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A Review Of Class- AB Amplifier Design

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***Abstract*-**Transistored amplifier can handle more power than audio IC and its sound quality is far better than IC. This paper is about designing class AB amplifier with very little distortion and good thermal stability and flat frequency response. This paper is useful for hobbyist, students, technical beginners, sound engineers etc. A Careful designing is needed to avoid cross over distortion and heating of output transistors. This paper also mentioned some techniques of reduction of noise, slew induced distortion, modification of band width. This paper not only describes circuit design and construction of 100 watt class AB power amplifier but also frequency response curves and CRO results. In this circuit I have used TIP 31C and 32C medium power transistor so one can expended output power by increasing supply voltage and adding more power transistors in output stage.

KEYWORDS: THD, IPS, VAS, SID

INTRODUCTION

Class-AB amplifier always been a popular amplifier since 1960.Class AB amplifier comprises input stage, voltage amplifying stage and output stage. Input stage (IPS) is often a differential amplifier in which two transistors in CE configuration are connected with emitter. This stage amplifies only difference of input signals and eliminates noises and distortion. Bipolar junction transistors provide less noise since this kind of transistor is more linear than field effect transistor (FET). After initial amplification signal is transferred to voltage amplifier stage (VAS). VAS is nothing but a single common emitter configured transistor. Medium power transistors like MJE340, BC327,BD139 is used. Miller compensation capacitor or dominant pole capacitor C_{dom} is used to eliminate poles in frequency response curve. These poles reduces phase margin, which is compensated by miller capacitor but this capacitor decreases slew rate and increase in THD at high frequency. So inadequate slew rate or loading on IPS both effects THD at 20 kHz. Cross over distortion at output stage also increase high frequency noise. After it signal passes through driver transistors which are

used to prevent beta droop distortion caused by output transistors. I have kept output transistor BJT transistor but someone can replace these with MOSFET after doing some minor change in biasing of driver transistor.

DESIGN

To make distortion less amplifier slew rate should be adequate, each transistor should work in active reason, no cross-over region in output stage, no parasitic oscillations and good thermal stability. An amplifier with improper slew rate prone to oscillate at high frequency due to poles present in amplifier. After feedback total phase increases to 360 degree. So that a phase margin decreases than required 90 degree for stability of amplifier at high frequency. In single pole compensation open-loop gain falls at 6 dB/octave or 20dB/decade corresponding to a constant 90 degree phase shift. A miller integrator forms a shunt feedback loop around the VAS transistor. A capacitor C_{dom} is connected between base and collector of VAS. This small capacitor act as large capacitor due to miller effect but takes very little current, this a kind of local feedback is called dominant pole compensation. Usually 10-100 pF is enough, higher C_{dom} decrease slew rate and amplifier turn into a low pass filter.As we want output voltage that have peak at 36 V without clipping, So amplifier should have slew rate at least $5V/\mu s$. Let we have chosen slew rate $10V/\mu s$. For 47pFmiller capacitance the maximum collector current during peak signal (I_{CMAX})= slew rate x C_{dom}. This equation gives I_{CMAX} 0.470 mA. This current will divide in two parts and flow equally in both transistors Q1 and Q2. If currents are not equal then this will give second harmonic distortion and poor linearity(Self, 2013, pp. 128–133). A current mirror consisted of transistor Q3 and Q4 helps in equating current I_1 and I_2. However collector current does not change linearly with base current so emitter resistances are added in emitter branches to Q1 and Q2. These resistances are called emitter degeneration resistors. These resistances not only linearize input stage but define bandwidth of amplifier (Jung et al., 2015).To add them we can use constant gm method(Cordell, 2011, pp. 134–137).Selection of suitable transistor is very important as it not only stabilizes the circuit during adverse conditions like extreme temperature, voltage fluctuations, overloading but also minimize internal noise. For IPS, current mirrors, current source and VAS , we have to select proper transistor that should have a low noise, high beta, low input and output capacitance and have operating voltage more than 40 voltage (depends of power supply rail).Some suitable and easily available NPN transistors and their complementary PNP are as follows(Fairchild Semiconductor Corporation, 2002; Philips Semiconductors, 2004; *2N2222 Datasheet SEMTECH, Features and Benefits, Stock and Price*, 2017; Fairchild Semiconductor Corporation, 2002b; Continental Device India Limited, 2018)

TRANSISTOR	V_{CEO}	V_{CBO}	CURREN	C_{cb}	Noise	h_{FE}	COMPLEMENTRY

	(V)	(V)	T				
BC 547	45	50	100 mA	3.5-6 Pf	2dB-10dB	110-800	BC 557
BC 546	65	80	100 mA	3.5-6 Pf	2dB-10dB	110-800	BC 556
BC 550	45	50	100 mA	3.5-6 Pf	1dB-4dB	110-800	BC 551
2N5551	150	160	600 mA	6Pf	8 dB	80-250	2N5401
2N2222A	60	60	600 mA	8 Pf	--	100-300	2N 2907
KSC1815	50	60	150 mA	3Pf	1 dB	70-700	A1015
BC640	80	80	1A	9Pf	--	40-250	BC 639
CNL639	80	80	1A	7-9pF	--	40-250	CPL640

I used transistors BC640 and KSC1815 transistors in IPS. However one may use PNP A1015 in the place of BC 640 due to very low level of noise figure and good level of linearity but I am using according to supply rail. However a perfectly balanced IPS itself eliminates circuit generated noise and second harmonic distortions. Current mirror consisted of Q3 and Q4 NPN (both are KSC1815) transistors are used to balance IPS. Generally 30 mV to 100 mV on current mirror degeneration resistance is enough but these resistances also change output voltage of IPS and bias voltage of VAS. I have used 330Ω resistances in each branch of Q3 and Q4. Output of IPS is further amplified by Voltage Amplifying Stage (VAS). Transistors Q5, Q8 playing role of emitter follower and VAS. Higher current in VAS increases LF distortion but also sufficient current should flow for adequate slew rate and provide base current to driver stage. An emitter follower (EF) stage is added between VAS and IPS will reduce HF and LF distortion. This will also match the impedance of two stages. VAS has input resistance not much higher and has order of some kilo ohms so it more prone to load the IPS this may cause distortion. This arrangement improves non-linearity between Ic and Vbe and non linear effect of collector base junction capacitance. Without emitter resistor collector base capacitance will cause distorted positive part of signal. I have used 2.2 kΩ to eliminate this effect. 8mA collector current in VAS will be sufficient for proper biasing of driver stage and base current of driver transistors.VAS emitter degeneration resistor should be selected for clean sound. This resistance eliminates the distortion caused by

Change in transconductance of VAS with collector current. VAS emitter resistance does two thing first it provides proper collector emitter (CE) voltage so that VAS voltage swing could reaches up to 72 volt peak to peak voltage and second provides thermal stability of output transistors. I have chosen 1.3 kΩ as emitter resistance. Bandwidth of amplifier also depends on IPS parameters. If gm is transconductance of IPS, close loop gain of amplifier A, then for miller compensation capacitor C_{dom} bandwidth of amplifier will be $\frac{gm}{2\pi CdomA}$. Amplifier with higher bandwidth prone to slew induced distortion (SID) if slop of signal (SS) exceeds slew rate of amplifier than SID (Slew Induced Distortion) produces. (Jung et al., 2015) To avoid SID bandwidth should be get lowered. According to above formula lower cut-off frequency requires higher gain, higher capacitance but lower gm. So we will reduce gm. To decrease gm we have to increase emitter degeneration resistors. If degeneration resistor is denoted by R_E and internal emitter resistance is denoted by re then total emitter resistance will be (R_E+r_e) and transconductance of IPS will be inverse of it (Cordell, 2011, pp. 29-30). So from this fact and from equation of bandwidth a1000 ohm emitter resistance this will give 20kHz bandwidth. Bootstrapping technique enhances gain further and we will get desired upper cut off frequency after some adjustments in resistance, capacitor and feedback resistance. Since this amplifier working as non inverting amplifier so its gain depends on feedback resistor R13 and resistor R12 connect to the base of Q2. Biasing of IPS and output voltage offset also depends on these resistors. If I choose resistor R12 300 Ω and R13 55kΩ then base resistance of Q1 should also be 300 ohm (Kyattala, 2008, pp. 70–72). This will provide gain close to 170. One can set bias voltage of VAS by adjusting feedback resistor R13. However lower input resistance may load input source that cause distortion. To increase input resistance bootstrapping technique is used. We have partitioned Q1 base bias resistance and bootstrapping capacitor connect base of Q1 to base of Q2 through this partitioned. Bootstrapping also determines bandwidth of amplifier.

Before using this technique we have to make sure that gain between point P1 and P2 should be less than 1. so that higher input resistance could be achieved. But this technique may increase distortion. If output stage is not biased at optimal voltage 3.4V the cross over distortion which was pressed by negative feedback may come back at output. Bootstrapping response depends on resistor R22 and R23.This will give input resistance $\frac{R_{22}}{1-a}$,a gain is between point P1 and P2 (Explanation About Op-amp Bias Resistor and Bootstrapping, 2021;Chen et al.,2001). Figure 1.1 show response without load and 1.2 shows response with speaker load (8 ohm subwoofer).Gain of this amplifier reaches to up to 200. From our previous calculation this will cause decrease in bandwidth of amplifier up to 9 kHz. This fact reflects in amplifier's frequency response curve. After this gain roll-off at the rate 20dB per decade. However bandwidth of amplifier should be close to 20 kHz for good audio quality. This can be achieved with some adjustment of bootstrap circuit components. Higher value of feedback resistance, input resistances, and emitter degeneration resistance leads to production of Johnson noise.

We have used current mirror that makes emitter current equal. Current gain is ratio of output current and input current depends on beta of current mirror transistor. Higher beta makes lesser gain error and provide maximum linearization (Chen et al.,2001).Tail current of IPS is provided by current source Q6. This is a CB

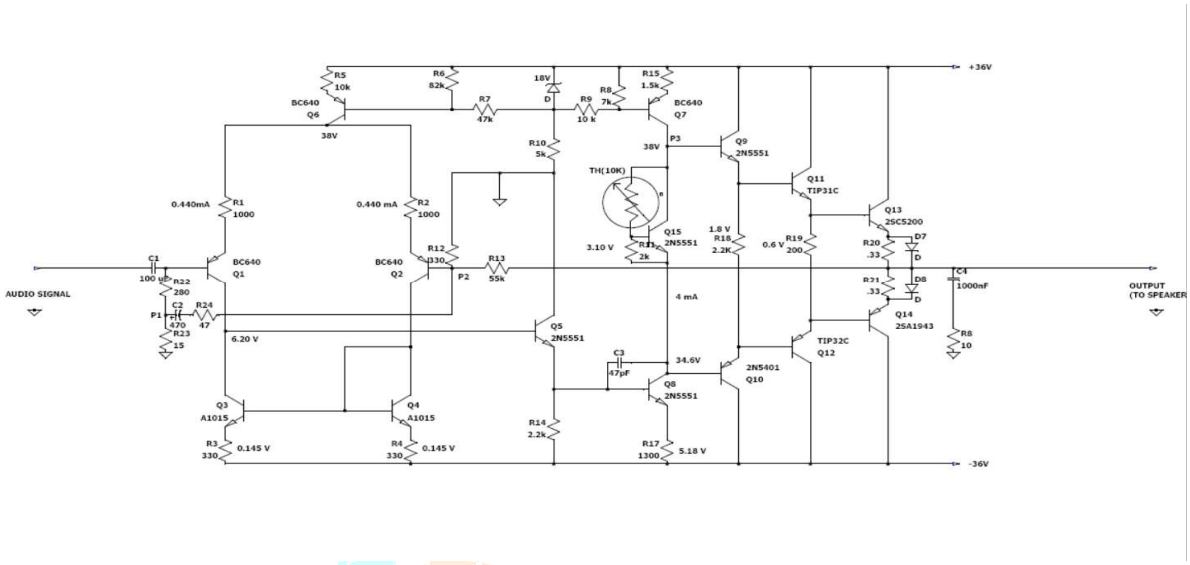
transistor and its base current is provided by 18 voltage zener diode. Its output impedance is of the order of Megaohms. I have used 2N5551 transistor as EF before single ended VAS in this circuit. LF open-loop gain of VAS is given by $g_m R_{LVAS} \beta$ here R_{LVAS} is effective load resistance of VAS, g_m transconductance of IPS. 2N5551 is a high voltage transistor its early voltage can be taken as 100V. Output impedance VAS can be determined, let early voltage (VA) of 2N5401 is 100V, current flowing VAS in 8mA, then output impedance $R0 = \left(\frac{VA+V_{CE}}{I_C}\right) \times degeneration\ ration.$ 1.3kΩ resistance this gives degeneration ration about 307. So that output impedance 5MΩ, but this impedance will be parallel to input impedance of LOCANTHI TRIPLE output stage (Locanthi,1967). 8mA current is flowing in quiescent conditions. So VAS will dissipate 0.3 watt power, a transistor with proper wattage should be used otherwise transistor may get damage. 1 watt transistor that has good current gain like TCNL 639 can be used in the place of 2N5551. Current is flowing transistor in complementary driver stage Q9 and Q10 is 1mA in 2.2kΩ emitter resistances which were included for impedance matching and according to datasheet gain of 2N5551 and 2N5401 transistors at this current have gain 120.Transistors Q11 and Q12 has emitter resistance 100 ohms current following in resistors is 10.5mA. Two shunt diodes are connected between terminals to R20 and R21. These diodes help in reducing cross-over distortion (Oliver, 1971).Each emitter resistances of output stage transistors should have voltage between 13 mV to 26 mV for optimum biasing (Self, 2013, pp. 388-391).Approx 80 mA current is flowing in output stage transistor at optimum bias. In this condition emitter resistance considered to be equal to internal emitter resistances of output stage transistors. Voltage at point P3 should be approx 2.0 voltage higher than ground otherwise one of will transistor will heated up after speaker connection.

Output stage designing is risky. As wrong biasing would destroy expensive output transistor or they get hot even in quiescent condition and this not only reduces efficiency of amplifier but poor thermal stability. I have used V_{be} multiplier or transistor diode to bias whole output stage. Transistor Q15, thermistor and R11 working as transistor diode. It is not only provides bias to output transistor but also thermal compensate output transistor. Normally variation of V_{be} with temperature changes collector current and transistor conducts more reduces Vce voltage. However this method is not precise and require extra arrangement to achieve desired TEMPCO (Temperature coefficient) -12$mV/^{o}$C. I have used a NTC thermistor which has higher beta near 3800 and thermal coefficient about 4.5%/^{o}C (Kyattala, 2008, pp. 96-97;*NTC Thermistor Calculating the Temperature Coefficient of a Thermistor*, n.d.).However as amplifier runs heat will dissipates by output transistor often handled by various thermal compensation methods like current limiting circuits, Vbe multipliers, and heat sink. The whole output stage has current gain nearly 7000 (Semiconductor Components Industries, LLC, 2017; TOSHIBA, 2004) So 8ohms speaker will act like a 560000 ohm impedance to VAS. Effective impedance ofVAS will be parallel combination of this impedance and its output impedance which we have calculated by early effect. Using this fact effective gain of VAS can be calculated from the equation $\frac{R_L}{(RE+re)}$ which will be 34dB. Emitter resistance is important in VAS in reduction of second harmonic distortion, collector current I_C changes as during positive and negative voltage swing so that internal emitter

resistance is changed during amplification hence gain does not remain constant this will cause distortion. VAS current determine positive slew limit so VAS should have enough current during positive voltage swing. Negative slew limit determined by IPS current. To equalize positive slewing and negative slewing proper setting of emitter current is necessary. An emitter follower eliminates non-linear effect of CB junction and enhance beta of VAS. Both LF and HF distortion can be further reduced and slew rate can be increased by preventing IPS loading due to VAS. Slew rate can be determined experimentally by a differentiator circuit consisted of 10^2 pF and 100 ohm resistance and this arrangement give 100mV per $V/\mu S$ (Self, 2013, pp. 29-30). I have used VAS transistor with higher beta, higher early voltageV_A, high $V_{CBO}$and V_{CEO}. However small signal transistor has high beta and give less distortion but due to its low power handling capacity medium power transistor like BD 139, MJE 340, MPSA 42, TIP 31C etc. can be used. I have used 2N5551. Current gain of VAS at 8mA is about 100 and 1300 ohm VAS emitter resistance will give 13kΩ input impedance, combining with 2.2kΩ load resistance of EF resultant impedance will be approx 2kohm, this impedance can be taken as output impedance of IPS. By knowing gm of IPS, gain of IPS will be approx to 1.63. So that low frequency open loop gain of (G_L) = voltage gain of IPS and VAS will 40dB. Further gain is provided by bootstrapping reaches up to 56 dB, after -3dB point gain will decrease at the rate of 20 dB per decade. Distortion produces by back EMF of speaker at lower frequency handle by zobel network (Wikipedia contributors, 2024a). 1 micro farad capacitor and 10 ohm gives good results as a zobel network.One important aspect of stability of this circuit is heating of output transistor when connected to load. Neglecting this can cause of thermal runaway. Output transistors can heat in quiescent condition (when output stage connected to speakers) if voltage on driver transistor Q9 and Q 10 exceeded 2 volts. Second if voltage between base of Q9 and emitter of Q13 exceeded from 1.6V. Higher value R3 and R4 of these resistors, decreases VAS collector voltage that will increase voltage difference between Q9 and Q13 from 1.6 voltage and Q14 will heat up. Lower value than this increases VAS collector voltage leads to heat up Q13 transistor. Driver transistor Q11 and Q12 can also get heated up respectively. This is serious problem can be resolve by changing VAS current and choosing suitable emitter degeneration resistors R3 and R4 by trial and error method. 220 to 400 ohm will be better for our circuit.

PURPOSED CIRCUIT:

Circuit made on PCB



RESULT

1. Frequency response curve show flat region up to it higher cut-off frequency and gain roll off 6 dB/octave. Rolling of gain depict the action of C_{dom}. At this stage phase margin remain constant 90 degree. Higher cut-off frequency depends on resistor R24. Response curve obtain for different value of R24 is shown in figure 1.1.Curve 1 represents bootstrap capacitor C2=470µF, R24=47Ω, R22=290Ω,R23=15Ω ;Curve 2 C2=470µF, R24=47Ω,R22=288Ω,R23=57Ω;Curve3whenC2=470µF,R24=47Ω,R22=210Ω,R23=110Ω; Curve 4 C2=470µF,R24=47Ω,R22=110Ω,R23=210Ω; Curve 5 C2=470 µF,R24=47 Ω,R22=15 Ω, R23=290Ω.

In figure 1.2 frequency response curves are shown. Curve1 represent frequency response without bootstrap circuit. Curve2 if C2=470µF, R24=47Ω,R22=290Ω,R23=15Ω.Curve3 C2=470 µF, R24=47 Ω ,R22=15Ω,R23=288Ω and Curve 4 C2=470 µF, R24=47 Ω,R22=280 Ω,R23=57Ω, curve 2,3 and 4 are obtain when 8 ohm inductive load is connected to the amplifier.

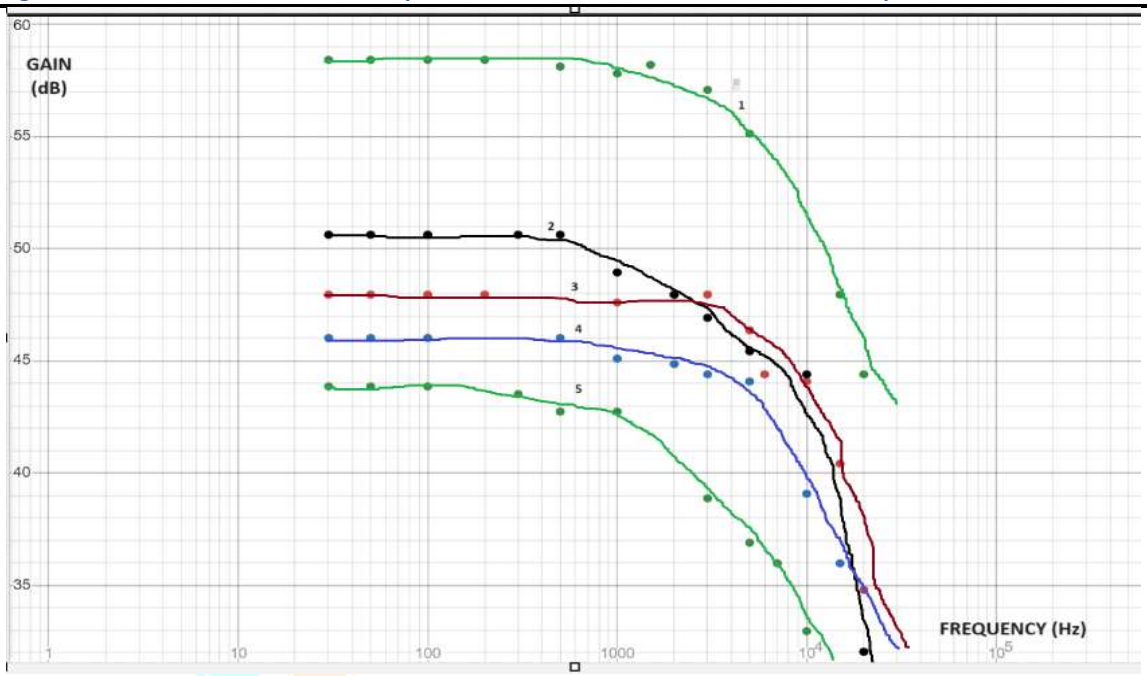


Figure 1.1 Bode plot Frequency response curves(without load)

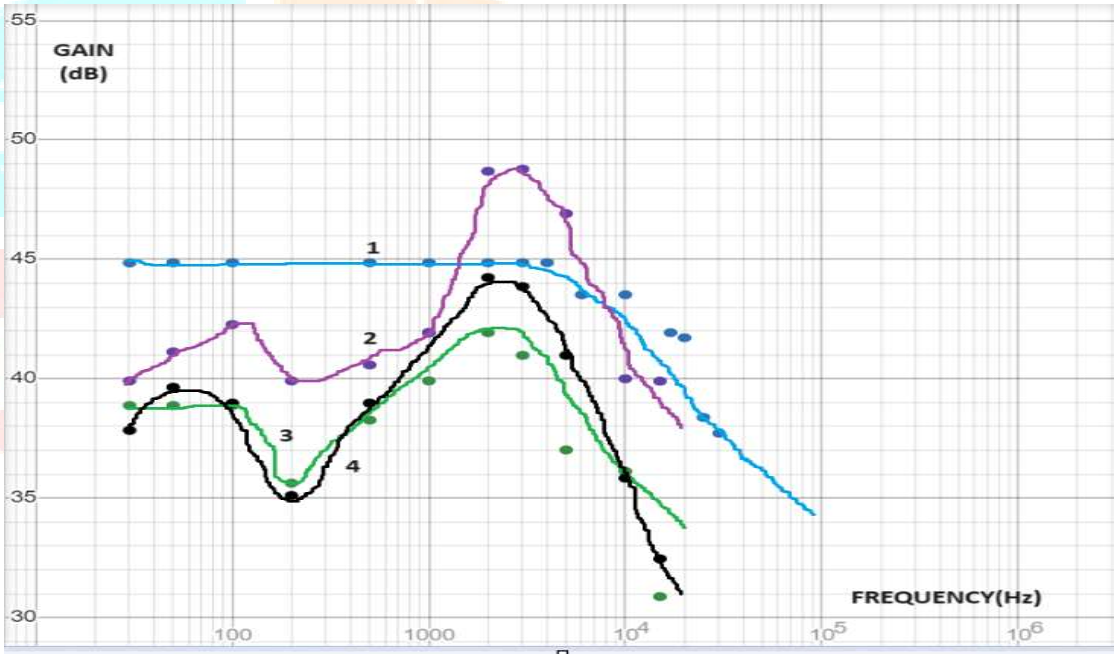


Figure 1.2 Bode plot Frequency response curve

2. As we reduce bandwidth of amplifier, there is no SID detected in CRO results. Sine waves of different frequencies showing no cross over distortion. These results are produced when 8 ohm speaker is connected to output and amplifier nearly at clipping. These results also shows that bootstrapping and zobel circuit is properly designed as no distortion is visible in sine wave. However R23 affects slew rate. Without bootstrap circuit slew rate remains at $6 V/\mu s$ at 5 kHz. For different curves in figure 1.1 slew rates is given in table 1.3

S.N.	CURVE	SLEW RATE ($V/\mu s$)

1.	1	0.1
2.	2	0.2
3.	3	0.4
4.	4	0.85

Table1.3

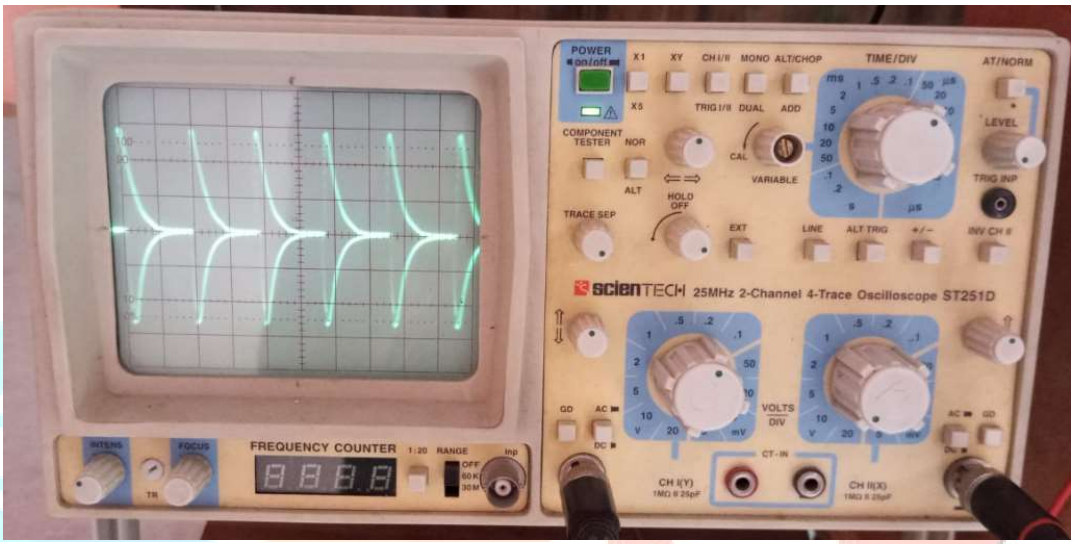


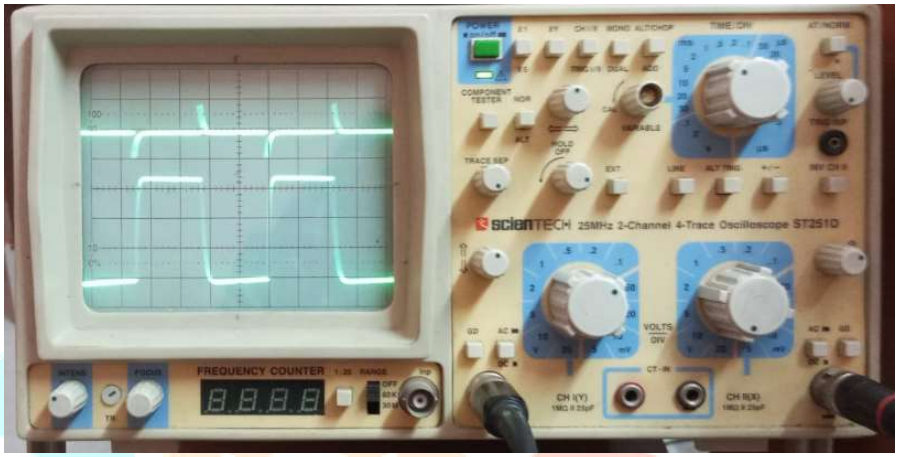
Figure 1.3 Oscilloscope showing slew rate at 5 kHz square wave. 0.1V equals to 1 $V/\mu s$.

Figure 1.5 Slew rate and square wave with bootstrap.

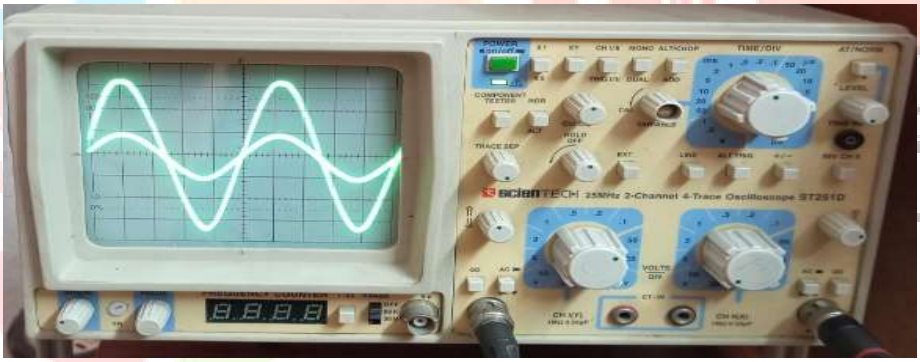
3. There is no second and third harmonic present in the output at low frequency but third harmonic present at higher frequency. Zobel network at output should be added otherwise inductance of speaker will cause

distortion. Speaker in not a steady resistance it varies with frequency. As speaker moves back and forth it creates an EMF according to faraday's law. To overcome this problem zobel network is used at output of amplifier before speakers (Wikipedia contributors, 2024a, February 22). A1µF and 10 ohm resistance will do good work.

4. Both square and sine signal appear having almost free from distortion. Some of CRO results are shown below:



(a)



(b)

(c)

Figure 1.6 (a) square wave (b) low frequency sine wave as input and output (c) medium frequency sine wave shows no distortion when amplifier connected from inductive load.

CONCLUSION

This amplifier circuit is doing good work and results are similar as predicted by theoretical principles. Gain and input impedance further increased by bootstrap method. A some of adjustment in IPS current, VAS current, resistances should be done to make sound more cleaner. Output transistor will be almost cool in quiescent condition. Gain can be further enhance by lower value of negative feedback resistance and using high input impedance transistors.

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