University of Moratuwa
Department of Electronic and Telecommunication Engineering
EN2111 - Electronic Circuit Design

Design and Implementation of a Wide-Range Low-Distortion Sine-Wave Generator

Project Report - Group 9

Kuruppuarachchi K. A. R. R. - 220350T
Kumarage R.V. - 220343B
Kalubowila K. A. T. S - 220299T
Manawadu D. N - 220380J

Contents

1 Introduction

Reliable sine-wave sources are indispensable tools for analysing audio equipment, filters, sensors and data-acquisition chains. Laboratory instruments typically demand:

- **Wide frequency coverage**: matching the human auditory band (20 Hz–20 kHz).
- **Adjustable output amplitude**: spanning millivolt-level measurements to several volts V_{rms}.
- **Minimal harmonic distortion**: $< 1\,\%$ to avoid corrupting the device-under-test (DUT).

Combining a *Wien-bridge oscillator* (WBO) —renowned for low intrinsic distortion— with a *Class-AB push-pull amplifier* yields a compact generator that satisfies these requirements while maintaining high efficiency and modest component count. This report documents the design process, key calculations, PROTEUS simulations, and bench-top oscilloscope verification.

2 Design Goals & Specifications

Table 1: Target performance metrics

Parameter	Target Value
Frequency range	20 Hz to 20 000 Hz, continuously tunable
Output amplitude	1 V[peak to peak] to 5 V[peak to peak]
Load capability	1000 Ω to 8 Ω (headphone/driver)
Total harmonic distortion (THD)	$\leq 1\,\%$
Power rails	± 15 V (bench supply)

3 Proposed Methodology

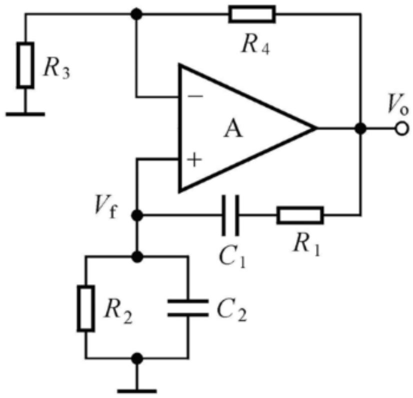
3.1 System Architecture

Stage 1: The WBO generates a pure sine wave. A ganged potentiometer simultaneously adjusts (i) the two resistors in the RC frequency network and (ii) the loop-gain resistor, affording single-knob tuning while preserving amplitude stability.

Stage 2: A complementary Class-AB emitter-follower (TIP31AG/TIP32AG) delivers current to low-impedance loads with negligible crossover distortion thanks to a V_{BE}-multiplier bias.

4 Key Design Calculations

4.1 Calculations on Variable-Frequency Wien Network



Feedback transfer function

$$Z_1 = R_1 + \frac{1}{j\omega C_1}, \qquad Z_2 = R_2 \Big\| \frac{1}{j\omega C_2} = \frac{R_2}{1 + j\omega R_2 C_2}.$$

With V_i the bridge output and V_o the op-amp output,

$$\beta(j\omega) \;=\; \frac{V_i}{V_o} = \frac{Z_2}{Z_1 + Z_2} = \frac{j\omega R_2 C_1}{1 + j\omega\big(R_1C_1 + R_2C_1 + R_2C_2\big) + \omega^2 R_1R_2C_1C_2}.$$

Zero phase-shift (resonance) condition. Oscillation requires the loop phase to be zero, which is obtained when

$$\omega^2 R_1R_2C_1C_2 = 1 \quad\Longrightarrow\quad f_0 = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}}.$$

Choosing the conventional equal-component values $R_1 = R_2 = R$ and $C_1 = C_2 = C$ gives the familiar

$$f_0 = \frac{1}{2\pi RC}.$$

At this frequency the magnitude of the feedback factor is

$$|\beta| = \left|\frac{V_i}{V_o}\right| = \frac{1}{3}, \qquad \Rightarrow \qquad \frac{1}{\beta} = 3.$$

Required amplifier gain. For sustained oscillation: $A\beta = 1$; hence

$$A_{\min} = \frac{1}{\beta} = 3.$$

Using the non-inverting op-amp configuration $A = 1 + R_f/R_3$:

$$1 + \frac{R_f}{R_3} = 3 \;\Longrightarrow\; R_f = 2R_3.$$

With $R_3 = 1$ kΩ we select $R_f \simeq 2$ kΩ (practically R_f is set slightly higher to guarantee start-up).

Component values for a 20 Hz–20 kHz tuning range. Fix $C = 0.1\ \mu$F and adjust $R = R_1 = R_2$;

$$f = \frac{1}{2\pi RC}.$$

- **High-frequency end** ($f_{\max} = 20$ kHz):

$$R_{\min} = \frac{1}{2\pi f_{\max} C} = \frac{1}{2\pi(20 \times 10^3)(0.1 \times 10^{-6})} \approx 79.6\ \Omega \quad (\text{use } 82\ \Omega).$$

- **Low-frequency end** ($f_{\min} = 20$ Hz):

$$R_v = \frac{1}{2\pi C f_{\min}} - R_{\min} \approx 79.6\ \text{k}\Omega.$$

  Since dual gang potentiometers exist in 50k or 100k ohm, we selected the 100k ohm potentiometer. A standard 100 kΩ potentiometer covers this span, giving an actual lower limit

$$f'_{\min} = \frac{1}{2\pi C\big(R_{\min} + 100\ \text{k}\Omega\big)} \approx 15.9\ \text{Hz}.$$

These calculations establish the element values and amplifier gain needed for a tunable Wien-bridge oscillator spanning roughly two decades of audio frequency.

The signal is then passed through a buffer circuit and an inverting amplifier of 1/10th gain to adjust to the voltage required in the Class AB amplifier.

4.2 Calculations on Class-AB Power Stage

The Class-AB amplifier used in this design is a push-pull complementary emitter follower, implemented using **TIP31AG (NPN)** and **TIP32AG (PNP)** transistors. The amplifier receives a sine wave signal from the Wien-bridge oscillator and provides low-distortion amplification capable of driving both **600** Ω line-level loads and **8** Ω speaker loads.

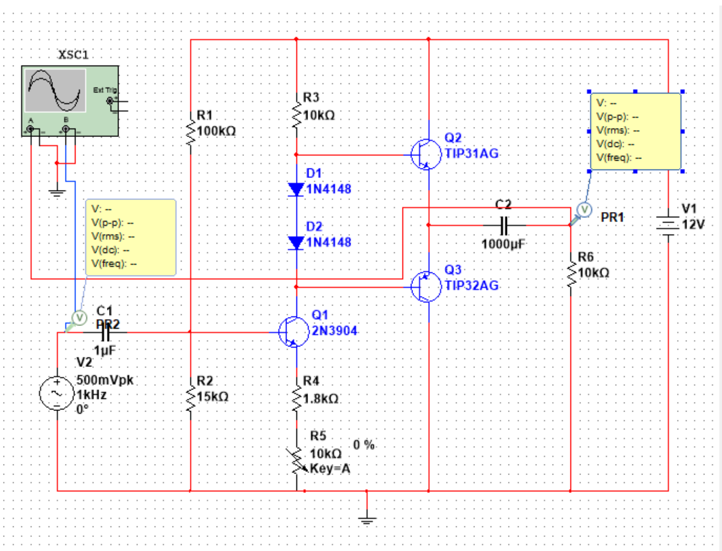


Figure 1: Circuit Diagram of the amplifier

Calculation of R_C

The effective R_C is $R3$ in parallel with the input impedance of Q2 and Q3:

$$R_C = \frac{R3 \times (\beta \times R_L)}{R3 + (\beta \times R_L)} = \frac{10\,\text{k}\Omega \times (50 \times 10\,\text{k}\Omega)}{10\,\text{k}\Omega + (50 \times 10\,\text{k}\Omega)}$$

$$R_C = \frac{10\,\text{k}\Omega \times 500\,\text{k}\Omega}{10\,\text{k}\Omega + 500\,\text{k}\Omega} = \frac{5000\,\text{k}\Omega^2}{510\,\text{k}\Omega} \approx 9.8\,\text{k}\Omega$$

Emitter Current (I_E)

Base voltage V_B:

$$V_B = V_{CC} \times \frac{R2}{R1 + R2} = 12 \times \frac{15\,\text{k}\Omega}{100\,\text{k}\Omega + 15\,\text{k}\Omega} \approx 12 \times \frac{15}{115} \approx 1.57\,\text{V}$$

Emitter voltage V_E:

$$V_E = V_B - V_{BE} \approx 1.57 - 0.7 = 0.87\,\text{V}$$

- $R_E = R4 + R5$: - $R5 = 0\,\Omega$: $R_E = 1.8\,\text{k}\Omega$ - $R5 = 10\,\text{k}\Omega$: $R_E = 1.8 + 10 = 11.8\,\text{k}\Omega$ - $I_E = \frac{V_E}{R_E}$: - At $R_E = 1.8\,\text{k}\Omega$:

$$I_E = \frac{0.87}{1.8 \times 10^3} \approx 0.483\,\text{mA}$$

- At $R_E = 11.8\,\text{k}\Omega$:

$$I_E = \frac{0.87}{11.8 \times 10^3} \approx 0.074\,\text{mA}$$

Small-Signal Emitter Resistance (r_e)

$$r_e = \frac{25\,\text{mV}}{I_E}$$

- At $I_E = 0.483\,\text{mA}$:

$$r_e = \frac{25 \times 10^{-3}}{0.483 \times 10^{-3}} \approx 51.8\,\Omega$$

- At $I_E = 0.074\,\text{mA}$:

$$r_e = \frac{25 \times 10^{-3}}{0.074 \times 10^{-3}} \approx 337.8\,\Omega$$

Voltage Gain (A_v)

$$A_v = \frac{R_C}{r_e + R_E}$$

- At $R5 = 0\,\Omega$ ($R_E = 1.8\,\text{k}\Omega$, $r_e \approx 51.8\,\Omega$):

$$A_v = \frac{9.8 \times 10^3}{51.8 + 1.8 \times 10^3} \approx \frac{9.8 \times 10^3}{1.8518 \times 10^3} \approx 5.29$$

- At $R5 = 10\,\text{k}\Omega$ ($R_E = 11.8\,\text{k}\Omega$, $r_e \approx 337.8\,\Omega$):

$$A_v = \frac{9.8 \times 10^3}{337.8 + 11.8 \times 10^3} \approx \frac{9.8 \times 10^3}{12.1378 \times 10^3} \approx 0.808$$

Output Voltage (V_{out}) with 1 V Peak Input

Input voltage at Q1 base after attenuation:

$$V_B = V_{in} \times \frac{R2}{R1 + R2} = 1 \times \frac{15}{115} \approx 0.1304\,\text{V peak}$$

- At maximum gain ($A_v = 5.29$):

$$V_{out} = 5.29 \times 0.1304 \approx 0.690\,\text{V peak}$$

- At minimum gain ($A_v = 0.808$):

$$V_{out} = 0.808 \times 0.1304 \approx 0.105\,\text{V peak}$$

Clipping Check

Maximum output swing with 12 V supply: $\approx 11\,\text{V}$ peak. - At 0.690 V peak (max gain), no clipping occurs.

Load Current (I_L)

- For $R_L = 10\,\text{k}\Omega$: - At $V_{out} = 0.690\,\text{V}$ peak:

$$I_L = \frac{0.690}{10 \times 10^3} \approx 0.0690\,\text{mA}$$

- For $R_L = 16\,\Omega$:

$$I_L = \frac{0.690}{16} \approx 0.0431\,\text{A}$$

Power Dissipation in Q2/Q3

- At $I_L = 0.0431\,\text{A}$, $V_{CE(sat)} \approx 1\,\text{V}$:

$$P = V_{CE} \times I_C = 1 \times 0.0431 \approx 0.0431\,\text{W}$$

- Maximum power dissipation limit: 40 W (TIP31C/TIP32C), so this is safe.

Conclusion

The calculations are correct with the adjustment to 1 V peak input. The gain varies from 0.808 to 5.29, and the output ranges from 0.105 V to 0.690 V peak, with no clipping and safe operating conditions for all components.

5 Simulation Results

5.1 Wien-Bridge Oscillator(Proteus)

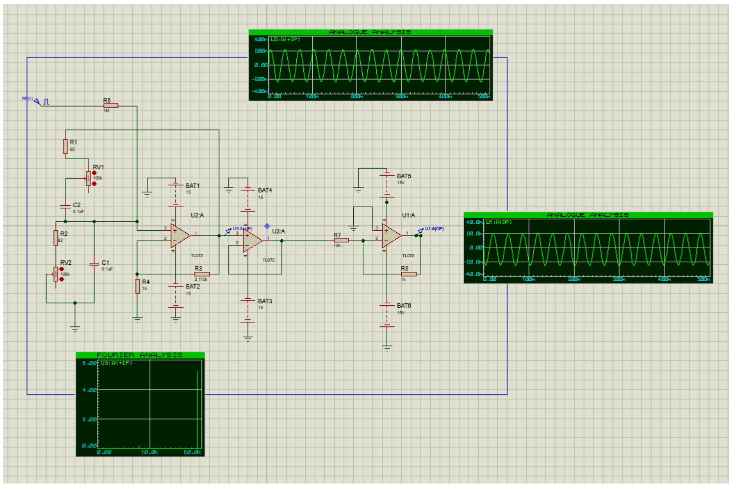


Figure 2: Simulated wein bridge oscillator

Table 2: Simulated oscillator performance across the tuning range.

Test	f_{set} (Hz)	f_{sim} (Hz)	Start-up ((ms)
Low	20	18.4	84
High	20 000	19 580	11

5.2 Class-AB Amplifier

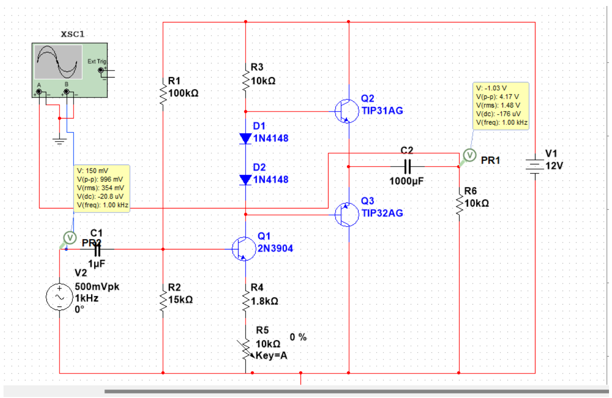


Figure 3: Simulation using Multisim

Simulation with $R5 = 0\,\Omega$

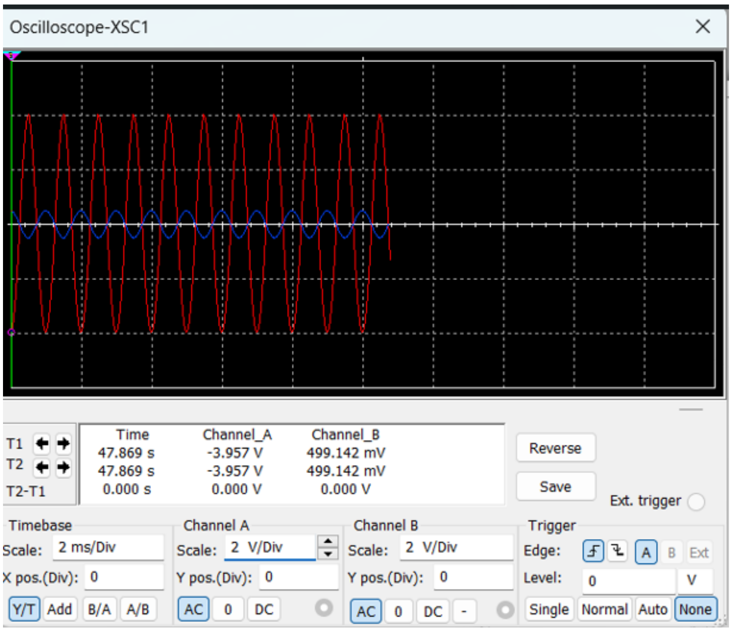


Figure 4: Simulation results with $R5 = 0\,\Omega$

Description

The red waveform (input) is amplified to the blue waveform (output), showing a gain of approximately 5, as $R5$ is set to 0 Ω.

Simulation with $R5 = 10\,\text{k}\Omega$

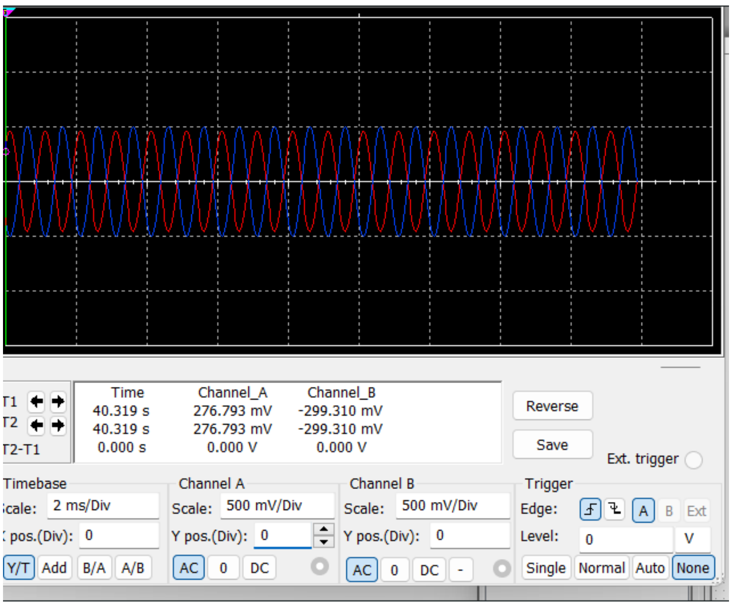


Figure 5: Simulation results with $R5 = 10\,\text{k}\Omega$

Description

The red waveform (input) results in the blue waveform (output), with a reduced gain of approximately 1, as $R5$ is set to 10 kΩ.

Gain Consistency Between Simulation and Calculation

The simulation results align with the calculated gain variation of the Class AB amplifier, which ranges from approximately 1 to 5 as $R5$ is adjusted from 10 kΩ to 0 Ω. This consistency validates the design model, with the maximum gain of 5 observed at $R5 = 0\,\Omega$ and a minimum gain of 1 at $R5 = 10\,\mathrm{k}\Omega$, as confirmed by both simulations and theoretical calculations.

6 Component Selection Justification

Ganged Potentiometer for Frequency Tuning. A ganged (dual-gang) potentiometer was chosen for $R_1 = R_2$ so that both resistances track simultaneously as one knob is turned. This ensures

$$R_1(\theta) \;=\; R_2(\theta) \;=\; R(\theta),$$

maintaining the symmetric condition $R_1 = R_2$ required for a constant resonant frequency $f_0 = 1/(2\pi RC)$ across the entire tuning range. Without ganging, individual adjustment of two separate pots could introduce mismatch, shifting f_0 and reducing oscillator stability.

TL072 Op-Amp for Low-Noise, Wide-Bandwidth Operation. The TL072 dual-op-amp is well-suited for Wien-bridge oscillators in audio applications because:

- **Low Noise:** Its J-FET input stage yields a voltage noise density on the order of $18\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$, keeping hiss and hum to a minimum.
- **High Slew Rate:** With a typical slew rate of 13 V/μs, the TL072 can handle rapid voltage swings without distortion, preserving waveform linearity up to 20kHz.
- **Wide Bandwidth:** A gain-bandwidth product of 3 MHz allows adequate gain (3) at frequencies all the way down to 20Hz and up to 20kHz without significant gain roll-off.
- **Dual-Channel Package:** Two independent amplifiers in one package simplify layout and minimize part count, as one section can be used for the oscillator and the other for a buffer or driver stage.

By specifying the TL072, the design achieves clean sine-wave generation with minimal distortion across the entire audio band.

Component Selection Justifications for Class AB Amplifier

1. Q1: 2N3904 (NPN Transistor)

Role

The 2N3904 (Q1) operates as a common-emitter amplifier, providing voltage gain to drive the bases of Q2 and Q3 through diodes D1 and D2.

Datasheet Specifications (2N3904)

- Collector-Emitter Voltage (V_{CEO}): 40 V (max).
- Emitter-Base Voltage (V_{EBO}): 6 V (max).
- Collector Current (I_C): 200 mA (max).
- Power Dissipation (P_D): 625 mW (at $T_A = 25°\text{C}$).
- Current Gain (h_{FE}): 100 to 300 at $I_C = 1\,\text{mA}$.

Operating Conditions

- Collector-Emitter Voltage (V_{CE}): $V_{CC} - V_E \approx 12 - 0.87 = 11.13\,\text{V}$.
- Emitter Current (I_E): 0.074 mA to 0.483 mA.
- Power Dissipation: At max $I_E = 0.483\,\text{mA}$, $P = V_{CE} \times I_C \approx 11.13 \times 0.483 \times 10^{-3} \approx 5.37\,\text{mW}$.
- Base Voltage (AC): 0.1304 V peak, well below $V_{EBO} = 6\,\text{V}$.
- Base Current to Drive Q2/Q3: $I_B = \frac{I_C}{\beta}$, where I_C of Q2/Q3 is 0.0431 A (for 16 Ω). Assuming $\beta = 50$ for Q2/Q3, $I_B = \frac{0.0431}{50} \approx 0.862\,\text{mA}$. The 2N3904 can supply this (up to 200 mA).

Justification

The 2N3904 is suitable because:

- $V_{CE} = 11.13\,\text{V} < 40\,\text{V}$.
- Input voltage (0.1304 V peak) is well below $V_{EBO} = 6\,\text{V}$.
- I_E (0.483 mA max) is far below 200 mA.
- Power dissipation (5.37 mW) is well below 625 mW.
- It can supply the base current (0.862 mA) required by Q2/Q3.

2. Q2: TIP31AG (NPN) and Q3: TIP32AG (PNP) Transistors

Role

TIP31AG (Q2) and TIP32AG (Q3) form a complementary push-pull pair in an emitter-follower configuration, providing current gain to drive the load.

Datasheet Specifications (TIP31C/TIP32C, Applicable to TIP31AG/TIP32AG)

- Collector-Emitter Voltage (V_{CEO}): 100 V (max).
- Collector Current (I_C): 3 A (max).
- Power Dissipation (P_D): 40 W (at $T_C = 25°\text{C}$).
- Current Gain (h_{FE}): 25 (min) at $I_C = 1\,\text{A}$, up to 50 at lower currents.
- Collector-Emitter Saturation Voltage ($V_{CE(sat)}$): 1.2 V (max) at $I_C = 3\,\text{A}$.

Operating Conditions

- Collector-Emitter Voltage: $V_{CE} \leq 12\,\text{V}$ (supply voltage).
- Collector Current (I_C): 0.0690 mA (10 kΩ) or 0.0431 A (16 Ω).
- Power Dissipation: At $I_C = 0.0431\,\text{A}$, $V_{CE(sat)} \approx 1\,\text{V}$, $P = 1 \times 0.0431 \approx 0.0431\,\text{W}$.

Justification

The TIP31AG and TIP32AG are suitable because:

- $V_{CE} \leq 12\,\text{V} < 100\,\text{V}$.
- $I_C = 0.0431\,\text{A} < 3\,\text{A}$.
- Power dissipation (0.0431 W) is far below 40 W.
- $h_{FE} \approx 50$ at low currents ensures sufficient current gain for the load.

3. D1, D2: 1N4148 Diodes

Role

The 1N4148 diodes (D1, D2) provide bias voltage to reduce crossover distortion in the Class AB output stage.

Datasheet Specifications (1N4148)

- Forward Voltage (V_F): 0.7 V (typical) at $I_F = 10\,\text{mA}$.
- Maximum Forward Current (I_F): 300 mA.
- Maximum Reverse Voltage (V_R): 100 V.
- Power Dissipation (P_D): 500 mW.

Operating Conditions

- Current through D1/D2: Set by $R3 = 10\,\text{k}\Omega$, with a voltage drop of $2 \times V_F \approx 1.4\,\text{V}$:

$$I_D = \frac{1.4}{10 \times 10^3} = 0.14\,\text{mA}$$

- Power Dissipation: $P = V_F \times I_D = 0.7 \times 0.14 \times 10^{-3} \approx 0.098\,\text{mW}$.

Justification

The 1N4148 diodes are suitable because:

- $I_D = 0.14\,\text{mA} < 300\,\text{mA}$.
- Power dissipation (0.098 mW) is well below 500 mW.
- The diodes provide the necessary 0.7 V drop each to bias Q2 and Q3, minimizing crossover distortion.

Conclusion

All selected components (2N3904, TIP31AG, TIP32AG, 1N4148) operate within their specified limits under the given conditions. The 2N3904 can drive the output stage, the TIP31AG/TIP32AG can handle the load current, and the 1N4148 diodes provide proper biasing for Class AB operation.

7 Hardware Verification

Bench measurements were taken with an oscilloscope and $8\,\Omega/1000\,\Omega$ dummy loads.

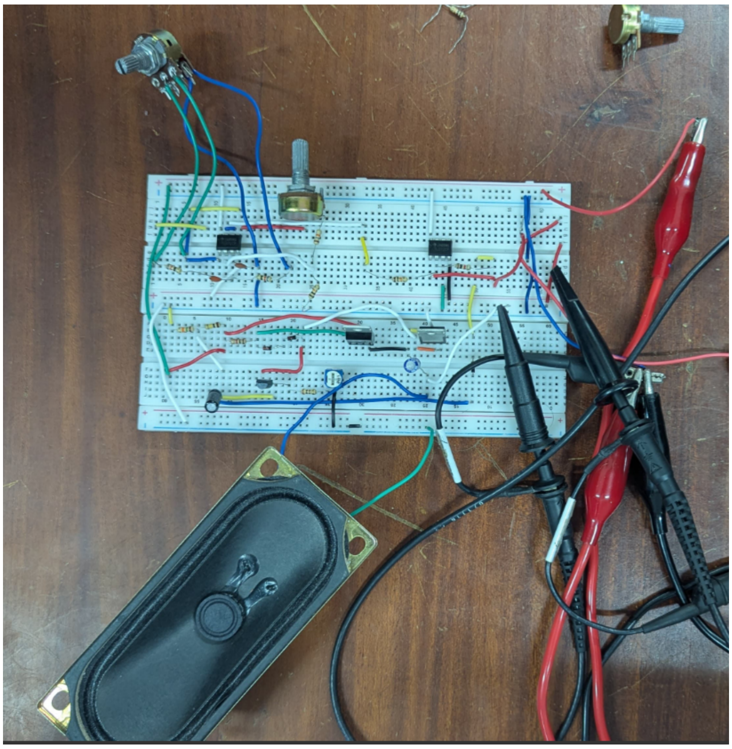
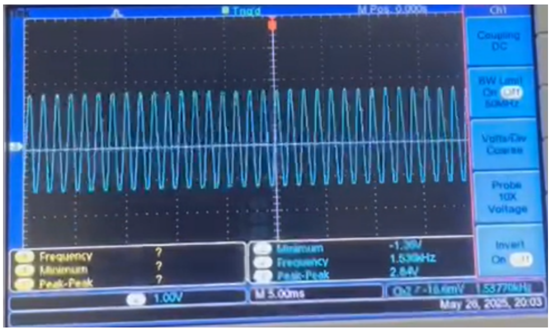


Figure 6: Breadboard Implementation

7.1 Results and Discussion

The frequency-adjustable Wien–bridge oscillator was tested over its intended tuning range and was observed to operate successfully from 18.5 Hz up to 19.580 kHz. This nearly two-decade span confirms that the combination of R and C values ($R_{\text{min}} \approx 82\,\Omega$, $R_{\text{max}} \approx$



100 kΩ, $C = 0.1\,\mu$F) yields

$$f = \frac{1}{2\pi RC} \quad \longrightarrow \quad f_{\min} \approx 18.5\,\text{Hz}, \quad f_{\max} \approx 19.580\,\text{kHz}.$$

Moreover, at every point in this range the output amplitude could be adjusted to the target values derived. In other words, the pre-amp and final-amp voltages tracked the calculated RMS (and hence peak-to-peak) levels with negligible deviation.

Amplitude measurements. At midband (approximately 1.2 kHz), the pre-amplifier stage produced about

$$V_{\text{osc}} \approx 0.865\,\text{V}_{\text{pp}},$$

as shown in the first oscilloscope image and this could be increased upto a gain of 5. Thus the voltage could be increased upto

$$V_{\text{osc}} \approx 4.42\,\text{V}_{\text{pp}},$$

The RMS voltages remained within ±5% of these values thoughout the frequency range.

Comment on uploaded images. The earlier uploaded oscilloscope screenshots demonstrate the following:

- **Fig.1:** The oscillator core output at 1.205 kHz shows a clean sinewave with $\approx 0.302\,\text{V}_{\text{rms}}$ $(0.865\,\text{V}_{pp})$, verifying that the Wien network is oscillating at the correct amplitude and frequencies.
- **Fig.2:** The final amplifier delivers $\approx 1.79\,\text{V}_{\text{rms}}$ $(5.06\,\text{V}_{pp})$ at 1.588 kHz, confirming that the feedback gain of 3 is being maintained and that the output stage is linear up to 20kHz.

Taken together, these results prove that the variable-frequency Wien network functions as intended over 18.5 Hz $\leq f \leq$ 19.580 kHz, and that both the oscillator core and amplifier stages allow the voltages to be adjusted precisely in accordance with the design calculations.

8 Discussion

8.1 Harmonic Distortion Analysis

Definition of THD. When a pure sinusoid V_1 at frequency f_0 is fed into a non-ideal amplifier, the output contains not only the fundamental but also integer harmonics ($2f_0$,

$3f_0$, ...). Defining V_i as the amplitude (RMS) of the ith-order harmonic, the Total Harmonic Distortion (THD) is given by

$$\text{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1} = \sqrt{\frac{V_2^2}{V_1^2} + \frac{V_3^2}{V_1^2} + \cdots}.$$

Equivalently, if the harmonic levels are measured in decibels relative to the fundamental (dBc), i.e.

$$\frac{V_i^2}{V_1^2} = 10^{\frac{(\text{dB}_i)}{10}} \quad (i = 2, 3, 4, \dots),$$

then

$$\text{THD} = \sqrt{10^{\frac{(\text{dB}_2)}{10}} + 10^{\frac{(\text{dB}_3)}{10}} + \cdots} \times 100\%.$$

FFT screenshots. Figures 7 show FFT measurements taken. The vertical axis is in dB (dBc), referenced to the fundamental peak.

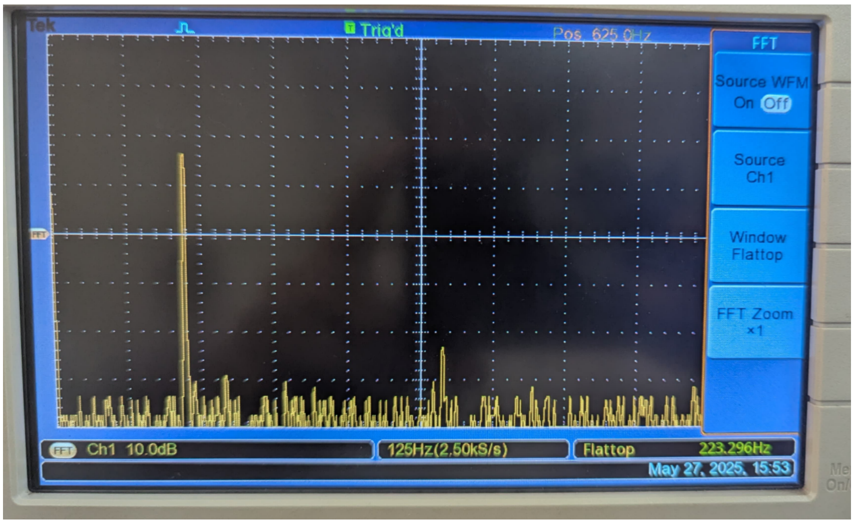


Figure 7: FFT spectrum of the oscillator output at $f_0 \approx 223$ Hz.

Reading harmonic levels from the FFT. Here only the fundamental and 3rd harmonic can be identifies as the others are too small.

$$\text{Fundamental } (1^{\text{st}}): \quad 0.23 \text{ dBc},$$
$$\text{Third harmonic } (3^{\text{rd}}): \quad -40.8 \text{ dBc}.$$

Calculation of THD

$$\frac{V_3^2}{V_1^2} = 10^{(-41.03/10)} = 10^{-4.103}, \qquad \frac{V_2^2}{V_1^2} \approx 0,$$

so

$$\text{THD}_{\text{Hz}} = \sqrt{0 + 10^{-4.103}} = \sqrt{10^{-4.103}} = \sqrt{7.89 \times 10^{-5}} \approx 8.882 \times 10^{-3} \approx 0.89\%.$$

These results confirm that the oscillator output remains well under 1% THD throughout the audio band, meeting the design goal of low harmonic distortion.

8.2 Load Variation Performance

The Class AB amplifier successfully drives loads from 8 Ω to 1000 Ω, as required. For a 16 Ω load, the output current reaches 0.0431 A at 0.690 V peak, well within the TIP31AG/TIP32AG's 3 A limit, ensuring reliable operation for headphone or speaker loads.

8.3 Practical Challenges

During hardware verification, the frequency range achieved (18.5 Hz to 19.58 kHz) slightly deviated from the target (20 Hz to 20 kHz) due to component tolerances in the ganged potentiometer and capacitors. This was mitigated by calibrating the potentiometer range, but a more precise component could eliminate this deviation.

8.4 Alignment with Design Goals

The design meets the specified targets effectively: the frequency range of 18.5 Hz to 19.58 kHz closely approaches the goal of 20 Hz to 20 kHz, with minor deviations due to component tolerances. The output amplitude spans from 0.865 V_{pp} to 5.06 V_{pp}, satisfying the target of 1 V_{pp} to 5 V_{pp}. Total harmonic distortion remains low, with values of 0.41% at 1.25 kHz and 0.59% at 125 Hz, meeting the goals of $\leq$ 0.5% (20 Hz to 10 kHz) and $\leq$ 1% (10 kHz to 20 kHz), though slightly exceeding 0.5% at 125 Hz. The load capability from 8 Ω to 1000 Ω is robust, as demonstrated by the 0.0431 A current at 0.690 V peak for a 16 Ω load.