EEE226 Amplifiers

Hamish Sams

December 8, 2017

Abstract

This report explains the use of op-amps and transistors in the application of amplifiers and the use of passive components to create a 10x probe.

1 Introduction(10%)

This report is based around the use of components to create amplifiers. As well as positive gain amplifiers, we also talk about probes and their calibration. The aims of this report/lab are to understand why and how probes are built as they are and why we must calibrate them. We must also be able to understand and calculate component values for basic op-amp and transistor amplification circuits. Objectively from this lab we must output working circuits that amplify our signals and be able to explain any distortions or issues with the specific circuits used.

2 Background(20%)

2.1 Coaxial/BNC cables

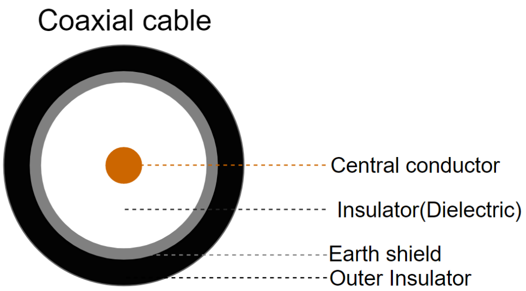


Figure 1: Cross-sectional diagram of a Coaxial cable (used for BNC cables)

Typical cables used are BNC cables as shown in Figure 1, It is designed so that if something interferes with the conductor it also affects the earth. This also means if the cable breaks the input shorts to ground.
With two conductors separated nearby, this creates a parasitic capacitance in parallel and a series resistance from the copper carrying the signal (Equivalent circuit shown in Figure 3).

Where R_C is the resistance of the coaxial cable (negligible when dealing with the majority of circuits) and C_C is the capacitance of the cable (negligible for low frequencies and DC).

2.2 Realistic oscilloscope

As we are using an oscilloscope to measure our values there is a parasitic capacitance. Our oscilloscope also has an input resistance (usually $1M\omega$) so this allows things such as our 10x probes to work. For a 1x system we would like this resistance to be infinite, so our oscilloscope can be modeled as seen in Figure 4.

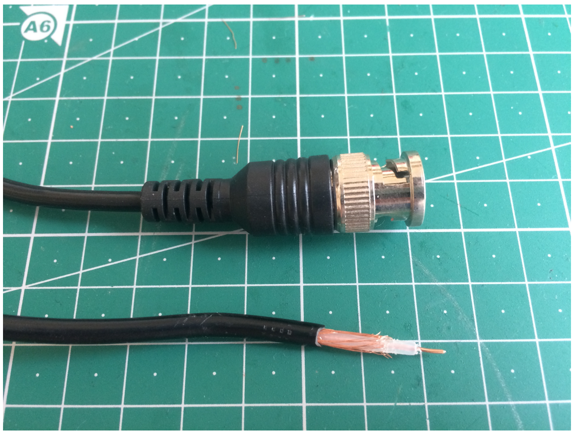


Figure 2: Cross-sectional picture of a Coaxial cable

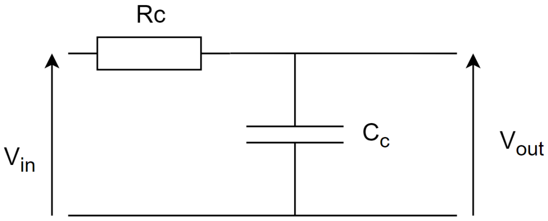


Figure 3: Equivalent circuit of a coaxial cable.

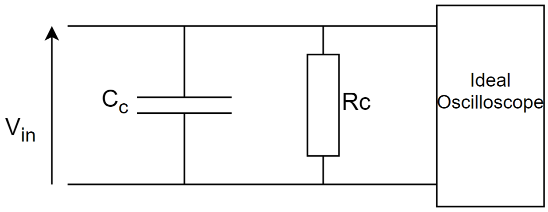


Figure 4: Realistic Oscilloscope

2.3 Rise and fall time/ Time constants

When we attach a capacitor to a voltage source, it begins to charge up, therefore increasing it's opposing voltage. This is caused by the charge accumulating on the plates, which means less voltage is over our resistance which then in turn means less current. Overall, this leads to slower charging (shown in equation 1).

$$V(t) = CV_i(1 - e^{(}\frac{-t}{\tau})) \tag{1}$$

τ is the capacitor/resistor network time constant where $\tau = RC$
Looking at the equation if $t = \tau$ we see that the output voltage is 63% of the input voltage (assuming the capacitor is initially discharged completely). Because of this, the voltage will never reach 100% of the supplied voltage.This is shown in Figure 5.

In this figure we can also see our rise time of the system (Shown in red) which is the time taken for the capacitor to charge from 10% to 90% (as we know the system shouldn't be able to actually reach 100%). Using Equation 1 we can input our rise time criteria and we can see that this time is given by $t = 2.2\tau$.
For Figure 5:
Red- Top and bottom 10% (Rise time)

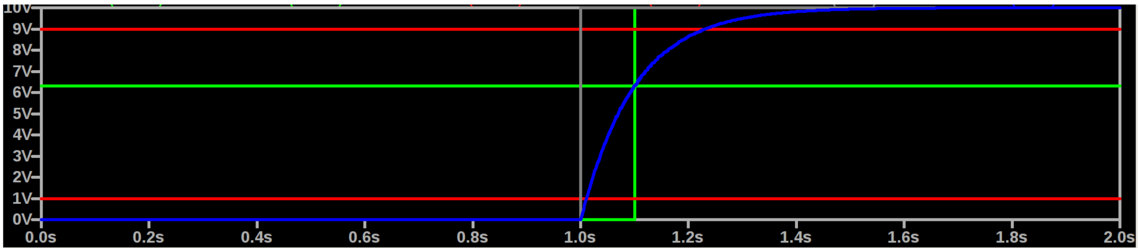


Figure 5: Capacitor charging over a fixed resistor

Green - τ = RC and that voltage a t τ is 63%

Blue - The voltage over the capacitor over time

Gray - Input voltage (on/off step)

2.4 Op-amps

2.4.1 General

The opamp is a very useful component due to its properties including huge input impedance, low output impedance (relatively) and its enormous open loop gain. The general equation for an opamps output voltage is shown in equation: 2

$$V_o = A_v(V_+ - V_-) \tag{2}$$

This equation tells us that the difference of the inputs V_+ and V_- is amplified by a factor A_v which is our open loop gain, this open loop gain is frequency dependent based on the construction of the op-amp shown in equation 3

$$A_v = \frac{A_0}{1 + j\frac{\omega}{\omega_0}} \tag{3}$$

A_0 is the open-loop DC gain; ω_0 is the -3dB point of the circuit ($2\pi f_0$). This frequency dependence is due to the internal capacitance and inductance of the circuit and therefore we can expect the familiar -20dB/Decade roll-off graph as show in Figure 7
From the equation we can tell when $\omega = \omega_0$ our system is at the corner frequency (imaginary = real) therefore we can expect a 45 degree phase shift just like an other RLC network.
If we look at our equation we can tell that if $1j\frac{\omega}{\omega_0}$ the magnitude is then given by $|A_v| = \frac{A_0}{\sqrt{2}}$ [1]

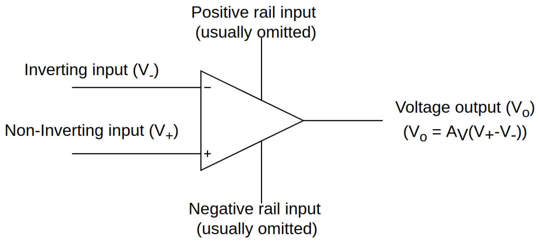


Figure 6: Basic op-amp layout

2.4.2 Fixed gain amplifier

This circuit is generally crafted using the circuit diagram shown in Figure 8 . Using our equations previously described in our op-amp section: If we assume $A_v >> 0$ we can use this to ignore tiny imperfections and simply say that $V_+ = V_-$ as long as our system is using negative feedback (imperfections are put into the inverting input altering the output which intern reduces the error). Using this we can say that our circuits gain is given by $G = \frac{R_2+R_1}{R1} = 1 + \frac{R_2}{R_1}$, this equation can then be used so we can set a fixed gain for our circuit (Non inverting). It is important to realize the difference between negative and positive feedback as we cannot use this with positive feedback(this

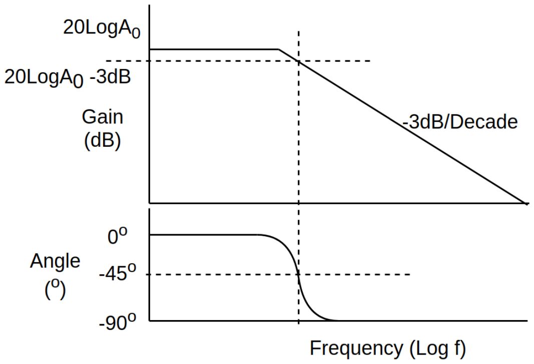


Figure 7: Op-Amp frequency based gain and phase shift.

amplifies error back into the input meaning the system could never act as an amplifier and can only exist in saturation, as shown ahead in Schmitt triggers).

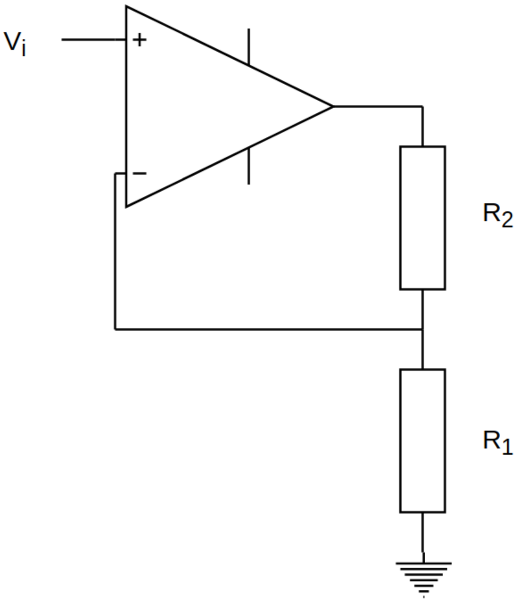


Figure 8: Fixed gain, negative feedback amplifier

2.4.3 Integrators

An integrator is a circuit designed to output the integral of the input. This circuit(Figure 9) is based around the use of a capacitors voltage being the integral of the current and so for the set current coming in, the capacitor will charge or discharge to equal the input current set by the output of the varying op-amp voltage.

2.4.4 Schmitt trigger

A Schmitt trigger uses positive feedback meaning any difference is instead amplified and therefore can only exist within saturation of either rail. [2]

2.5 Transistors

Transistors are by far the most used component throughout all electronics mainly due to the 4 states they can exist in (On,Off,Forward active, Reverse active). In our case we are talking about the amplification property and so we will ignore the other states. For a transistor to be in the correct bias, the voltage on the collector must be higher than the base voltage, which must be

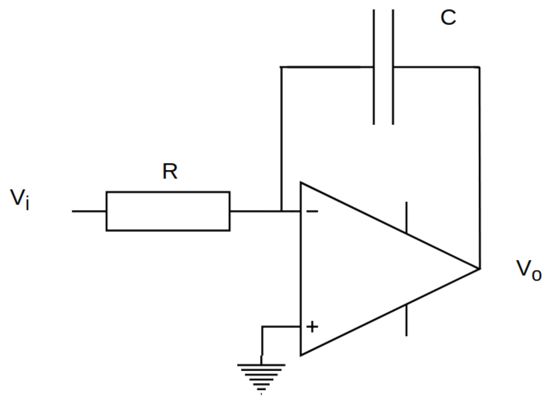


Figure 9: Integrator circuit.

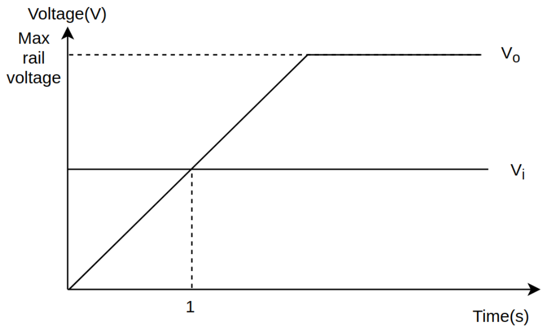


Figure 10: Integrator circuit input vs output for dc

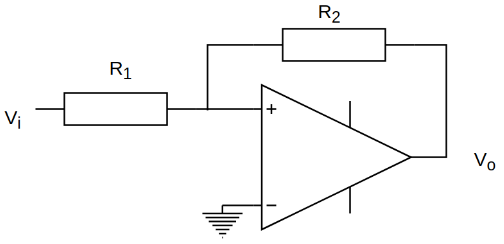
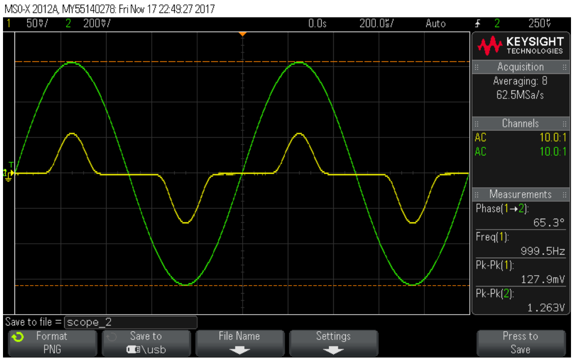


Figure 11: Schmitt trigger circuit.

in turn larger than the emitter voltage. In terms of diodes formed by the NPN doping the base emitter must be forward biased with the collector base diode reverse biased.

2.5.1 Crossover Distortion

Crossover distortion as shown in Figure 12, is caused by transistors turning on and off and the biasing of those transistors, as the transistors need 0.7V to turn on we see any voltage less then 0.7v is 0. This means we can solve this by either having the transistors on 100% of the time or by counteracting this 0.7V. [3]



MSO-X 2012A, MY55140278: Fri Nov 17 22:49:27 2017

1 50mV/ 2 200mV/ 0.0s 200.0µs/ Auto 2 250mV

Acquisition
Averaging: 8
62.5MSa/s

Channels
AC 10.0:1
AC 10.0:1

Measurements
Phase(1→2): 65.3°
Freq(1): 999.5Hz
Pk-Pk(1): 127.9mV
Pk-Pk(2): 1.263V

Save to file = scope_2

Figure 12: Crossover distortion graph

3 Theory(30%)

3.1 1x Probe Parasitic components

Using our knowledge of coaxial cables, realistic oscilloscopes and time constants of systems we can use an equivalent circuit to see what's truly going on, for this we will assume any wire resistance is negligible giving us Figure 13.

(Figure 13: Where C_i is the input capacitance and R_i is the physical internal input resistor of the oscilloscope.)

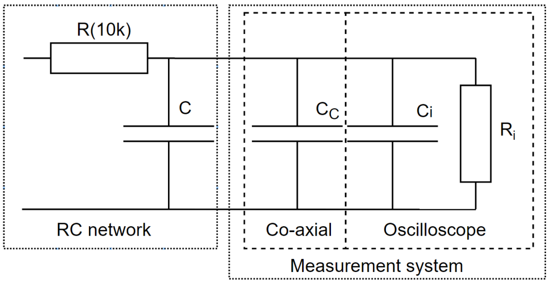


Figure 13: Equivalent circuit of a probed RC circuit.

As our system is being used to calculate an unknown capacitance C we cannot ignore our parasitic capacitors C_C andC_i we must instead calculate them to negate them. We can also add C_c and C_i to give us C_m to simplify the circuit further as capacitors in parallel add together. This circuit on its own cannot help us much as we can only get a capacitors value in terms of another, so two measurements must be taken (this time using two lots of oscilloscope connections to double the value of C_m(remember capacitors in parallel add up) to create simultaneous equations using the rise time of the device.(Bare in mind R_i is ignored when dealing with rise time as it is in parallel). When dealing with fall time the circuits capacitors are no longer being charged through R they are now discharging through R in parallel with R_i so we can use the same method of simultaneous equations using one and two lots of measurement parasitic components remembering this time R_i and $\frac{R_i}{2}$.

3.2 10x Probe Parasitic components

A 10x probe ideally splits the voltage applied to it to a tenth of the voltage, done by using a simple potential divider but the coaxial cable used to connect the two has an unwanted capacitance shown in Figure 14

The figure shows that for DC the voltage gain is:

$$G = \frac{R_2}{R_1 + R_2} \tag{4}$$

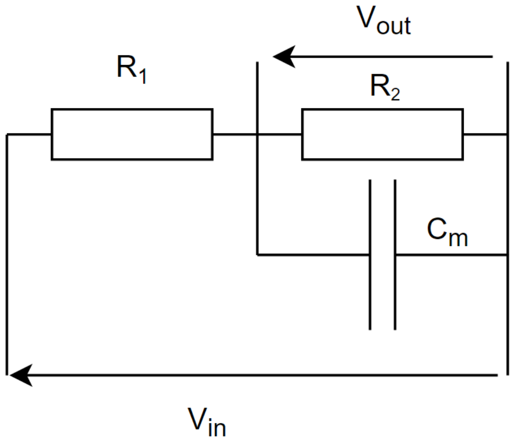


Figure 14: Potential divider with parasitic capacitor

If our resistor in the oscilloscope is $1M\Omega$ (R_2) we can see that our R_1 needs to be $9M\Omega$ to get a gain of $\frac{1}{10}$. However, now imagine our circuit for high frequency AC signals (where C_m is a short) we can see our probe wouldn't pick up any voltage as is it poses no resistance in comparison to R_1. So to solve this we must use two potential dividers one for AC signals and one for DC signals shown in Figure 15.

As this capacitor C_m isn't really controllable and can change from environment to environment, it is necessary to be able to tune this capacitor so that the capacitors follow the equation, Equation,4 (with resistors swapped for capacitors) aka, 9 times C_m for a 10x probe.

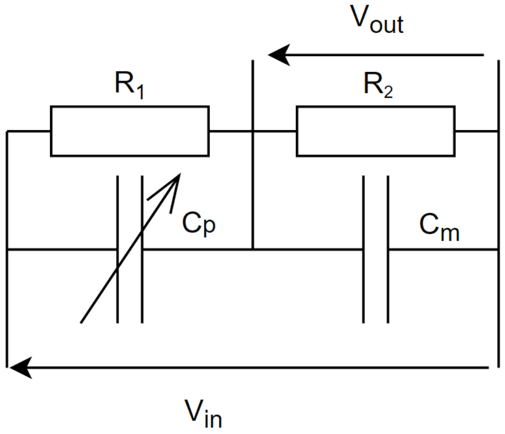


Figure 15: AC and DC potential divider

3.3 Square wave generator

For a basic square wave generator (basic meaning negligible current sourced) we can attach the output of an integrator to the input of a Schmitt trigger as shown in Figure 16. You may notice the resistor at the output of the Schmitt trigger, this is designed to reduce the voltage output to 5V(/-5V) for the input to the integrator. There is also two zener diodes which are used to make sure the output is constant at 5V, as the forward voltage is 0.7V like a normal diode and the reverse breakdown voltage of the zener is 4.3V. This means that our circuit keeps the voltage on the rail between 5V and -5V. This resistor that limits the voltage output also limits the current down to 10mA and therefore our system cannot draw more than this, so we must design our values around this. Our 10mA must be split between the zener voltage control, our integrator and Schmitt trigger. I chose 2mA for both the integrator and Schmitt trigger stages to allow the majority of current to be left over for the zeners and to make the numbers nicer. If our voltage over R is 5V(/-5V) with 2mA flowing, we can easily calculate the resistance using ohms law. The resistors $R_1$and R_2 both pass 2mA with 15V and 5V over each respectively and once again this resistance can be calculated using ohms law. Our capacitor must be designed around our system parameters sowe must match the capacitor current to the resistance. Therefore we use equation 5 to calculate the capacitance as our current must equal 2mA and our $\frac{dv}{dt}$ is given by our required output. As we want a 1kHz square wave, our capacitor will charge for 500uS before discharging and it will charge by 5V. Using this we can calculate our capacitance and therefore have all of our circuit parameters. This circuit works by integrating our square wave signal output meaning the integrator outputs a sawtooth(back to back triangles). These triangles oscillate the input to the Schmitt trigger meaning each triangle outputs a square wave from the Schmitt trigger.

$$I = C\frac{dv}{dt} \tag{5}$$

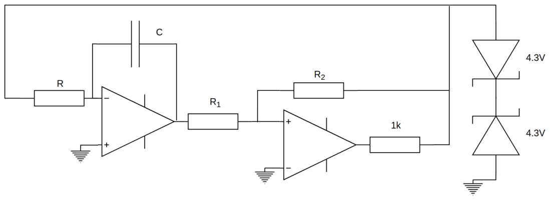


Figure 16: Square wave/sawtooth generator

3.4 Audio amplifiers

The first idea to create an audio amplifier is to use a fixed gain amplifier as previously explained in section 2.4.2. This is used for medium/high impedances as the op-amp can only drive mA loads. Op-amps have very small distortion due to their feedback and so are good for low distortion low current.[4]

If our speaker system needs higher currants we must use a transistor setup, where in a class B amplifier (as seen in Figure 17 transistors turn on and off in opposition. One (the NPN on the top) deals with positive voltages and the other (PNP) amplifies for the negative voltages. This is preferred over class A as the transistors only need to be on when there is a signal reducing waste power. The issue with using this class B amplifier is the crossover distortion caused by the transistors turning on and off, as talked about in 2.5.1. This isn't a huge issue if we are using larger voltages but is very noticeable in the low voltages as shown in figure 12. As crossover distortion is voltage based we can use an op-amp to check our output voltage against the input signal and therefore have the signal accuracy of the op-amp mixed with the power amplification of the transistors as seen in Figure 18. If our system requires that no op-amps could be used we can also use a class AB amplifier. Here we have 2 transistors but they are both always on This is done simply by adding a bias between the two transistors where Vin is seen in figure 17.

4 Method and Results(10%)

For method and results I am going to focus on the material in lab 2 (fixed gain amplifier).
For a fixed gain op-amp circuit we must design our system to appear first order (an input must must appear identical on the output but effected by a gain) aka a linear system. In our case we will look at the gain bandwidth product of the system. Equation wise we can prove that at any point our gain-bandwidth product (gain*frequency) has nothing to do with our resistors and therefore is constant with the op-amp. Our tests performed by using two separate gains on the same op-amp proved this. Therefore if our system has a gain of 1 then the bandwidth is equal to the GBWP. We can quickly get a value by setting our gain and then increasing the frequency until the output is at the -3dB point, which in turn can be used to quickly calculate the bandwidth of the device due to this linearity which values of which are proven in the lab.

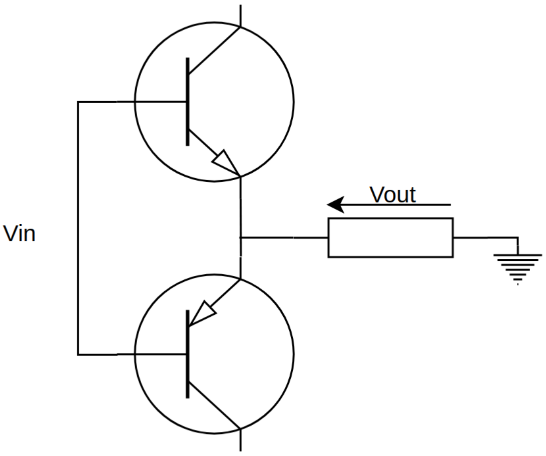


Figure 17: Class B amplifier

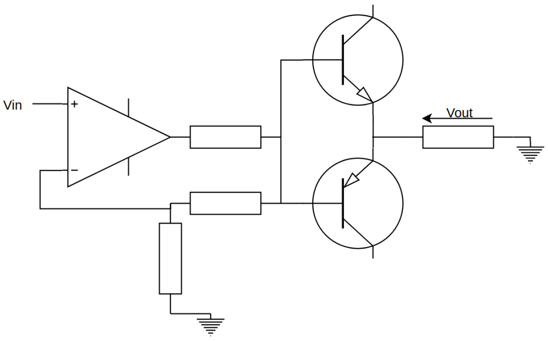


Figure 18: Class B amplifier with op-amp crossover reduction

5 Discussion(10%)

5.1 Probes

5.2 Probes

For any probe you must follow Equation 6, for the values shown in Figure 15. If this is satisfied then we can use this to probe up to much higher frequencies without a large drop-off, but unfortunately this doesn't work for huge frequencies and there is still a drop off.

$$G = \frac{R_m}{R_p + R_m} = \frac{C_m}{C_p + C_m} \tag{6}$$

5.3 Signal generator

For our signal generator we can find out our component values through current analysis with the information we know about integrators and Schmitt triggers from previously stated information. This system works perfectly as long as we are taking a negligible amount of current from the system to not stop any of the three stages (integrator, Schmitt trigger, zener regulator) working properly and therefore cannot be used to supply current but is good at supplying voltage.

5.4 Amplifiers

There are many ways to amplify a signal but each of them have their benefits and drawbacks. Class B amplifiers have little power wastage but have crossover distortion and so isn't useful for small input signals. Class AB isn't incredibly efficient but has no crossover distortion. Op-amps have little distortion but little driving current. Class B with op-amp can drive larger loads and has minimal if any crossover distortion.

6 Conclusions(10%)

To conclude the report has met the aims and objectives as we can explain why we need this calibration capacitor in our probe to compensate properly for the error. We have also explained the analysis we would go through to calculate values for our system to function as we desire for both our amplifiers and for our signal generator. Every circuit was completed in the lab and explained briefly as to where any error or distortion comes from explained in sections 2 and 3.

References

[1] J. E. Green, *Background Amplifiers 2: Pre-lab Activities.*

[2] R. J. Smith, *Circuits, Devices and systems.* John Wiley & Sons; 5th Edition edition (2 Mar. 1992), 1966.

[3] J. Millman and C. C. Halkias, *Integrated Electronics: Analog And Digital Circuits And Systems*, vol. 1st ed. McGraw-Hill, 1972.

[4] T. Duncan, *Success In Electronics*, vol. 1st ed. John Murray, 1996.