Theremin Design and Simulation

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Outline

Introduction to Theremin

- An electronic musical instrument played without physical contact.
- Invented by Léon Theremin around 1920.
- Uses two antennas to control pitch and volume based on hand proximity.
- Operates on the principle of heterodyning: mixing two high-frequency signals to produce an audible difference frequency.
- **Why heterodyning instead of generating audio directly?**
    - LC oscillators are more stable and precise at higher frequencies (100s of kHz to MHz).
    - Producing stable low-frequency (20 Hz–20 kHz) tones directly with LC circuits is inefficient and inaccurate.
    - Heterodyning down to audio gives better control and tunability.
- The player's hands act as the grounded plates of variable capacitors, influencing the frequency of oscillators.

Working Principle of a Theremin

- **Capacitive Sensing**: The player's hands near the antennas alter the capacitance in oscillator circuits.
- **Oscillators**:
  - **Variable Frequency Oscillator (VFO)**: Frequency changes based on hand distance from the pitch antenna.
  - **Fixed Frequency Oscillator (FFO)**: Generates a constant reference frequency.
- **Heterodyning (Mixing)**: The VFO and FFO signals are combined (mixed). The output contains sum and difference frequencies.
- **Filtering**: Low-pass filtering isolates the difference frequency ($f_{VFO} - f_{FFO}$), which falls within the audible range.
- **Volume Control**: Typically uses a separate oscillator circuit affected by the volume antenna to control the final output amplitude. We are using a different approach. Potentiometer (Standard Volume Knobs)

Circuit Overview

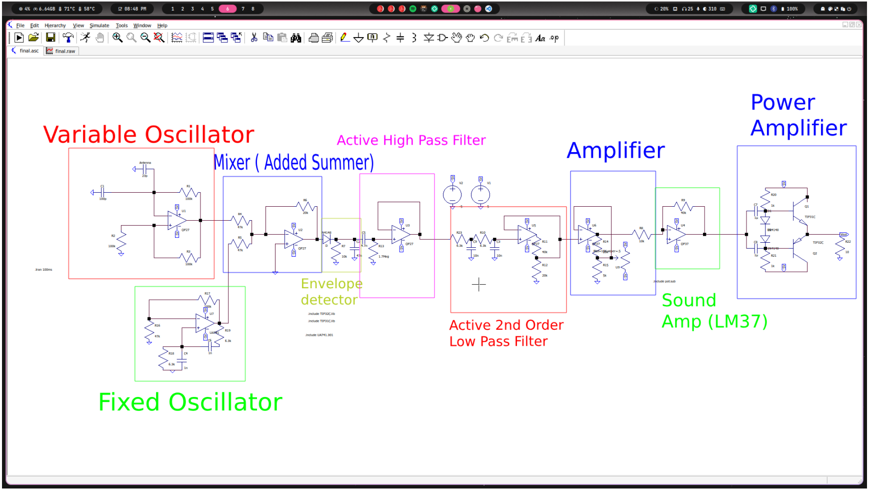


Figure: Simulated Theremin Circuit Schematic (LTSpice)

- The circuit consists of several stages: Variable Oscillator, Fixed Oscillator, Mixer/Summer, Filters, Amplifiers, and Power Amplifier.

Physical Circuit Overview

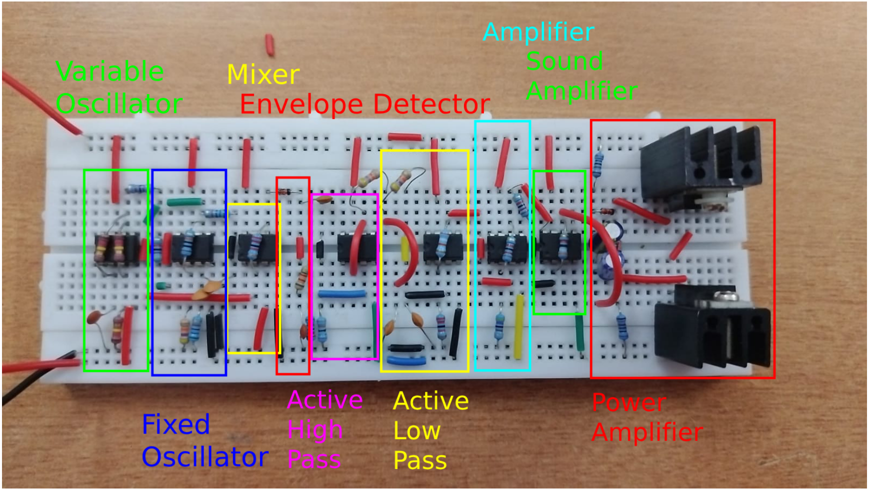


Figure: Theremin Circuit Schematic (Physical)

Variable Oscillator (Pitch Control)

- **Function**: Generates a frequency signal that changes based on hand capacitance near the 'Antenna'.
- **Topology**: Op-Amp based oscillator (OP27). Likely a relaxation type oscillator. Reference
- **Key Components**:
  - U1: OP27 Op-Amp
  - R1, R2, R3: $100\,\mathrm{k\Omega}$ resistors (biasing and feedback)
  - C1: $100\,\mathrm{pF}$ capacitor
  - Antenna: $23\,\mathrm{pF}$ capacitor (base capacitance, hand adds variable capacitance in parallel)
- **Operation**: The total capacitance at the input influences the oscillation frequency. As the hand moves closer, capacitance increases, typically lowering the frequency.
- **Note**: You will hear high frequency oscillation when hand is getting closer because of the heterodyning effect. As this frequency decreases , the difference in frequencies increases and you will hear a high pitch sound.
- **Calculation**:

- **Oscillation Frequency (f_o)**:

$$f_o = \frac{1}{2RCln\frac{1+k}{1-k}} \approx \frac{1}{2(120k)(175p) \cdot ln(3)} \approx 21.92\,\text{kHz}$$

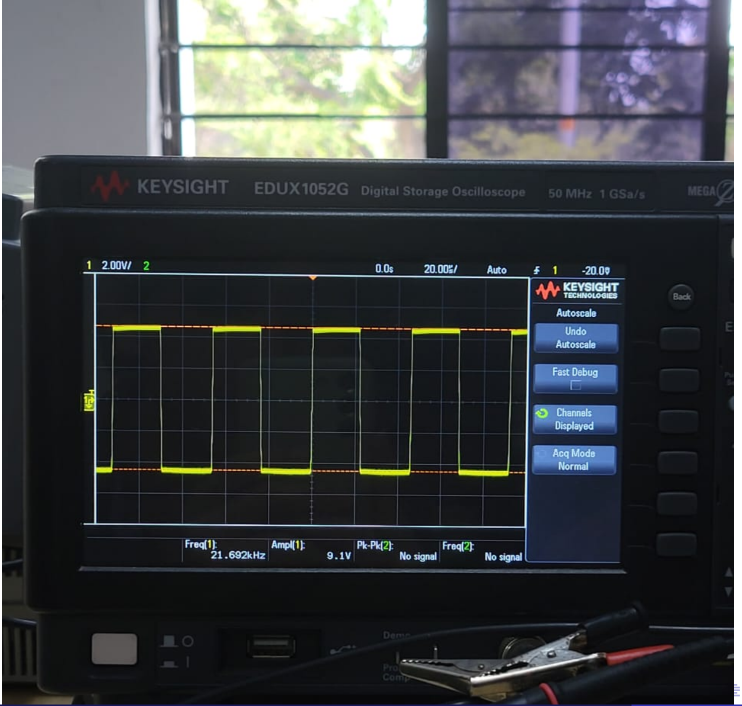
$$\text{where} k = \frac{R2}{R1 + R2}$$

- **Total Capacitance (C_{total})**:

$$C_{total} = C_{base} + C_{hand} = 60p + C_{hand}$$

- As C_{hand} increases, f_o decreases.
- **Capacitance Change**:

$$C_{hand} = \frac{C_{base}}{(1 - \frac{f_o}{f_{max}})} - C_{base}$$


KEYSIGHT
EDUX1052G Digital Storage Oscilloscope
50 MHz 1 GSa/s
1 2.00V/ 2
0.0s
Auto
Autoscale
Undo Autoscale
Fast Debug
Channels Displayed
Acq Mode Normal
Back
Freq(1): 21.692kHz
Ampl(1): 9.1V
Pk-Pk(2): No signal
Freq(2): No signal

Fixed Oscillator (Reference)

- **Function**: Generates a stable reference frequency for heterodyning.
- **Topology**: Wien Bridge Oscillator using U7 (UA741 Op-Amp).
- **Key Components**:
  - U7: UA741 Op-Amp
  - Frequency Determining Network: R18=6.3 kΩ, C4=1 nF, R19=6.3 kΩ, C6=1 nF
  - Gain Setting Network: R16=47 kΩ, R17=100 kΩ

Fixed Oscillator (Reference) - Calculations

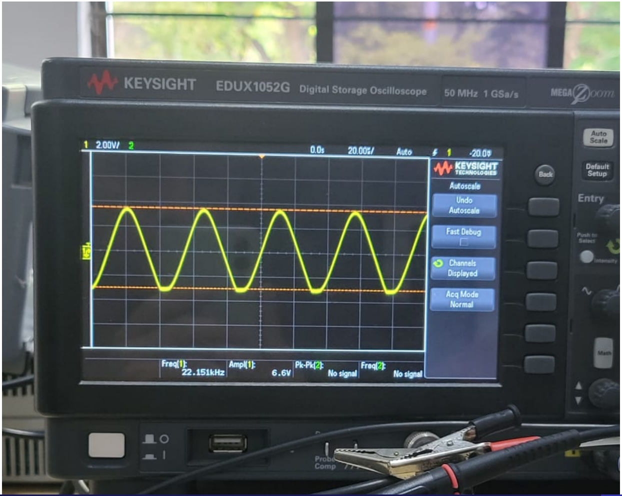
- **Calculation**:
  - Oscillation Frequency (f_o):

$$f_o = \frac{1}{2\pi RC} \approx 23.26\,\text{kHz}$$

  - Required Gain (A_v): $A_v \approx 2.13$

Fixed Oscillator (Reference) - Output

- **Note**: The frequency (∼25 kHz) is lower than typical Theremin RF oscillators.But because our relaxation oscillator is working at around 21KHz, we are using this frequency to get a better sound.



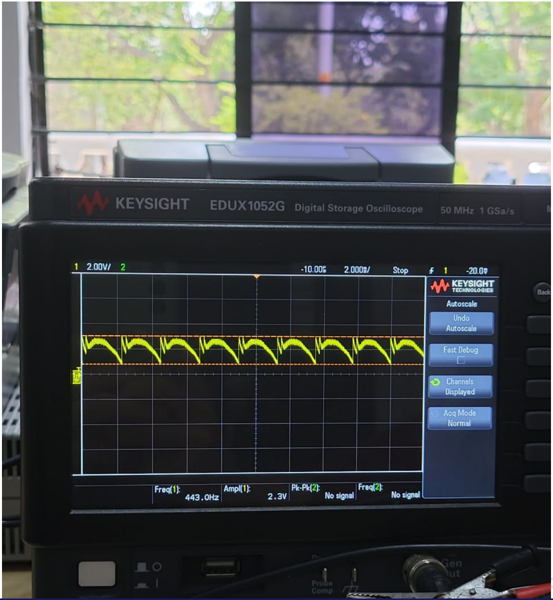
Mixer (Summing Amplifier)

- **Function**: Combines the signals from the Variable and Fixed Oscillators.
- **Topology**: Inverting Summing Amplifier using U2 (OP27).
- **Key Components**:
  - U2: OP27 Op-Amp
  - Input Resistors: R4=47 kΩ (from Variable Osc.), R5=47 kΩ (from Fixed Osc.)
  - Feedback Resistor: R6=20 kΩ
- **Calculation**:
  - Gain for each input: $G = -\frac{R_f}{R_{in}} \approx -0.426$
  - Output Voltage: $V_{out} = -0.426 \times (V_{VarOsc} + V_{FixedOsc})$

Envelope Detector

- **Components**: Diode D (1N4148), R7 ($10\,k\Omega$), C2 ($47\,nF$)
- **Function**: Half-wave rectification followed by RC low-pass filtering. Extracts the envelope of the signal from the mixer. Reference
- **Time Constant**: $\tau = R7 \times C2 = 0.47\,\text{ms}$
- **Cutoff Freq.**: $f_c \approx 1/(2\pi\tau) \approx 339\,\text{Hz}$
- **Note**: Placement after mixer is unconventional for standard Theremin volume control. And is intentional design choice to suppress the DC offset created by the envelope detector.

Envelope Detector Output



Active Filters

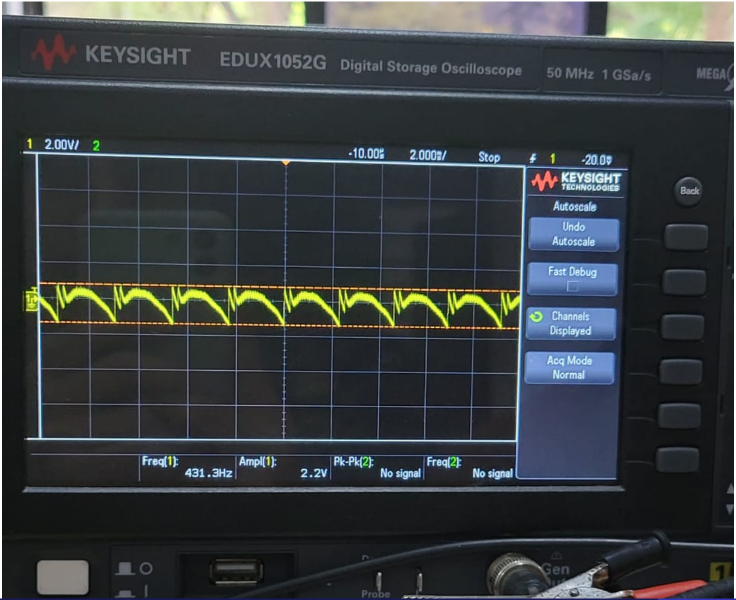
Active High Pass Filter

- **Components**: U3 (OP27), C5 (4.7 nF), R13 (1.7 MΩ)
- **Topology**: 1st order HPF using Op-Amp buffer.
- **Function**: Removes DC offset and very low frequencies.
- **Note**: The cutoff frequency is set to allow audio frequencies while blocking DC. This is important because of the envelope detector output.
- **Cutoff Freq.**: $f_c = \frac{1}{2\pi R13C5} \approx 19.9\,\text{Hz}$

Active 2nd Order Low Pass Filter

- **Components**: U5 (OP27), R10 (6.3 kΩ), R11 (40 kΩ), R12 (20 kΩ), C3 (10 nF),R23 (6.3 kΩ) , C9 (10 nF)
- **Topology**: 2nd order LPF using Op-Amp Feedback for amplification.
- **Function**: Removes high-frequency components above the desired audio range.
- **Cutoff Freq.**: $f_c = \frac{1}{2\pi R10C3} \approx 2.53\,\text{kHz}$
- **Gain**: $G_{DC} = 1 + \frac{R11}{R12} = 1 + \frac{40}{20} = 3$

High Pass Output



Pre-Amplifier / Volume Control

- **Components**: U6 (OP27), R14 (20 kΩ), R15 (5 kΩ), U9 (Potentiometer, 10 kΩ)
- **Topology**: Non-inverting amplifier with adjustable gain via potentiometer U9.
- **Function**: Amplifies the filtered audio signal and provides user volume control.
- **Gain Range**: $A_v = 1 + \frac{R14}{R15+R_{U9}}$
  - Min Gain (U9=10 kΩ): $A_v = 2.33$
  - Max Gain (U9=0 kΩ): $A_v = 5$

Sound Amplifier

- **Components**: U4 (OP37), R9 (40 kΩ), R8 (10 kΩ),
- **Topology**: Sound amplifier using OP37.
- **Function**: Further amplifies the audio signal to drive the power amplifier.
- **Gain**: $G = -\frac{R9}{R8} = -4$

Power Amplifier

- **Function**: Boosts the signal power to drive a low-impedance load like a speaker (R22).
- **Topology**: Class AB Push-Pull Output Stage.
- **Key Components**:
  - Q1: TIP31C (NPN BJT)
  - Q2: TIP32C (PNP BJT Complementary Pair)
  - D1, D2: 1N4148 diodes for biasing (reduce crossover distortion)
  - R20, R21: 1 kΩ base current limiting/biasing resistors
  - C7, C8: 1 μF bypass/filtering capacitors
  - R22: 10 Ω Load Resistor (representing speaker)
- **Operation**: Q1 conducts for positive signal swings, Q2 conducts for negative swings. Diodes provide a small forward bias to minimize the "dead zone" near zero crossings.

Power Supply Requirements

- **Dual Rail Supply**:
  - Voltage: $\pm 5\,V$ DC (V1 and V2)
  - Current: $10\,mA$ to $100\,mA$
- **Battery Implementation**:
  - Two 9V batteries connected in series
  - Center tap connection between batteries
  - Voltage regulation:
    - LM7805 for +5V regulation
    - LM7905 for -5V regulation
- **Power Consumption**:
  - Op-Amps: Low power consumption
  - BJT stages: Moderate current draw
  - Total power typically under $3\,W$

Conclusion

- A Theremin circuit based on Op-Amps and a BJT push-pull stage was designed and simulated and tested.
- Key stages: Variable Oscillator, Fixed Wien Bridge Oscillator, Summing Amplifier, Active Filters, Volume Control Pre-Amp, Buffer, and Class AB Power Amplifier.
- The design utilizes heterodyning, capacitive sensing, filtering, and amplification principles.
- Component values and calculated parameters were determined from the schematic.
- Operates on $\pm 5\,\mathrm{V}$ power rails.
- Our design choices differ from traditional Theremin designs, particularly in the volume control stage.

Thank You

Thank you for your attention!

Questions?