# Digital Controlled Oscillator for Piano Synthesizer

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## I. Introduction

A modern electronic piano synthesizer contains the capability to manipulate pitch and filter envelopes, providing expressivity and sophisticated control over sound. Three key factors—amplitude, frequency, and envelope—are considered while developing a piano synthesizer. Amplitude is controlled by the level of the control signal produced by hitting a piano key, while frequency is controlled by the rate at which the digital oscillator generates a square waveform. The envelope waveform describes how the sound changes over time, and in a piano, it has a quick initial attack, a sustained period, and a gradual release. This is normally regulated by a digital ADSR circuit, although due to component restrictions, an RC-oscillator can be used as a substitute. The range of piano note frequency for an A440-tuned piano is 16.35Hz to 7902.133 Hz. The design would strive to provide such frequencies as precisely as possible while minimizing frequency distortion. In this work, we will offer a novel circuit design based on a cheap but effective piano synthesizer based on a digital controlled oscillator, and we will evaluate the three parameters and their impacts of electrical signal to audible audio signal.

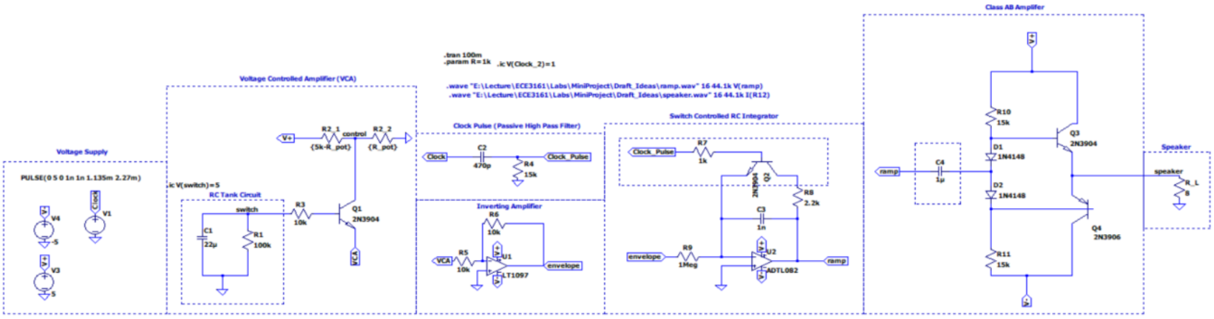

Fig 1. Circuit Schematic

## II. Design Requirements

### A. Components

The components used to construct the circuit and their corresponding cost are listed out. The total cost amounted to RM 12.

TABLE I. COMPONENTS DETAILS

| **Components** | **Components details** | | |
|---|---|---|---|
| | ***Specifications*** | ***Quantities*** | ***Cost per Quantity (RM)*** |
| Resistors | 1kΩ<br>2.2kΩ<br>10kΩ<br>15kΩ<br>100kΩ<br>1MΩ | 1<br>1<br>3<br>3<br>1<br>1 | 0.10<br>0.10<br>0.10<br>0.10<br>0.10<br>0.10 |
| NPN Transistors | 2N3904 | 2 | 0.50 |
| PNP Transistors | 2N3906 | 1 | 0.50 |
| Op-amps | TL082 | 2 | 0.30 |
| Capacitors | 270pF<br>1nF<br>1µF<br>22µF | 1<br>1<br>1<br>1 | 0.30<br>0.30<br>0.30<br>0.50 |
| Diodes | 1N4148 | 2 | 0.30 |
| Power Supply | Square Wave $5V_{pp}$<br>+5V power supply | 1<br>2 | -<br>1.20 |
| Speaker | 8V, 0.5W | 1 | 2.50 |
| Potentiometer | 10 kΩ | 1 | 2.00 |

## III. Methodology

### A. RC Tank Circuit

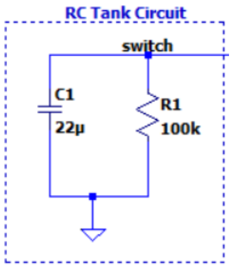


Fig 2. RC Tank Circuit Configuration

A RC tank circuit consists of a resistor (R) and a capacitor (C) connected in parallel. It is used to mimic the behavior of ADSR envelope circuit. It shapes the amplitude and frequency of the sound produced by the piano synthesizer. In real circuit configuration, the *switch* node is connected to a 5V DC supply, cutoff by a switch, when the switch is pressed and released, the capacitor is charged, then quickly discharged. As the capacitor discharges, the voltage across it gradually decreases until it reaches a steady-state value determined by the resistance and capacitance of the circuit. The RC tank circuit would output the decaying control voltage to mimic the effect of piano key becoming softer gradually over time after hitting it.

$$V_c = V_0(1 - e^{\frac{t}{RC}})$$

Where $V_c$ is the voltage across the capacitor at time $t$, and $V_0 = 5V$ is the initial voltage across the capacitor, and $R$ is the resistance of the tank circuit. Based on the values chosen, the time taken to reach below 0.65 V is

$$t_{<0.65V} = -RC * ln(\frac{V_c}{V_0})$$

$$t_{<0.65V} \approx 4.488ms$$

## B. *Voltage-Controlled Amplifier*

A voltage-controlled amplifier (VCA) is an important component of a piano synthesizer as it allows the control voltage signal to modify the volume of the audio stream. A NPN transistor in common emitter configuration is used to implement the VCA. The output of the RC tank circuit was linked to the base of an NPN transistor via a resistor, while the control voltage signal is connected to the collector terminal of the transistor.

In this circuit, the RC tank circuit decay signal is applied to the base of the transistor, which technically acts as a *variable resistor*. As the decay signal becomes smaller over time, the control signal is less amplified thus the output sound will have smaller amplitude over time. The emitter is connected to a virtual ground of the op-amp instead of the collector terminal, since we have many fluctuating signals which will cause interference with the control signal, thus corrupting it if we were to connect it to the ground. If the voltage at *switch* node is less than $V_{BE_{sat}} = 0.65V$, the transistor Q2 is OFF, not allowing the control signal to pass through.

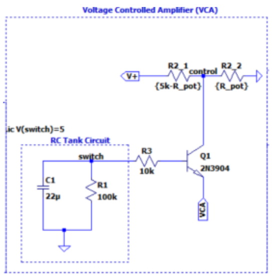


Fig 3. Voltage Controlled Amplifier (VCA) Circuit Configuration

## C. *Inverting Amplifier*

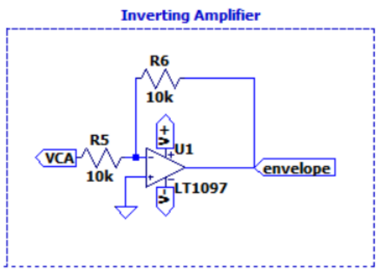


Fig 4. Inverting Amplifier Circuit Configuration

This circuit configuration is a simple inverting amplifier with a gain of -1. The emitter terminal of the NPN transistor is connected to the virtual ground through the resistor to prevent interference. Since the integrator would decrease if a positive voltage is applied, a negative voltage input is needed to allow the integrator to have a positive output, hence the inverting amplifier.

$$G_{envelope} = -\frac{R_{12}}{R_{11}} = -1$$

## D. *Passive High-Pass Filter based Clock Pulse Circuit*

The clock pulse circuit consists of a 470pF capacitor and a 15 kΩ resistor which is connected to the ground. The main problem with voltage-controlled oscillators (VCOs) is that the control voltage needed to determine the frequency is produced from a complicated circuit that is sensitive to temperature changes and manufacturing differences. As a result, the control voltage generated may not match the target note frequency, resulting in an out-of-tune sound. Furthermore, even if the voltage is set for a particular temperature, it will need to be adjusted again if the temperature rises or falls, resulting in repeating tuning.

Digitally controlled oscillators (DCOs), in contrast, have a unique way of controlling frequency. DCOs use an electronic clock signal that operates as a square wave with a specific frequency rather than an analogue control voltage to determine frequency. A microcontroller is used in a real piano synthesizer to control the frequency of the clock signal in order to create various tones.

$$V_{pulse} = \frac{sR_4C_2}{1 + sR_4C_2} V_{clock}$$

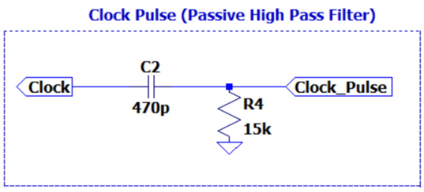


Fig 5. Clock Pulse Circuit Configuration (Passive High Pass Filter)

In particular, the passive high-pass filter is used as an RC differentiator, it takes square wave of different frequencies as an input and converts it into sharp pulses to manipulate the frequency of the output audio signal. The RC time constant of such configuration must be smaller than the time period of square wave input to the node *clock* such that the pulse decay time does not span more than 1 unit period. The RC constant of this circuit is $\tau_{clock} = 7.05\ \mu s$. The reason for choosing this value will be mentioned below.

## E. *Switch-controlled RC Integrator*

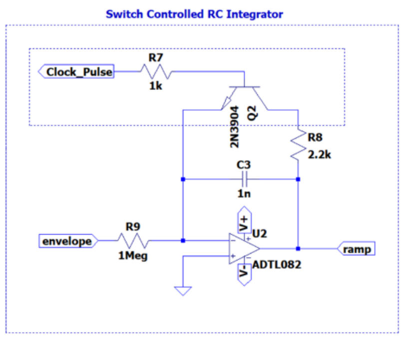


Fig 6. Switch Controlled RC Integrator Circuit Configuration

The switch-controlled RC Integrator consists of 3 resistors (1kΩ, 2.2kΩ and 1 MΩ), 1 op-amp (TL082), 1 transistor (2N3904) and 1 capacitor (1 nF).

This unique configuration is used to generate sawtooth waveform. The NPN transistor functions as a switch for the capacitor in the RC integrator to charge and discharge. When the transistor is OFF, the capacitor would be an open circuit, build up charge, causing increase in voltage. When the clock pulse turns ON the transistor, the circuit is closed and the discharge cause the voltage to drop quickly, effectively generating a sawtooth waveform. The general rule of thumb in designing such DCO is the time constant of clock pulse circuit $\tau_{clock}$ must be greater than the time constant of discharging portion of RC integrator, $\tau_{integrator_{discharge}} = 2.2\mu s$ for the discharge time to be enough for voltage to drop to its minimum, but not distorting the sawtooth waveform.

The relationship of frequency and the RC integrator output is given by

$$V_{out} = -\frac{1}{R_9 C_3} V_{in} t$$

$$f_{max} = \frac{V_{control}}{R_9 C_3 V_{out}} = \frac{1}{R_9 C_3} = 1000Hz$$

Since the theoretical maximum of ramp generator is $V_{out} = 5V$, the range of frequency generated without muffling or distortion being 1000 Hz. However, since the distortion is minimum, to human ears the signal could go up to 2000 Hz without noticeable distortion in our trial experiments. The values of $R_9$ would determine the range of frequency that could be generated with low distortion, as shown above. The 1 MΩ resistor is selected for high input impedance.

The transfer function of the RC integrator is

$$T(s) = -\frac{R_8}{R_9}\frac{1}{1 + sR_8 C_3}$$

### F. Class AB Amplifier

In order to boost the signal power produced at the output stage, the speaker is often connected to the ramp generator using a class AB amplifier. The ramp generator normally produces a low-power signal that cannot be used to directly drive a speaker. Class AB amplifier can increase the accuracy and quality of the audio signal by minimising frequency distortion and providing clean and precise sound reproduction near to the piano note frequency. Class AB amplifiers is used instead of op-amp because it is capable of delivering relatively larger current to the speakers, which is necessary for proper speaker operation. Op-amps are voltage-driven devices and may not be able to supply the required current levels to drive speakers effectively.

The biasing resistors are chosen to be $R_8 = R_7 = 15k\Omega$ to enable sufficient current gain to drive the load. Specifically, the speaker used here is 8Ω, 0.5W speaker.

$$Current\ Gain, \beta = \frac{I_{out}}{I_{in}} = \frac{36.319mA}{241.92\mu A} \cong 150.13$$

$$Power\ Gain, G_P = \frac{P_{out}}{P_{in}} = \frac{10.552mW}{178.07\mu W} \cong 59.28$$

In addition, the capacitor $C_3$ is decoupling the ramp generator from the amplifier, in order to blockade DC component of the signal, hence removing the offset.

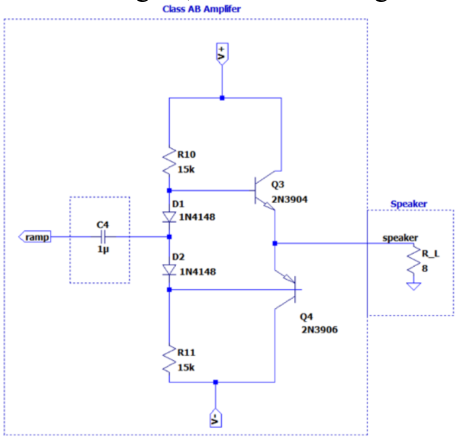


Fig 7. Class AB Amplifier Circuit Configuration

### G. Real Circuit

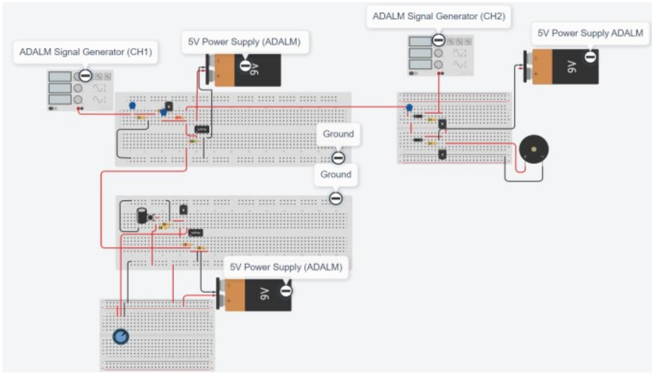


Fig 8. Practical TinkerCAD Circuit Configuration

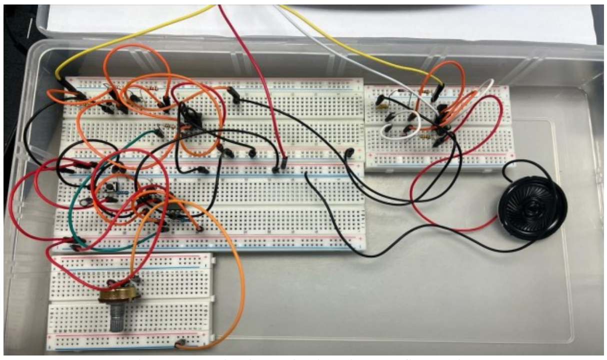

Fig 9. Practical Real Circuit Configuration

## IV. Results and Discussions

### A. Time Domain

The graph below shows the voltage and current across the clock pulse, ramp generator, and speaker, measured in Spice and prototype circuit.

#### 1) Clock Pulse

We may see that the clock pulses are a series of sharp voltage decay, effectively turning on the NPN transistor for a short while to complete the discharge circuit, allowing the voltage at $V_{ramp}$ to fall, then turning off the discharge circuit to turn off the NPN transistor, enabling the building up of the voltage across capacitor, thereby creating a sawtooth waveform.

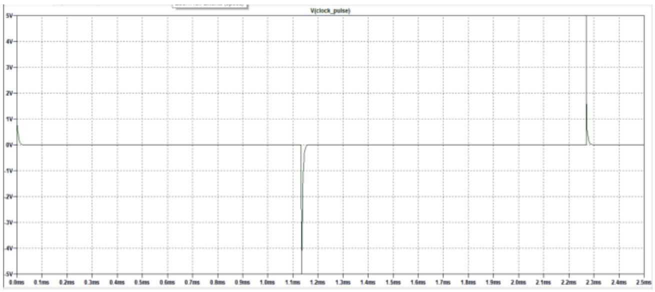

Fig 10. LTSpice Clock Pulse Voltage Waveform

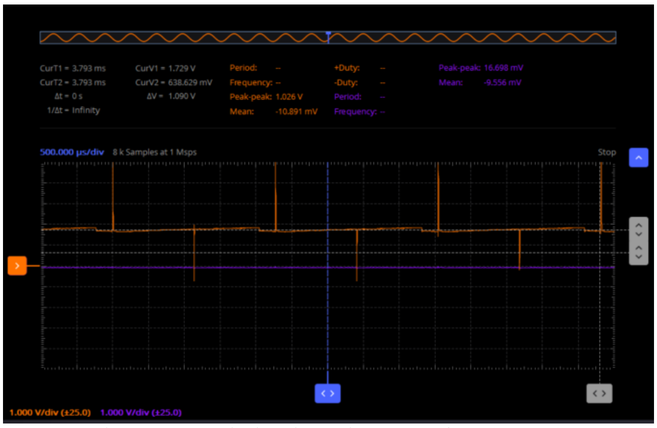

Fig 11. Scopy Clock Pulse Voltage Waveform (Orange)

### 2) Ramp Generator

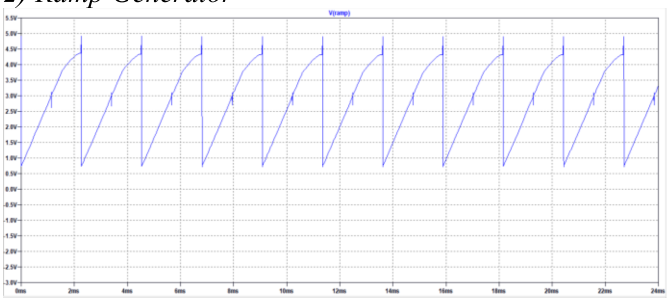

Fig 12. LTSpice Ramp Generator Voltage Waveform

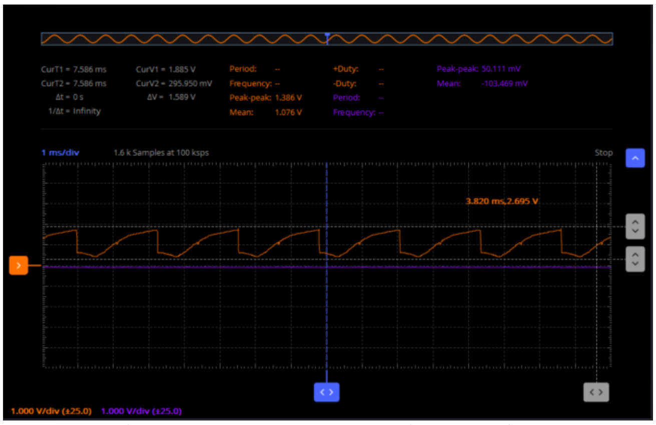

Fig 13. Scopy Ramp Generator Voltage Waveform

### 3) Speaker

As shown below, the waveform generated across the speaker is also a sawtooth wave with high frequency precision. Sawtooth waveform gives a bright, piercing sound even at lower power ranges.

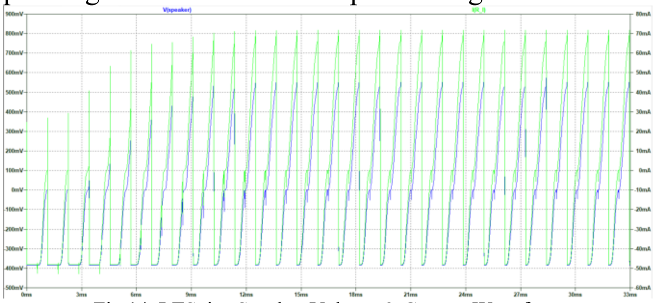

Fig 14. LTSpice Speaker Voltage & Current Waveform

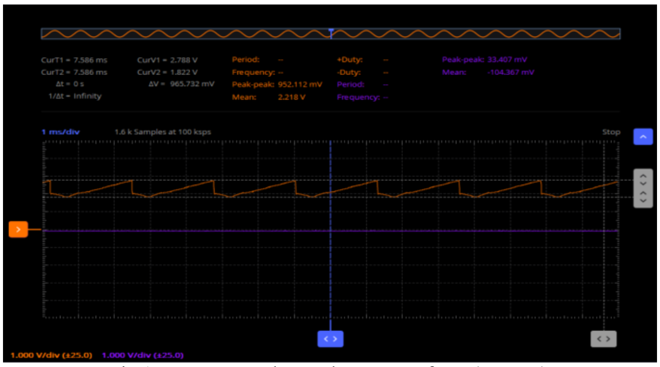

Fig 15. Scopy Speaker Voltage Waveform (Orange)

## B. *Frequency Domain*

In the graph below, the first peak is shown at the fundamental frequency.

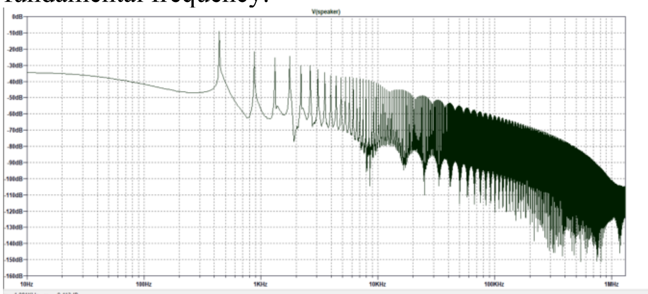

Fig 16. Bode Plot when Control Voltage = 2V, Clock Frequency = 440Hz

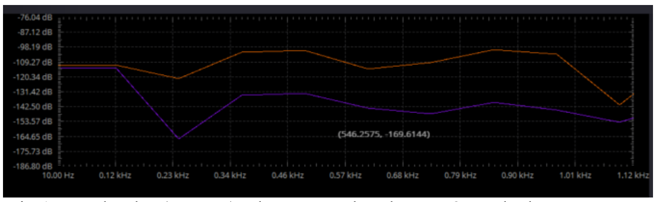

Fig 17. Bode Plot (Orange) when Control Voltage = 2V, Clock Frequency = 440Hz

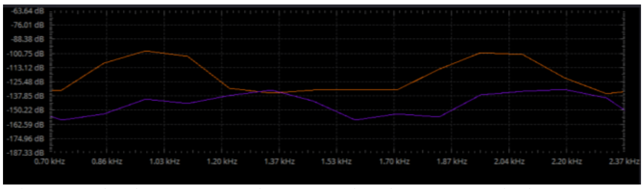

Fig 18. Bode Plot (Orange) when Control Voltage = 2V, Clock Frequency = 1000Hz

The FFT plot was measured in Spice simulation and actual prototype circuit. The peak of the plot is the frequency in which the audio signal is generated, which is at 440 Hz, the 1st harmonics peaked at 880 Hz. The presence of harmonics is expected since this is a sawtooth waveform, and the harmonics are needed to some degree to create rich and complex audio signals. The distortion of the waveform in relation to the frequency is tabulated in the table below, with the control voltage setting, $V_{control} = 2V$.

TABLE II. THEORETICAL AND MEASURED FREQUENCY

| **Clock Square wave Frequency (Hz)** | **Measured Frequency (Hz)** | **Distortion Error (%)** |
|---|---|---|
| 440 | 438.7 | 0.295 |
| 880 | 882.3 | 0.261 |
| 1000 | 1002.6 | 0.260 |

From table II, we may observe that DCO-controlled piano synthesizer has very low distortion error, below 0.3%. The presence of distortion error is expected since sawtooth wave has many harmonics, albeit at a lower magnitude than the fundamental frequency.

### *C. Power Consumption*

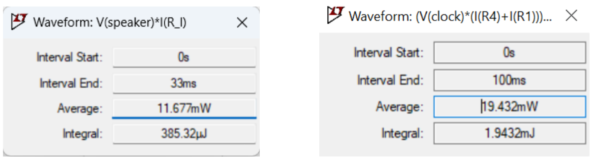

Fig 19. Power consumed by the speaker (left) and total input power of the circuit (right)

The power consumed by the circuit and speaker alone are measured and tabulated, with control voltage, $V_{control} = 2V$. The power consumed by the speaker has been measured to be 11.677mW and the input to the circuit has been measured to be 19.432 mW. The power dissipated by this circuit is 7.755 mW. The efficiency of the overall circuit has been computed to be 60.09%.

### *D. Noise*

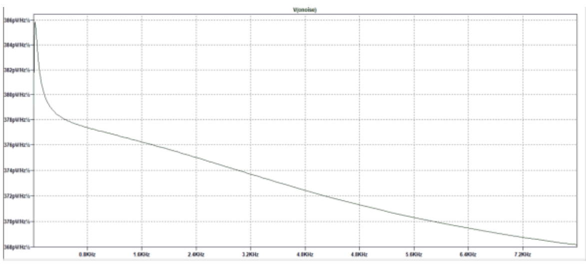
Fig 20. Noise response from 10Hz to 8000 Hz at the speaker

The power supply is injected with noise of frequency varying from 10Hz to 8000Hz, covering the whole range of piano notes, with a value below $386pV/\sqrt{Hz}$ The Spice directive used is `.noise`. The noise response remains roughly similar as the frequency of the clock varies, this shows an advantage over traditional analog voltage-controlled oscillators as digital controlled oscillators' noise response is stable, therefore removable with noise gates, or an equalizer.

## V. CONCLUSION

The design of the audio synthesizer involves an RC Tank Circuit, a Voltage Controlled Amplifier (VCA), an inverting amplifier, a Passive High Pass Filter based clock pulse circuit, a switch-controlled RC Integrator, and a class AB Amplifier. The audio synthesizer that we have designed and constructed works as intended as it is able to produce sound of varying frequency that falls within the human audible range (20Hz – 20kHz), meeting the design requirement. The audio synthesizer also consists of a pushbutton that will activate the speaker when the push button is held onto. The signal quality of the design of our audio synthesizer is also on par with the currently available audio synthesizer on the market. The advantage of utilizing a digital-controlled oscillator is evident as the noise response remains consistent across varying clock frequencies, allowing for potential noise removal through noise gates or equalizers. However, due to the limitation of the number of components allowed and the voltage supplied, the speaker will not be as loud as intended. In a nutshell, the design of our audio synthesizer meets the design requirements and functions as intended.

## VI. CONTRIBUTION STATEMENT

**Izaac Chong Yen Juin**: Spice circuit construction; SPICE Simulation; Report writing, **Nigel Tan Jin Chun**: Physical circuit construction; Physical circuit testing; Report writing.

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