquad \ldots(3)$$

Gain (R_4) for transimpedance amplifier is: $V_{out} = I_{ac} \times R_4 \rightarrow R_4 = 75\ k\Omega$ ... (4)

The feedback capacitor C_3 compensates for parasitic capacitance at the op-amp inverting input which can cause instability. Capacitor C_3 also forms a pole with a resistor R_4 in the response of the pre-amplifier. The frequency of this pole must be high enough not to affect the microphone transfer function within the audible bandwidth. For this design, a response deviation of $-0.1\ dB$ at $10\ kHz$ is acceptable. The location of the pole can be calculated using the relative gain at $10kHz$:

$$f_p = \frac{f}{\sqrt{\left(\frac{g_0}{g_f}\right)^2 - 1}} = \frac{10\ kHz}{\sqrt{\left(\frac{1}{0.989}\right)^2 - 1}} = 66.862\ kHz \qquad \ldots(5)$$

Where g_0 and g_f are the gains at low frequency and gain at frequency "f" in this case $f = 10\ KHz$. 0.989 ($-0.1\ dB$) for g_f. It gives pole frequency at $66.862\ kHz$. The feedback capacitor calculated as:

$$C_3 = \frac{1}{2 \times \pi \times f_p \times R_4} = 30\ pF \qquad \dots (6)$$

The standard value is $33\ pF \pm 10\%$

The resistor R_1 biases the internal JFET of the microphone. [1] Microphone operating voltage (V_{MIC}) is $2\ V$, and Current consumption is (I_S) 0.5 mA. Therefore, the value of a resistor

$$R_1 = \frac{V_{cc} - V_{MIC}}{I_S} = 6\ k\Omega \qquad \dots (7)$$

The standard value is $6.2\ k\Omega \pm 5\%$

A large value of R1 is required because of two reasons

1. Noise gain of the op-amp → $A_N = 1 + \frac{R_4}{R_1}$
2. C_1 is large enough that its impedance is much less than a resistor R_1 at audio frequency.

Resistor R_1 and capacitor C_1 form a high-pass filter. The corner frequency of this filter must be low enough not to attenuate low-frequency sound waves. A $5\ Hz$ corner frequency is used to calculate the value of C_3:

$$C_1 = \frac{1}{2 \times \pi \times 5\ Hz \times R_1} = 5.3\ \mu F \qquad \dots (8)$$

The standard value is $5.6\ \mu F \pm 10\%$

LM324 is used to implement the pre-amplifier. [4] LM324 has an output swing from $0\ V$ to $V_{CC} - 1.5\ V$. In this case, $V_{CC} = 5\ V$ therefore, voltage swing is 0 V to 3.5 V. Therefore, to set the swing with minimum distortion, DC level is set to $2\ V$. R_2 and R_3 are selected such that the virtual ground shifted to $2\ V$. Capacitor C_2 is included to filter thermal noise created by the resistors and any noise present on the power supply. C_2 is selected such that corner frequency is less than the audible frequency range.

$$f_c = \frac{1}{2 \times \pi \times (R_2 \parallel R_3) \times C_2} \qquad \dots (9)$$

$$\therefore\ R_2 = 10\ k\Omega\ ; R_3 = 6.8\ k\Omega\ ; C_2 = 10\ \mu F$$

The above circuit is simulated in TINA TI. An electret microphone is replaced with the below model.

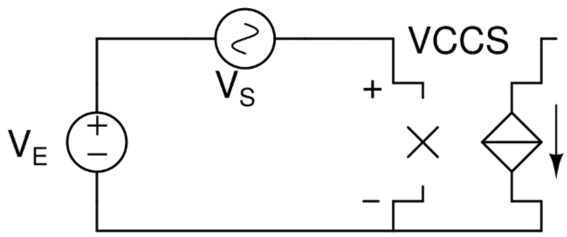

Figure 3: Equivalent Model of Microphone for Simulation

The model uses a voltage-controlled current source (VCCS) that mimics the internal JFET of the microphone. A voltage generator V_s is used to represent sound pressure level (SPL) in pascals ($1\ V = 1\ Pa$), and the DC voltage source produces bias current through VCCS. To determine the dc source voltage V_E using standard current consumption of microphone.

$$V_E = \frac{I_S}{\frac{8.083\ \mu A}{V}} = \frac{0.5\ mA}{8.083\ \mu A/V} = 61.858\ V \quad \ldots (10)$$

V_S is set to 1 V_{rms} and 1 kHz frequency. sinusoid in order to simulate an input signal of 94dB SPL to the microphone.

Table 3: Preamplifier Components

Resistor (Ω)		Tolerance
R1	6.2 k	5%
R2	10 k	5%
R3	6.8 k	5%
R4	75 k	5%

Capacitor (F)		Tolerance
C1	5.6 μ	10%
C2	10 μ	10%
C3	33 p	10%

3. Full-Wave Precision Rectifier

Based on the observation made during waveform analysis, the clap signal had both positive and negative peaks, and, in a few cases, the negative peak was more dominant. Therefore, a single-supply full-wave rectifier (FWR) is implemented. The virtual ground of the design shifted to 2 V. We use a Precision full-wave rectifier to overcome the diode drop of $0.6 - 0.7\ V$ in a regular rectifier circuit.

CASE 1: $V_{in} > 0$: D_1 is forward biased, and D_2 is reverse biased. Since no current flows through resistors R_1 and R_3 connected between a negative input terminal of U_1 and a Positive input terminal of U_2, both these points are equipotential.

$$V_{out} = V_{in} + V_{ref} \quad \ldots (11)$$

CASE 2: Vin < 0: The output voltage of A1 swings to positive, making diode D1 reverse biased and diode D2 forward biased.

$$V_{out} = -V_{in} + V_{ref} \quad \ldots (12)$$

Input to the Precision full-wave rectifier is an amplified audio signal. We bypass the pre-amplifier stage for simulation, so audio is recorded via phone mic given to the rectifier circuit. (As the phone has an inbuilt pre-amplifier stage)

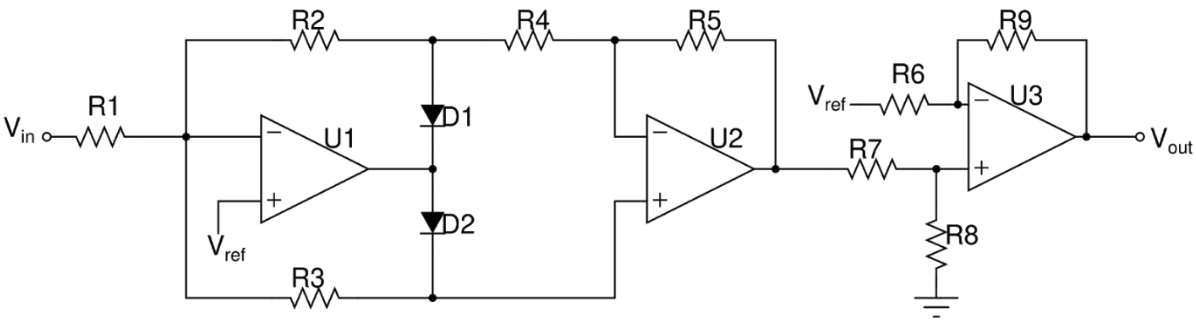

Figure 4: Full-Wave Precision Rectifier Circuit

Table 4: Components of Full Wave rectifier

Resistor (Ω)		Tolerance
R1, R2, R3, R4,	10 k	5%
D1, D2	1N4148	-

Resistor (Ω)		Tolerance
R5, R7, R8	10 k	5%
R6, R9	20 k	5%

4. Envelope and Peak Detector

The unique feature of clap is its decay time which is captured using an envelope detector. An envelope detector is a precision peak detector with a decay time larger than the period of individual cycles but short enough to respond to envelope decay. The duration of the envelope is usually between $120 - 150\ ms$ for clap signal. According to envelope detection in AM demodulation RC time constant must follow the below expression:

$$\frac{1}{Fc} \ll RC \ll \frac{1}{Fm} \qquad \ldots(13)$$

In our case, F_c is the sampling frequency used to sample the clap audio in audacity/MATLAB software which is $44.1\ kHz$, and F_m is the clap signal frequency which is in the range of $1\ kHz$ to $2.5\ kHz$.

If we consider $F_m = 2\ kHz$, then $\frac{1}{F_m} = 500\mu s$, $so\ RC \ll 500\ \mu s$, we do not get a proper envelope to use in the next stage. So, we increase the RC Time constant ($RC = 36\ ms$) so that the envelope follows all the lower peaks. The peak of the clap is detected by a precision peak detector with a relatively large decay time so that the peak is retained for the clap interval. The RC time constant of the peak detector is $1.5\ sec$. The single-supply precision Envelope and Peak detector are implemented as follows.

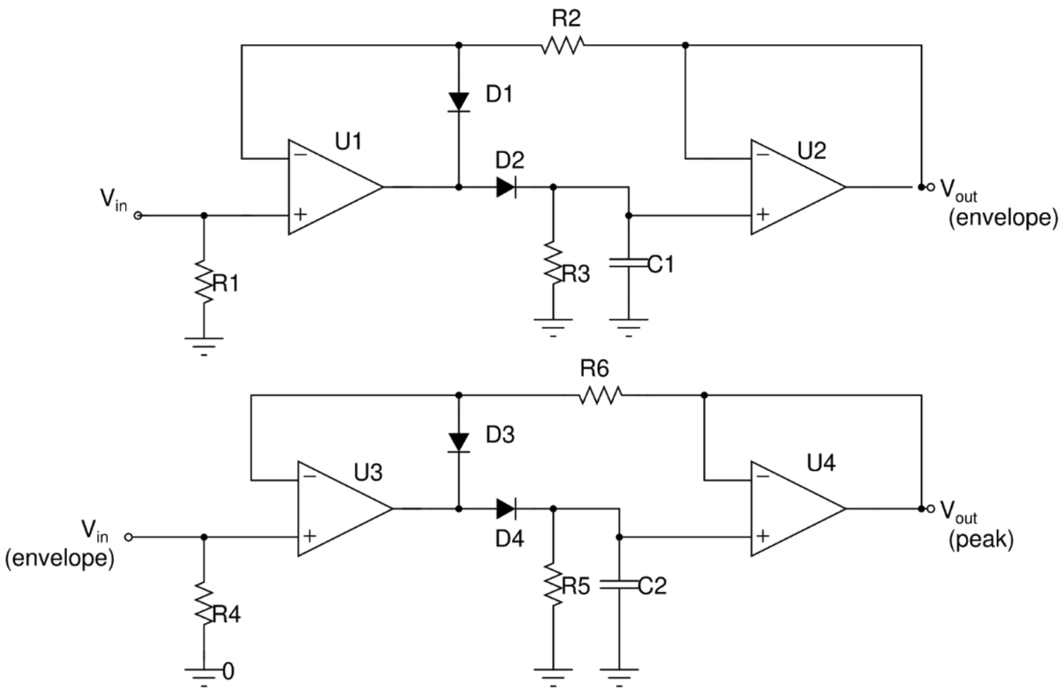

Figure 5: Envelope and Peak Detector Circuit

Table 5: Components of Envelope and Peak detector circuit

Resistor(Ω)		**Tolerance**	**Capacitors(F)**		**Tolerance**
R1, R2 R4, R6	10 k	5%	C1	1 μ	10%
R3	36 k	5%	C2	1.5 μ	10%
R5	1 M	5%			

5. Window Comparator

Decay period from 60% to 10% of detected peak signal value is measured, which signifies the window to confirm the available input is clap signal. Two different window comparators are used with two thresholds (10% and 60 % of peak). The output of the comparator is fed to the XOR gate, which gives pulse for the duration of decay in consideration. The pulse duration for the clap signal is between $62 - 68\ ms$.

To design the window comparator, we have used LM324 OPAMP and DM7486 for the XOR gate. DM7486 has the High-Level Input Voltage (VIH) of $2\ V$ minimum. Thus, the limited output swing of LM324 will not cause any error for logic High.

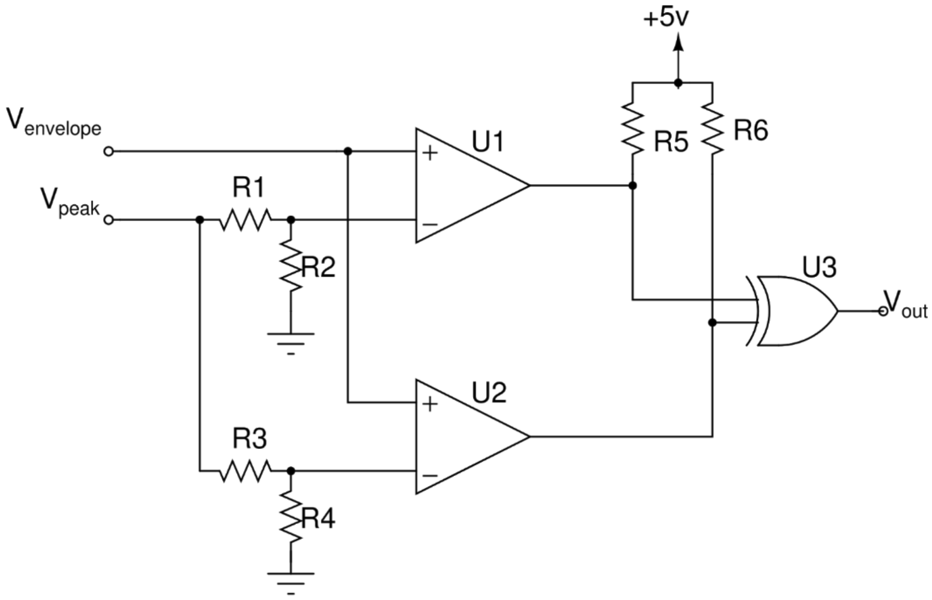

Figure 6: Window Comparator Circuit

Table 6: Components of Window Comparator

Resistor(Ω)		Tolerance
R1	4.3 k	5%
R2	6.2 k	5%
R3	9.1 k	5%
R4	1 k	5%
R5, R6	10 k	5%

6. Clap Detection and Control code Generation

The output of the window comparator is the pulse of a duration of $62 - 68\,ms$. This duration is sufficient to confirm to be a clap. Any audio signal having a different duration should be rejected. A decade counter (CD4017) has been used to achieve this, which operates at $\sim 100\,Hz$ at $\sim 52\%$ duty cycle. The clock of $\sim 100\,Hz$ is generated using NE555 operating in astable multivibrator mode. The output from the window comparator is given as enable to the decade counter CLKINHIBIT pin. The state at the O7 pin of the decade counter is recorded into the DF/F when the pulse goes low. The same holds O7 state until a reset is given on the RST pin, triggered by another NE555 after $100\,ms$ which is also triggered at the same time as CLKINHIBIT. If the state at pin O7 is "High," then we say that we have a clap, or else it is considered as noise. On successful detection of the first clap, the circuit will activate the detection of the ON/OFF state of the appliance. To not keep the activation active for a long duration, with the help of NE555 in the monostable mode, we generate a high pulse for 1 second, and the circuit waits for 1 second for either two consecutive claps or a single clap. If the activation duration 2 claps are detected, then the appliance in consideration turns "OFF" and if one clap is detected, then the appliance in consideration turns "ON". The counting of the claps is implemented using a BCD counter. Both the first clap detected and the activation signal are given to an AND gate, and the output of the AND gate is used as a clock for the BCD counter. Thus, the BCD counter will count the total number of claps. If the BCD counter counts two claps, then we generate a control code "0" (i.e., LOW), and if BCD Counter counts three claps, then we generate a control code "1" (i.e., High). The control code will not change for any other outcome, and the appliance's state is unchanged. The state of the BCD counter is checked only after the activation period is complete.

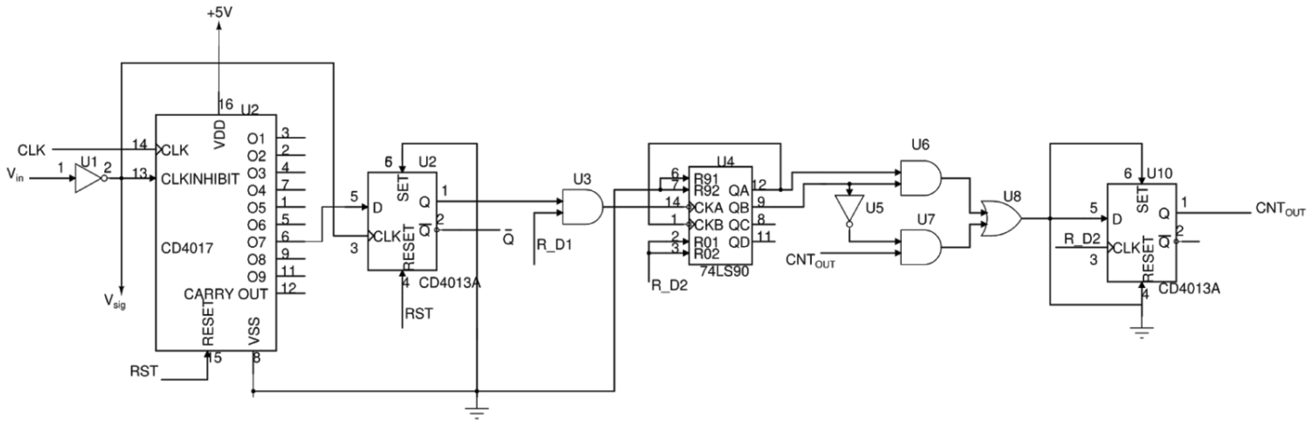

Figure 7: Clap Detection and Code Generation Circuit

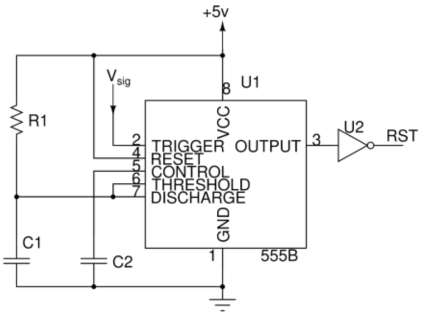

Figure 8: Reset Circuit

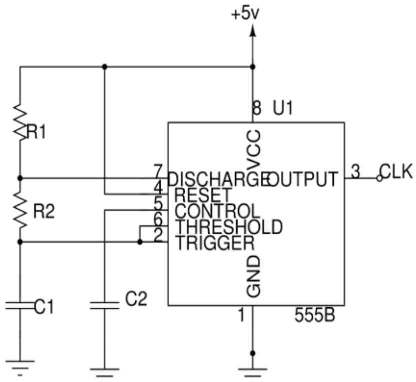

Figure 9: Clock Generator

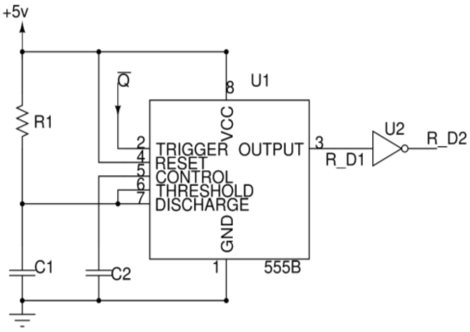

Figure 10: Activation Period

Table 7: Components of IC555 Circuits

Resistor(Ω) & Capacitor(F)		**Tolerance**
R1	91 k	5%
C1	1 μ	10%
C2	0.01 μ	10%

Resistor(Ω) Capacitor(F)		**Tolerance**
R1	680	5%
R2	6.8 k	5%
C1	1 μ	10%
C2	0.01 μ	10%

Resistor(Ω) Capacitor(F)		**Tolerance**
R1	4.3 k	5%
C1	10 μ	10%
C2	0.01 μ	10%

Control Code Equation: $CNT_{OUT} = Q_B \times Q_A + \overline{Q_B} \times CNT_{OUT}$ ... (14)

Testing Method

The complete circuit was tested on a simulator (in our case PSpice). All the stages involved in the implementation were tested separately and then integrated for final testing. At each stage, the simulation took time, which hindered our testing process

The input coming through an electret microphone, the input current outputted by the mic is very low. This signal was amplified by the circuit design. Since the audio signal can have negative peaks, we had to rectify the amplified audio signal. When we were confident with all the critical features of the audio signal in our FWR output, we went on with ways to find out the peak and envelope of the audio signal. Initially, we implemented a simple RC envelope/peak detector, but the output was favorable most of the time. We then implemented a precision envelope/peak detector, which gave us accurate results most of the time.

Having detected the peak and envelope, we had to implement a window comparator to detect a window directly related to the clap decay time (60% - 10%). This was tweaked to precisely differentiate clap with other similar sounds in the background also captured by the electret mic. Once we could detect clap, the next part was to generate a control code to control appliances. For this, we implemented a digital circuit.

Test Results

A. Preamplifier Test Output

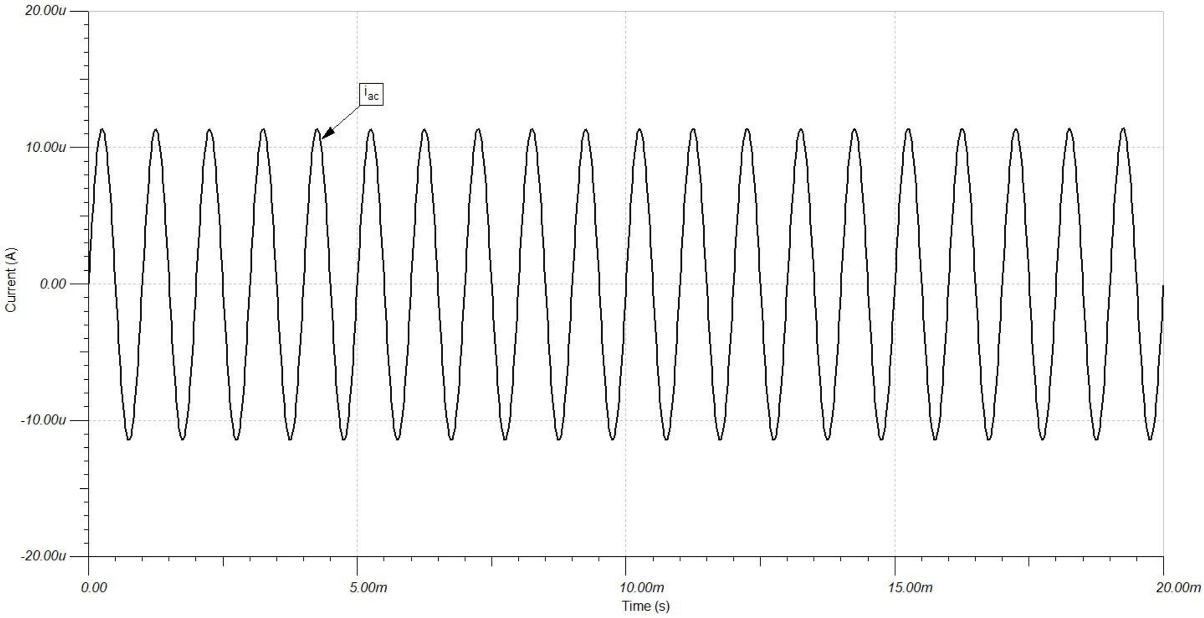

Figure 11: Preamplifier Input

The input of the pre-amplifier is plotted. The equivalent model of the microphone is modeled in the TINA TI [1]. The I_{ac} $r$epresents the ac component of the voltage-controlled current source.

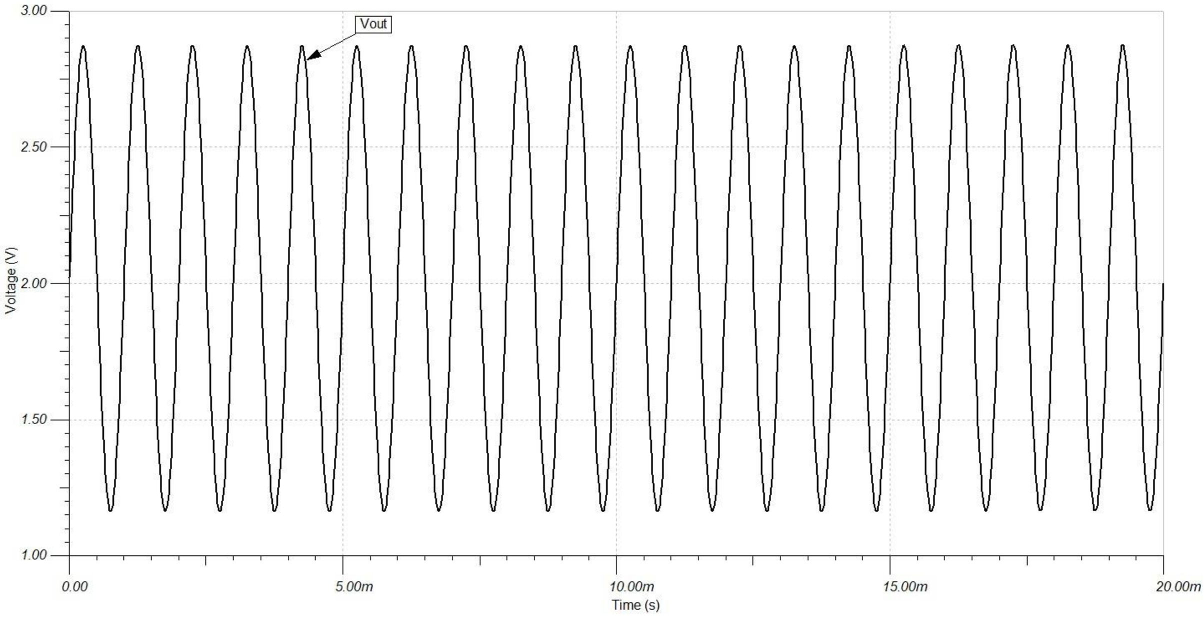

Figure 12: Pre-amplifier Output

The above signal is the output of the single supply op amp-based transimpedance amplifier. Input to the amplifier is a current from the microphone equivalent circuit. The gain depends on the feedback resistance between the output and inverting terminal of OPAMP. 2 V reference voltage at a non-inverting terminal connected to shift the virtual ground for single-supply op-amp application.

B. Full-Wave Precision Rectifier Test Output

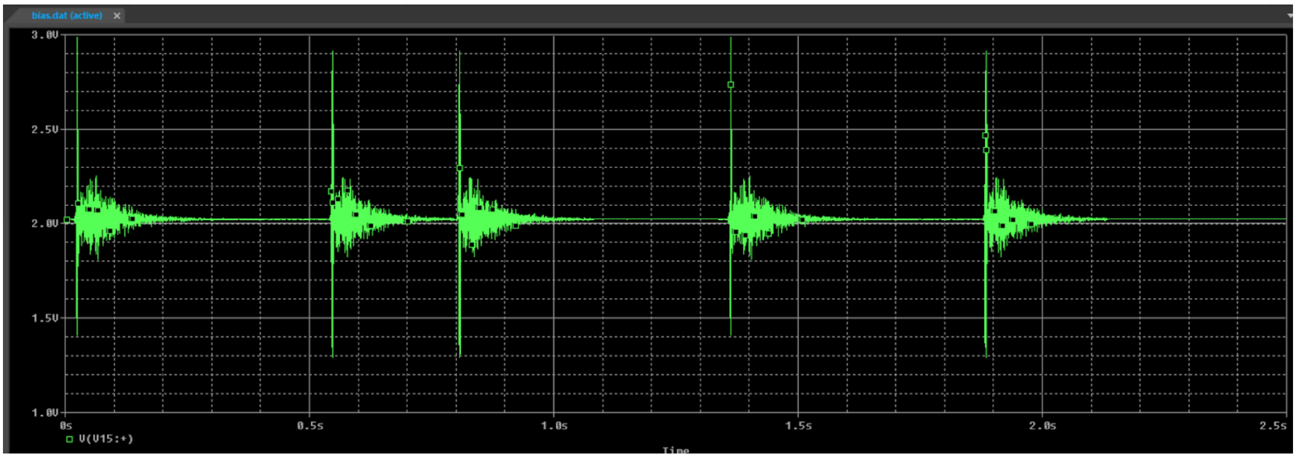

Figure 13:Phone Recorded Input Signal (Clap)

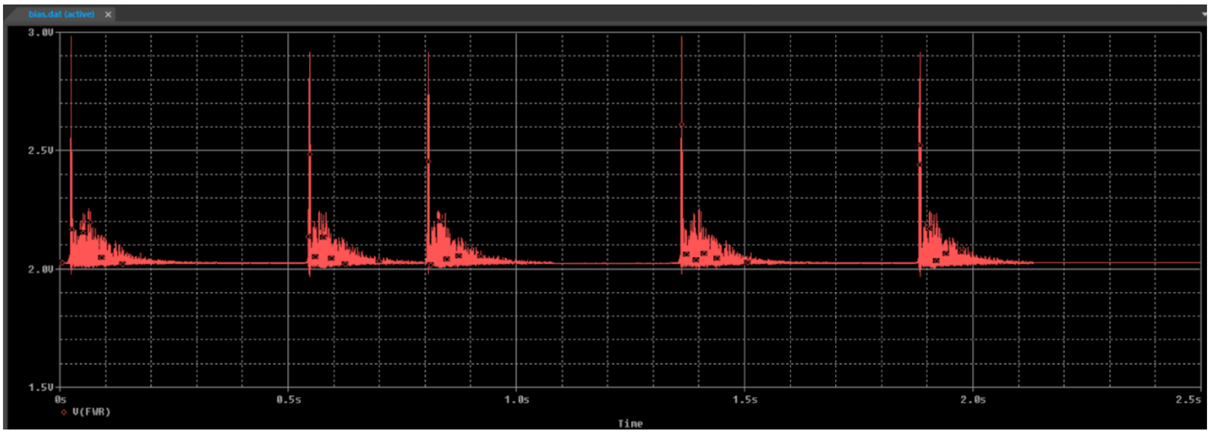

Figure 14: Rectified Output (DC shifted)

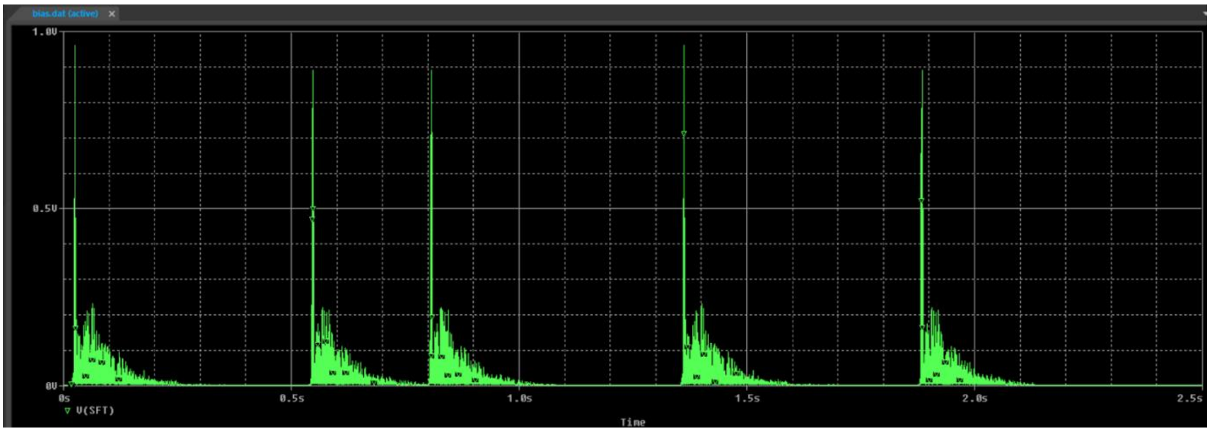

Figure 15: Rectified Output

Figure 13 shows the clap signal having a DC offset of 2 V. This is the output of the pre-amplifier circuit (for simulation, we have used phone recorded signal and converted it to .csv file with its amplitude and time. PWL technique is used to input this CSV file in P-Spice). Figure 14 is the rectified output of the Full-wave precision rectifier. As we have to input this rectified output to the envelope detector, we need to remove the DC offset, we tried to remove the DC component using a coupling capacitor, but the capacitive coupling of the rectified wave causes a DC offset of its own since the cap output go to the average value of the rectified signal. Thus, we used a subtractor to remove the DC offset. Figure 15 shows the output of the subtractor.

C. Envelope and Peak Detector Test Output

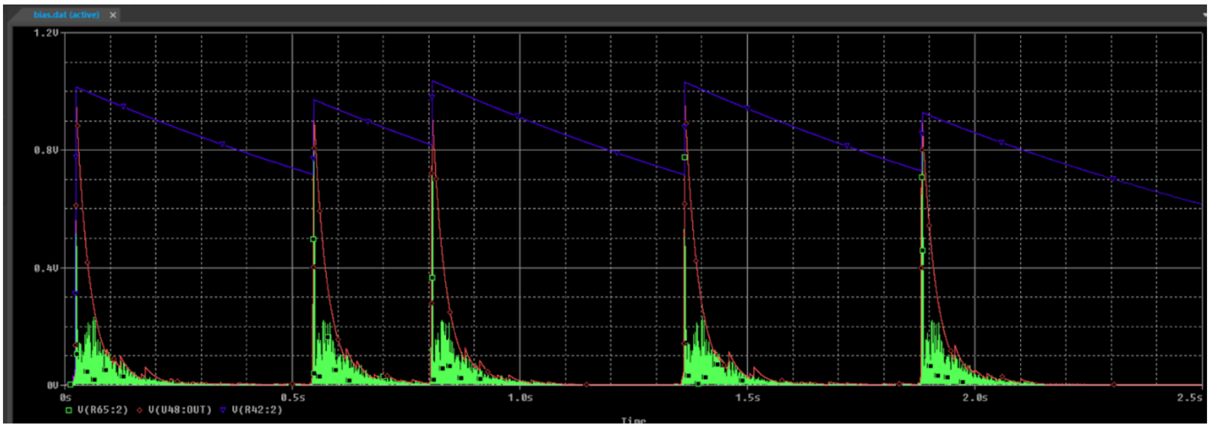

Figure 16: Envelope and Peak Detected

In Figure 16, the green waveform is the output of the subtractor fed as input to the envelope detector, the red waveform is the envelope of the input signal (clap), and the blue waveform is the output of the peak detector. This envelope and peak are used in further circuits (Window comparator) to determine the decay time.

D. Window Comparator Test Output

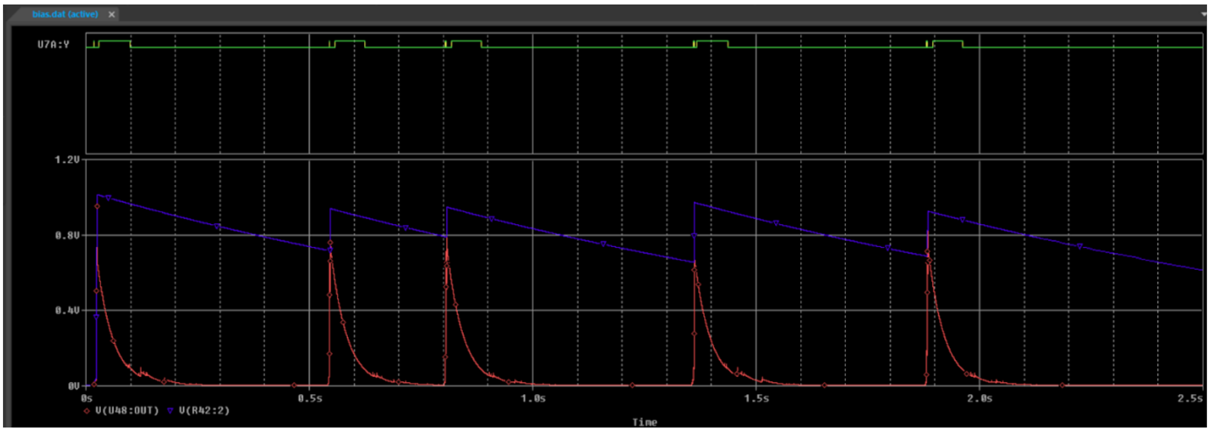

Figure 17: Window Comparator Output

In Figure 17, The blue waveform is the output of the peak detector, and the red waveform is the envelope, and the green waveform (U7A: Y) is the output of the window comparator. We can observe that the pulse duration (i.e., decay time) we get for clap to decay from 60% to 10% of peak value is almost constant.

E. Control Code Test Output

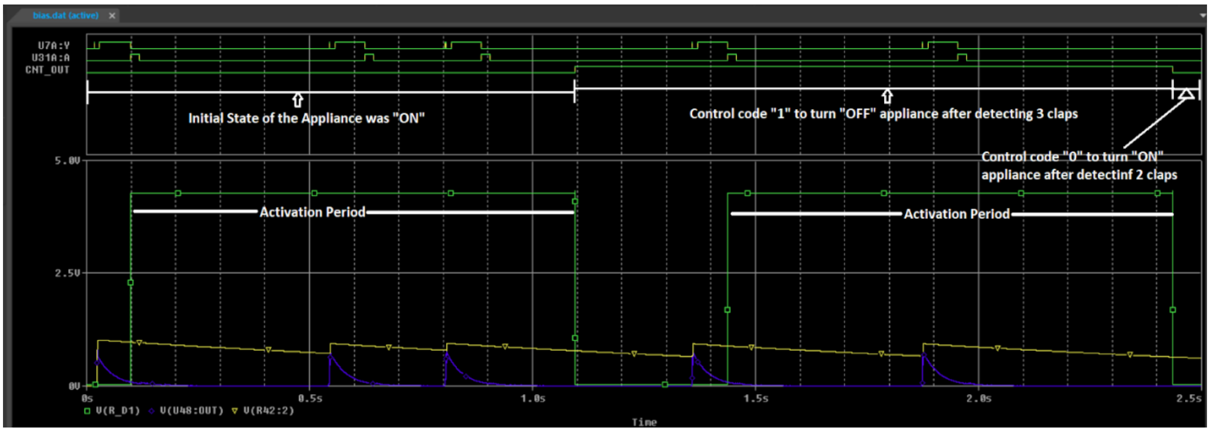

Figure 18: Control Code (Clap)

In Figure 18, U7A: Y is the output of the window comparator, U31A: A is the output of the decade counter in the waveform; a high pulse indicates that a proper clap is detected. After detecting the first clap 555 timer generates a 1 *sec* activation signal (Highlighted in the above image). From the image, we can see that two more claps are detected in the duration of the activation period, and the CNT_OUT signal goes high, indicating the appliance has to be turned off. As soon as the activation signal goes low, it reset the counter, and the current state is latched. Again, when a clap is detected, the activation signal goes high, and during this period, only one more clap is detected. Thus CNT_OUT goes low, indicating the appliance has to be turned on. (The blue waveform and yellow waveforms are envelope and peak of clap signal respectively, shown in the image for reference).

F. Test Result for Metal Glass Audio Signal

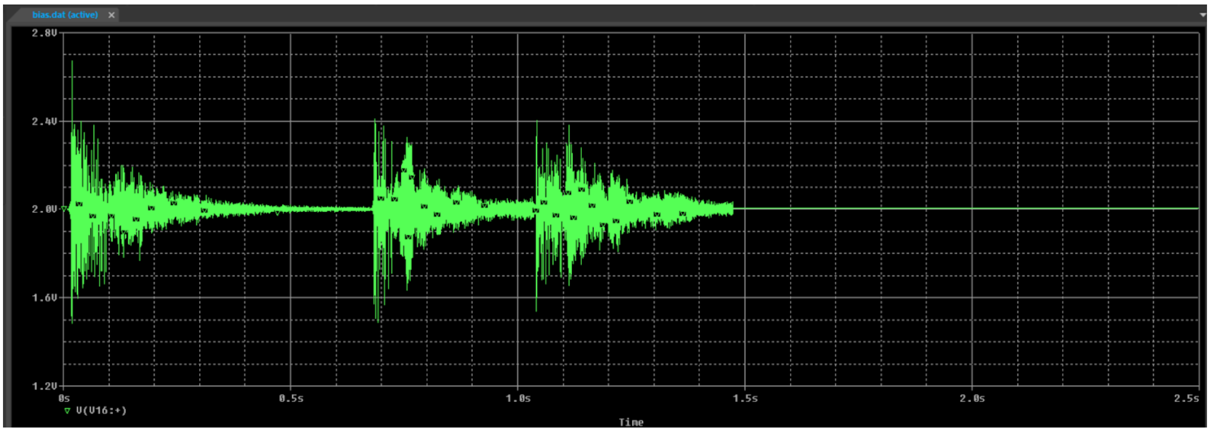

Figure 19: Phone recorded Input Signal (Metal Glass)

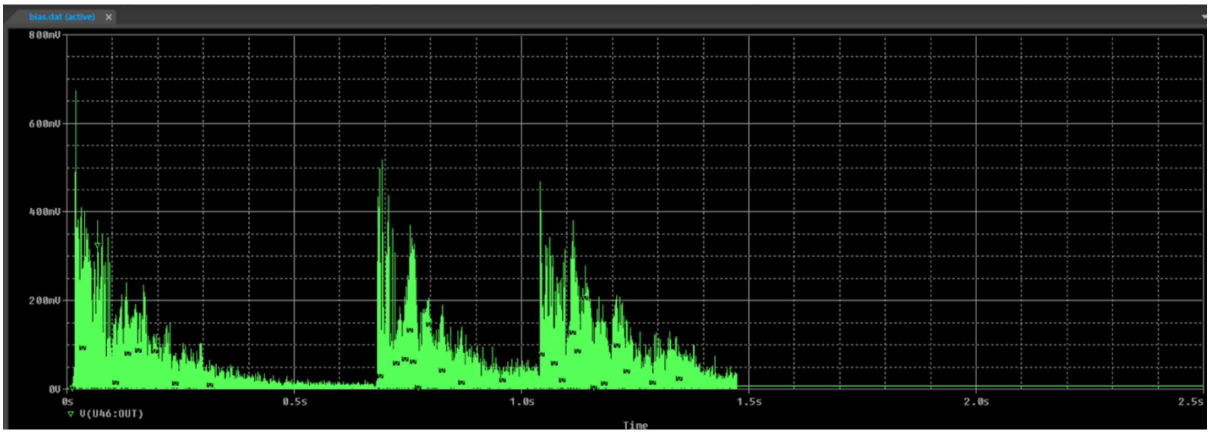

Figure 20: Rectified Output (Metal Glass)

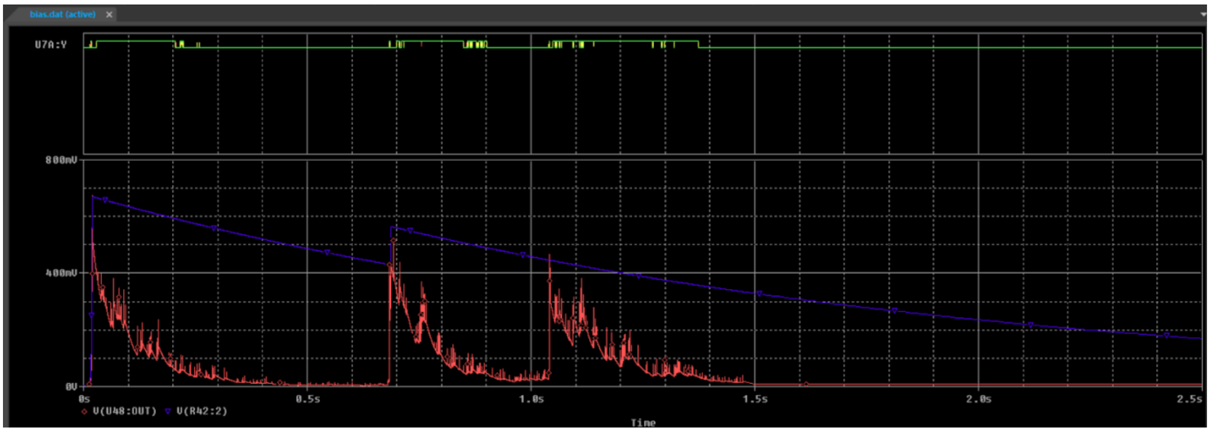

Figure 21: Window Comparator Output

In Figure 21, The red waveform is the envelope, and blue is the peak of the rectified metal glass audio signal, and the green waveform (U7A: Y) is the output of the window comparator. Here we can observe that we are getting an abrupt pulse due to large decay time. Thus, we use this as a distinguishing parameter between clap and other audio signals.

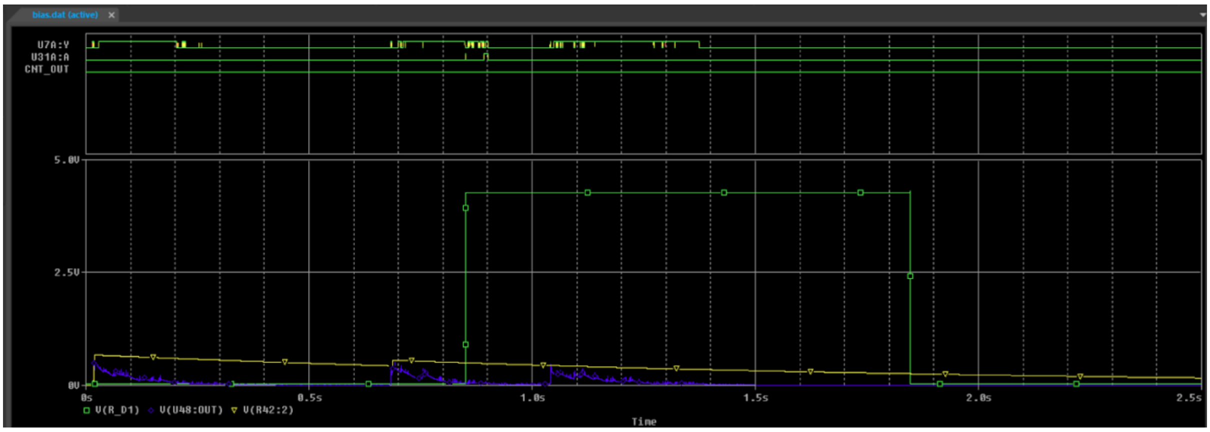

Figure 22: Control Code (Metal Glass)

In Fig j, we see that the circuit can distinguish between clap and metal glass falling audio signal. Thus, the control code (CNT_OUT) is unchanged, and the stage of appliances does not change.

Results

Figure 13-15 shows the waveforms from the time of detecting the first clap until the control code generated was working successfully. It can be seen that the five claps were detected on the U31A(Figure 13) digital line, and by keeping track of the claps during the activation period, we were able to produce control code as shown in Figure 15 on CNT_OUT digital line. After detection of three consecutive claps, the control code changes from "0" (i.e., ON) to "1" (i.e., OFF), and After detection of two claps, the control code changes from "1" (i.e., OFF) to "0" (i.e., ON)

Conclusion and Suggestions

The objective of the project was to design an analog circuit that can detect claps in an audio signal captured by an electret microphone and generate control code. The circuit was designed to detect claps for controlling a toy or appliance's ON/OFF state. The design can also handle a single false clap (Figure 16) detected by not generating a control code. This was checked for the steel glass falling on the ground sometimes had similar properties of clap (frequency and decay time). Since the glass falling had repeated clap-like oscillations, the duration (500ms - 600ms) of decay was longer.

The decade counter sometimes does not detect clap as the clock and output of the window detector is asynchronous. It is also challenging to distinguish between table taps and door knock as it has a similar envelope. The device is not tested for highly noisy environments. Also, the decay time varies with respect to distance and phone to phone. Hence the system works only for a trained environment (i.e., user 1 phone clap signal).

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Appendix

In implementing the project, we had difficulty getting our circuit working for steel glass falling on the floor. As seen in the study made in Table 1, the frequency of steel glass falling was between 4kHz to 6kHz, and since its decay time is more than that of clap. Our circuit used sometimes to detect this steel glass falling as a clap.

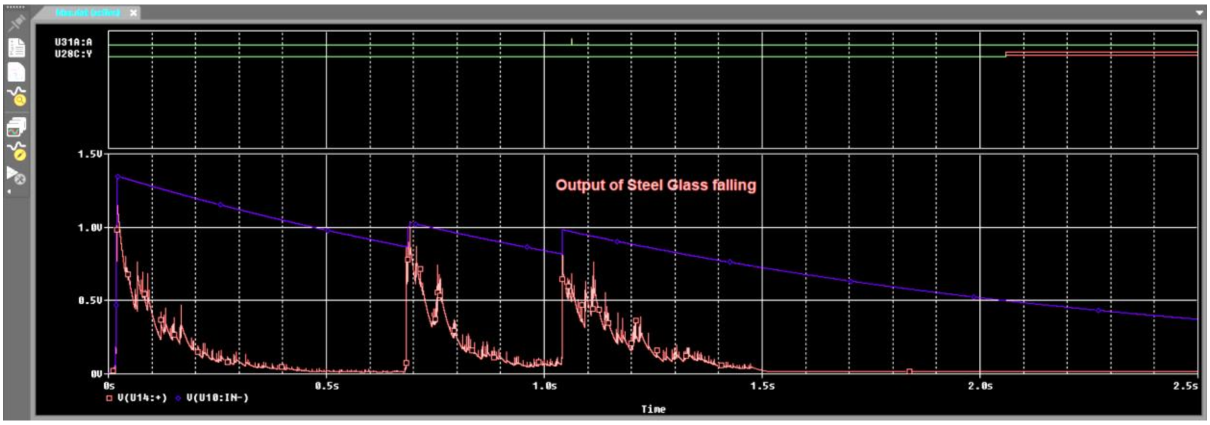

Figure 23: Steel Glass Falling Detected as Clap

To handle this issue initially, the approach was to use a bandpass filter to attenuate frequency higher than 3kHz, but this approach resulted in an envelope much similar to that of a clap signal and caused false triggering. As we can observe in Figure 16, the digital line U31A shows a false clap for a very small duration. Also, the simulation time required to use BPF was around 30-35mins for 8-sec audio signal input.

Bandpass Implementation (not used in the final design)
We designed a bandpass filter to pass all signals in the frequency range 500 - 2.5K Hz for the required frequency to distinguish clap from other sounds. For further circuit testing, the audio file is converted to .csv format and given input (Piecewise linear - PWL) to our BPF circuit. For design, we have used the Analog filter design tool. LM324 is not best suited for active filtering as it has a limited output swing with high DC error. The OP-AMP we have selected is MCP6021 for the bandpass filter.

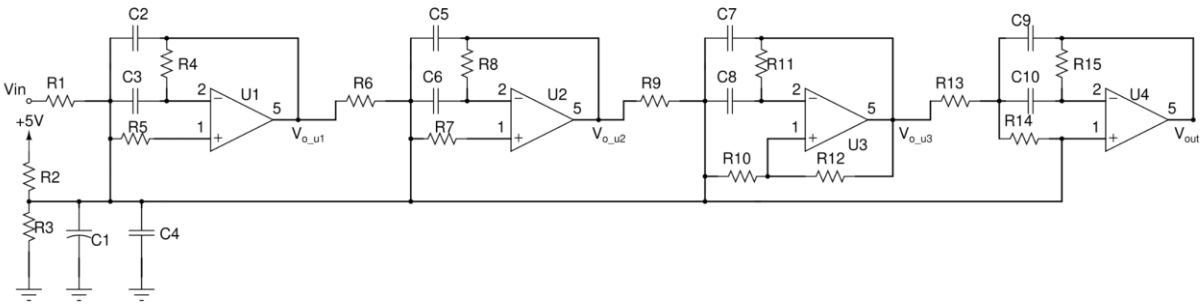

Figure 24: Bandpass Filter Circuit

Table 8: Components for Bandpass Filter

	Resistor(Ω)	Tolerance		Resistor(Ω)	Tolerance
R1	43.2k	1%	R9	124k	1%
R2	9.1k	5%	R10	53.6k	1%
R3	10k	5%	R11	48.7k	1%
R4	270k	1%	R12	16.2k	1%
R5	17.8k	1%	R13	71.5k	1%
R6	71.5k	1%	R14	261k	1%
R7	29.4k	1%	R15	165k	1%
R8	442k	1%			
	Capacitors(F)	**Tolerance**		**Capacitors(F)**	**Tolerance**
C2,C3 C7,C8	1n	10%	C9,C10	1.5n	10%
C5,C6	2.2n	10%			

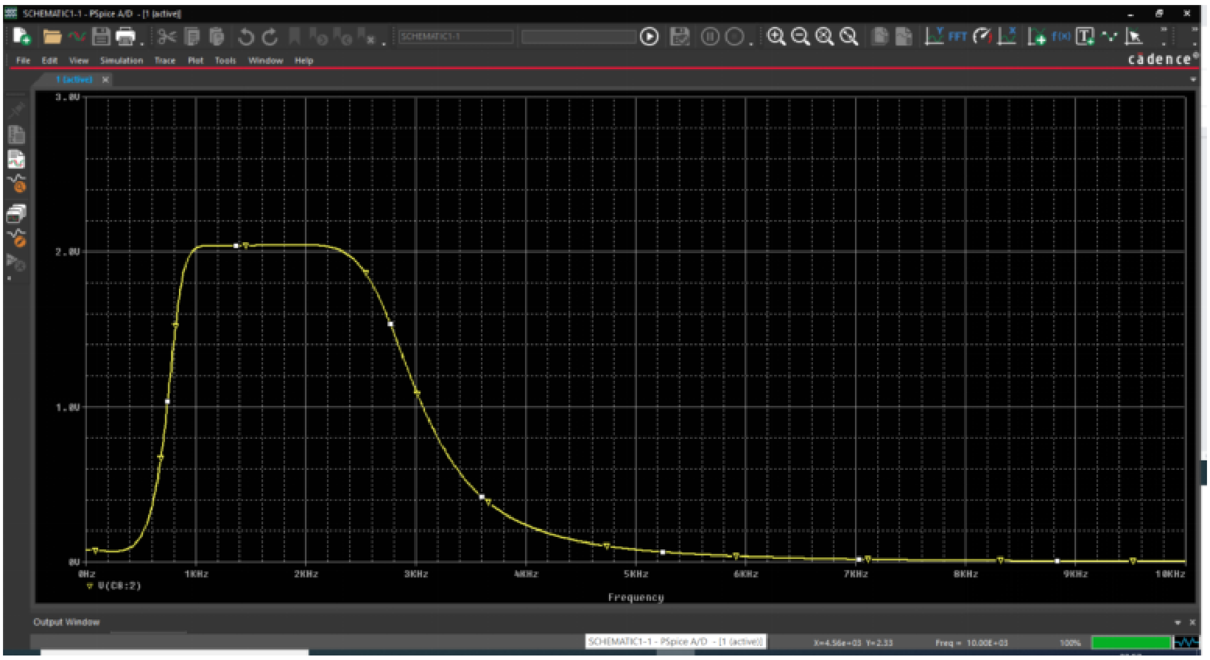

Figure 25: Frequency response of Bandpass Filter

Audio Signal

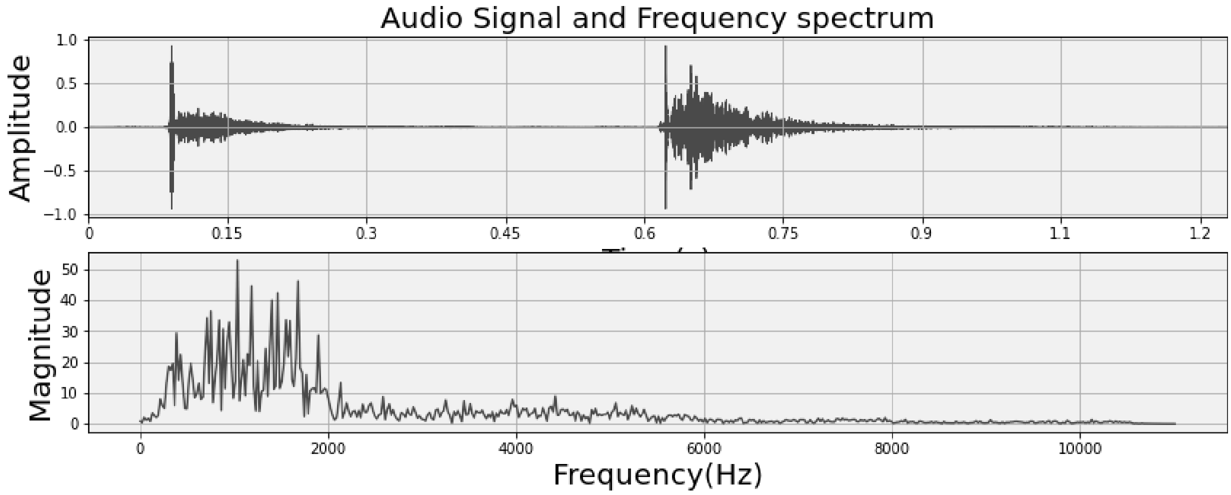

Figure 26: Member-1 two claps

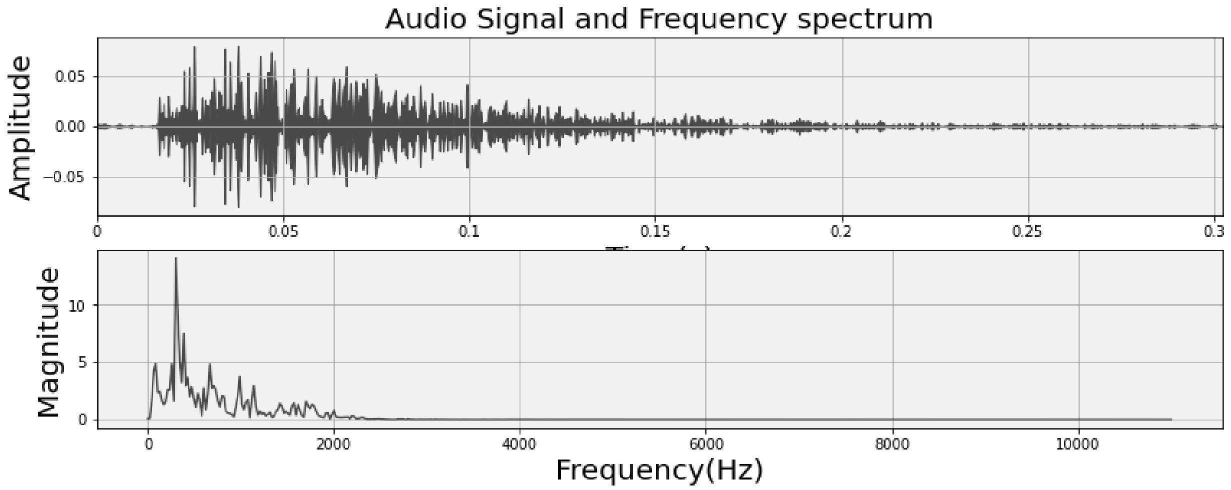

Figure 27: Doorknock

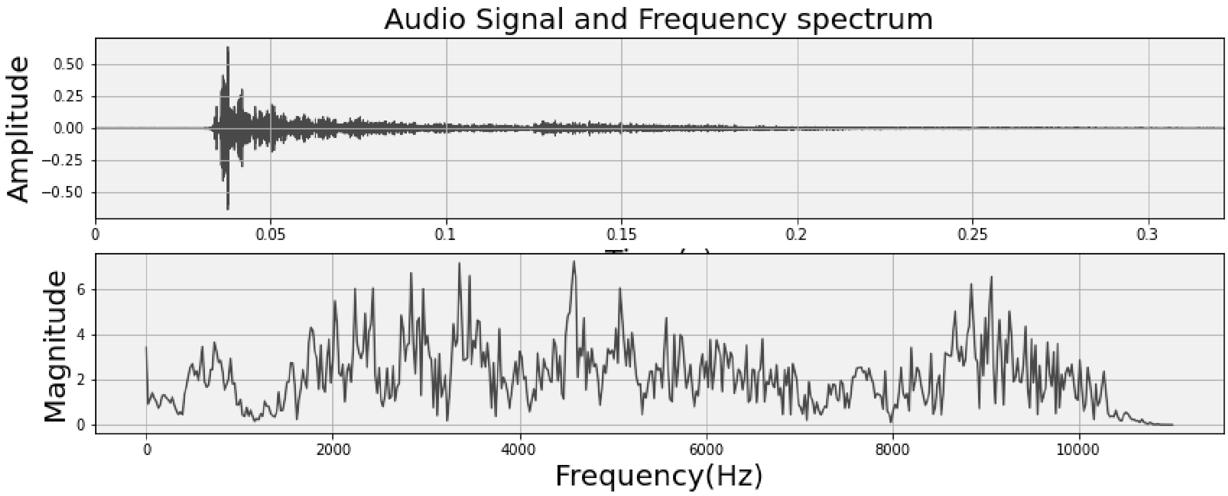

Figure 28:Member-2 single clap

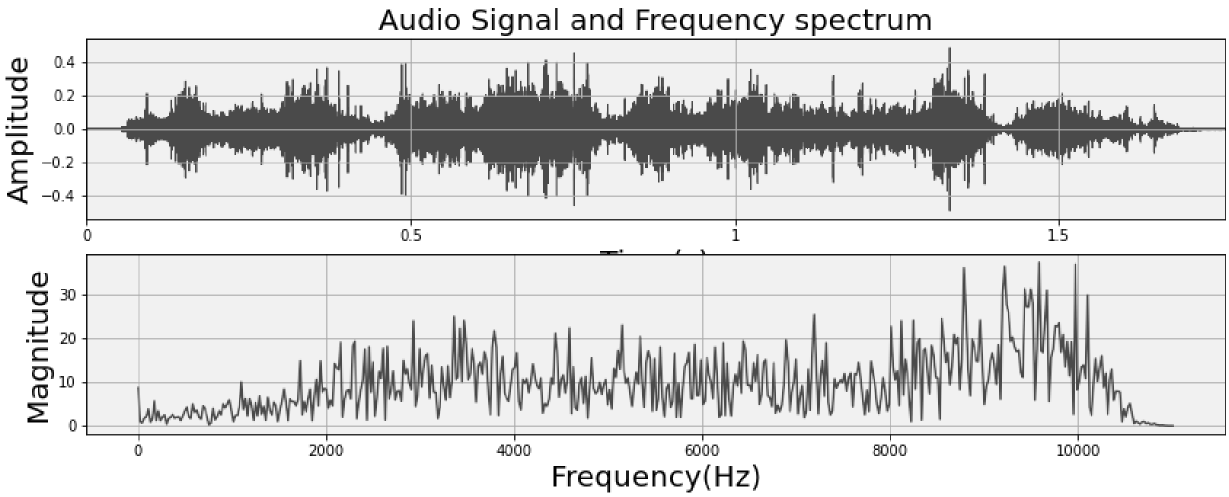

Figure 29: Plastic noise

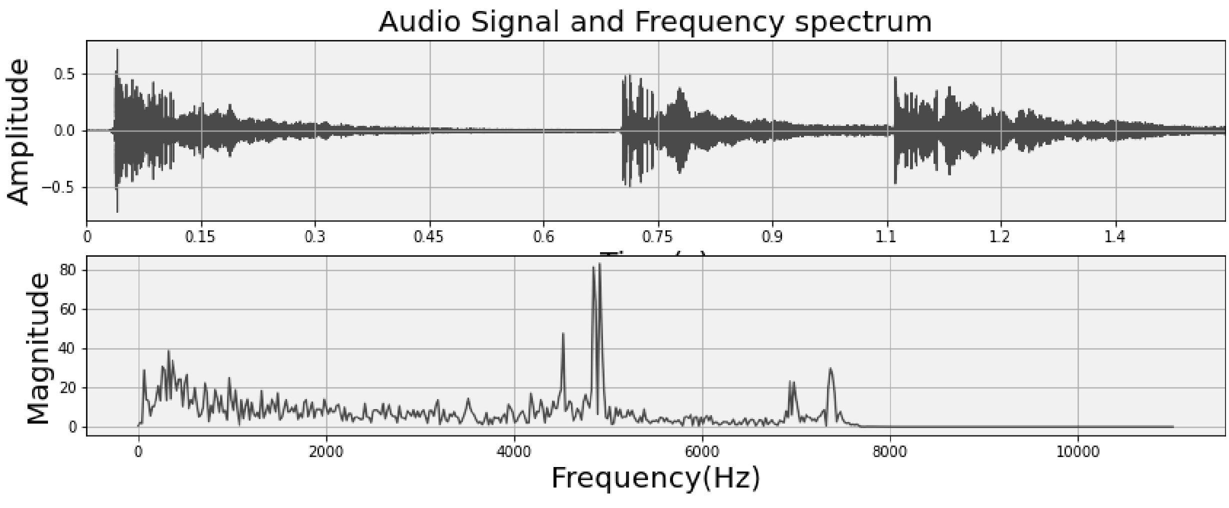

Figure 30: Glass Drop

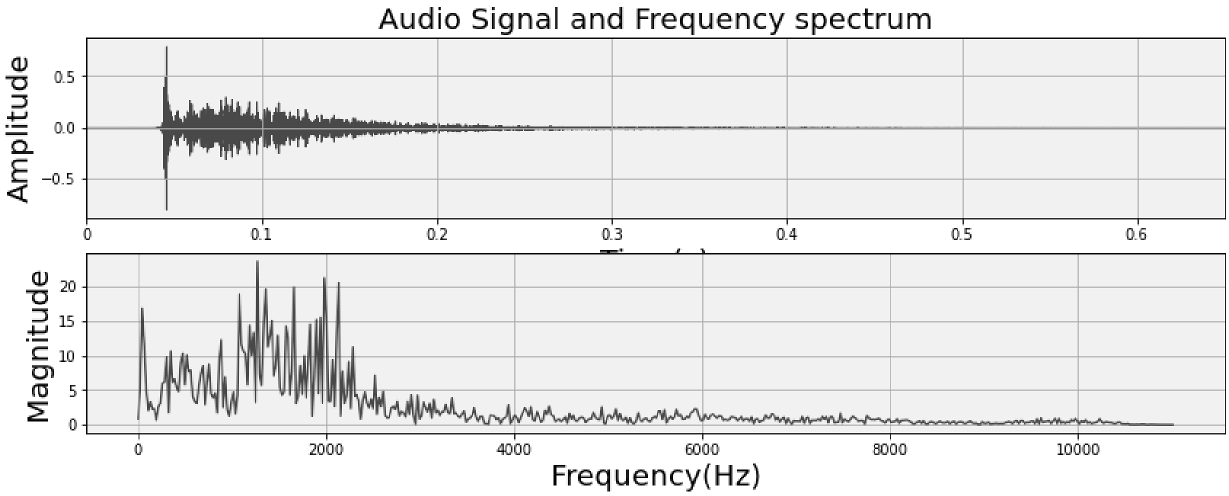

Figure 31: Member-1 single clap