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AMPLIFIERS REPORT

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Introduction

The purpose of this lab is to show how the performance of an operational amplifier circuit in the frequency domain can be represented by a first order model. Different power amplifier circuits will be constructed, to compare differences in performance and investigate the effects of feedback to correct defects. Furthermore, the effects of measuring equipment such as oscilloscope probes and BNC cables on a circuits performance will be investigated.

Background

The first part of the lab looks into the effects of cable impedance and capacitance on the circuits performance it is measuring from. It is important to interpret measurements carefully because the measured values shown on the oscilloscope may not necessarily be accurate due to the impedance and capacitance of the probes interacting with the circuit.

For example, when measuring the rise time of a pulsed signal through an RC circuit, the **rise time changes** when **multiple BNC** cables are used as opposed to one. Hence great care must be taking when interpreting measurements, since the values were different despite there being **no physical change** to the circuit. The purpose is to demonstrate how measuring equipment effectively becomes **part of the circuit**, and how the effects can be alleviated by using a balanced 10:1 oscilloscope probe.

The second part of the lab focusses on showing how an operational amplifier with feedback can be characterised by a **first order system**, where mathematical relationships link time domain and frequency domain measurements together. This will be shown by taking measurements in the time domain and frequency domain, where they can be compared to their theoretical values using mathematical relationships.

For example, for a non-inverting amplifier, the rise time and corner frequency can be measured using an oscilloscope. The relationship between the rise time and time constant can be used to calculate the corner frequency, which, if equal to the measured value, proves the relationship.

The third part of the lab focusses on power amplifiers, and identifies why there are defects and how they can be avoided. This is important in many applications such as audio amplification where you want to amplify a signal, while maintaining its shape.

For example, when a push-pull amplifier configuration is constructed and tested, a defect in the output signal is seen.

Theory

Operational amplifiers, also known as op-amps are high gain DC and AC signal amplifiers which have a range of uses and can be configured in ways to exhibit specific behaviours such as voltage adders and differential amplifiers.

As seen in *figure 2*, op-amps are 3 terminal devices, with an inverting input, non-inverting input and output terminal, where the **input terminals** having **infinite impedance** and the **output terminal** having a very **low impedance**. Op-amps operate by **amplifying the difference in voltage** at their inputs by its open-loop gain, which is ideally infinite.

The operational amplifier equation that shows this is:

$$V_{OUT} = A_o(V^+ - V^-) \tag{1}$$

Where V^+ and V^- are the non-inverting and inverting voltage respectively, and A_o is open-loop gain (explained later).

Operational amplifiers can be modelled as **first order systems**, where the corner frequency (f_o), time constant (τ) and phase angle (ϕ) have a **defined relationships**.

The **corner frequency** is where the signal is **attenuated by -3dB**.

The voltage gain decibel:

$$dB = 20\log_{10}\left(\frac{V_{out}}{V_{in}}\right) \tag{2}$$

Hence the voltage-gain at the -3dB point will be approximately 70.8% of the maximum gain value.

The corner frequency:

$$f_0 = \frac{1}{2\pi\tau} \tag{3}$$

Where $\tau = RC$, the time constant of the circuit.

The time constant has the following relationship to the rise time:

$$Rise\ Time = 2.2\tau \tag{4}$$

Where the rise time (seconds) is the time it takes for a square wave pulse to go from **10% to 90%** of its maximum value.

The phase angle is related to the frequency of the input signal (*figure 1).*

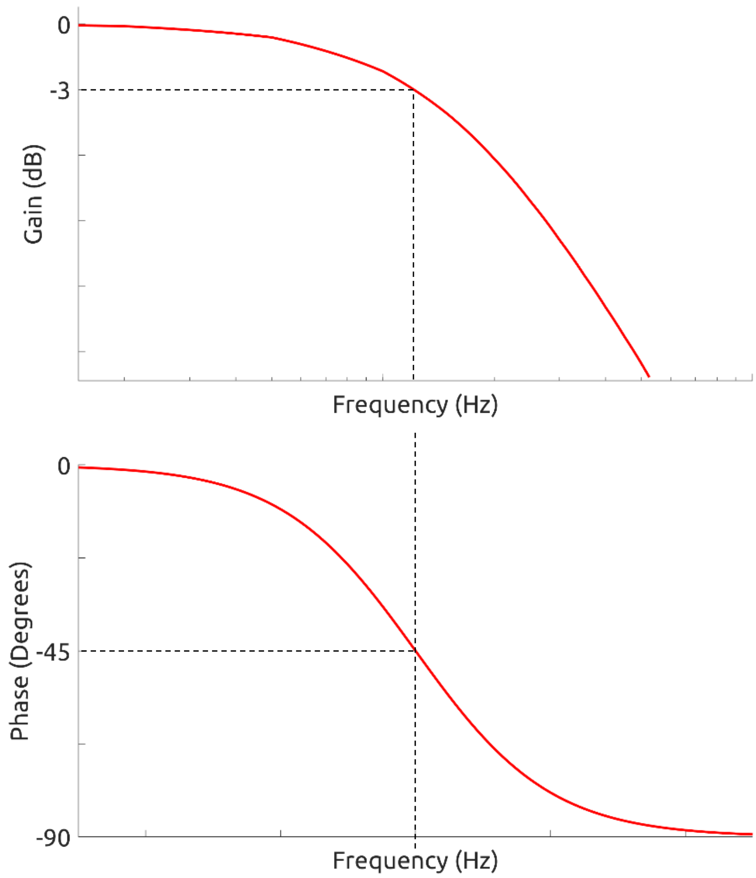

Figure 1: Phase angle at half power frequency.

The phase angle varies with frequency, with the corner frequency having a phase shift of **+45°.**

In the second part of the lab, a standard non-inverting op-amp amplifier set-up was used as shown in *figure 2*.

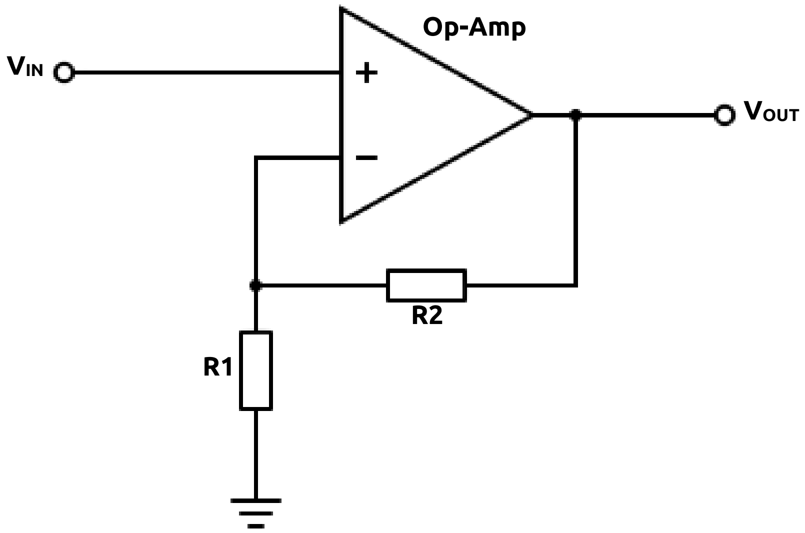

Figure 2: Non-inverting op-amp circuit

Where the gain of this amplifier is given by:

$$Gain = \frac{V_{OUT}}{V_{IN}} = 1 + \frac{R2}{R1} \quad (5)$$

The gain equation (4) assumes the open loop gain is infinite. The **open loop gain** is defined as the gain when there is **no feedback**, typically around 20,000. However, due to internal **parasitic capacitances** within the op-amp itself, as the **frequency increases**, this capacitance exhibits a lower reactance, effectively **reducing the gain**. The effects of this can be clearly seen in *figure 3*, where the open loop gain is only maintained at low frequencies below 10Hz, and is then attenuated at a rate of 20db per frequency decade. [1]

The effect of the op amps parasitic capacitance explains why the output is **phase shifted** as the **frequency increases**, because the **reduced reactance** of the capacitances causes the voltage to **lag behind the current.**

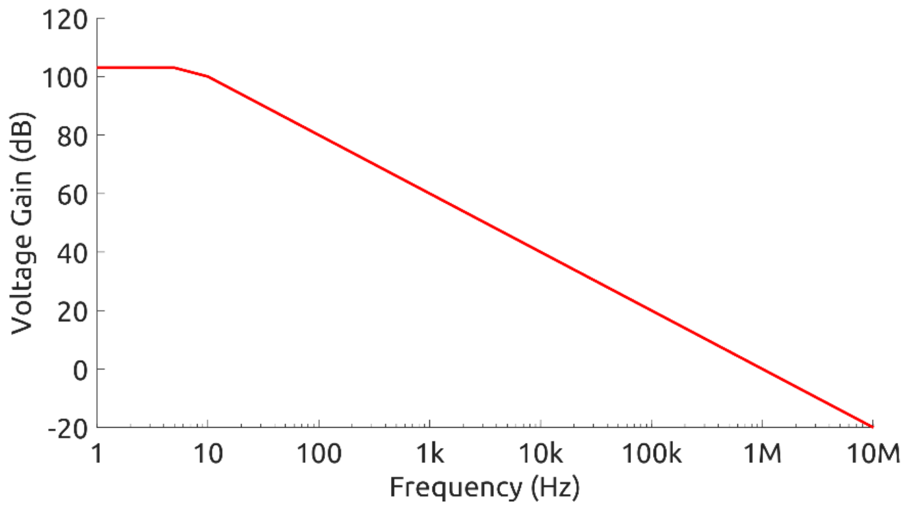

Figure 3: Open loop gain against frequency.

In order to achieved a constant gain with a better frequency response, **negative feedback** is used. Negative feedback involves taking a **fraction of the output** signal and feeding it into the **inverting input** of the op-amp. Since the op-amp has an exceedingly high gain, to get an output voltage to be within the supply rails**,** the **difference** in the **input voltages** must essentially be **zero.**

In order for this to happen, the op-amp will **try to make its inputs the same**, and will **adjust its output** to ensure this happens. This produces a **closed-loop gain**, which is **lower** than the **open-loop gain**, but with a **greater bandwidth**, enabling a **stable gain** across a **wider frequency range**. [2]

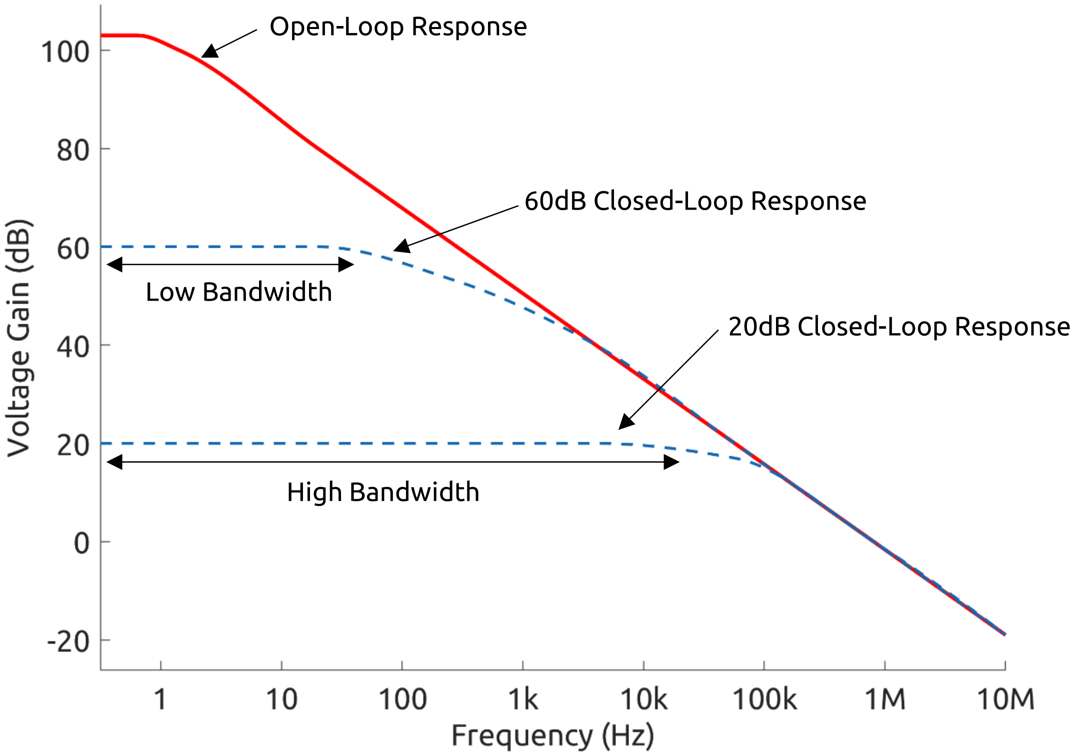

Figure 4: Closed loop gain against frequency.

Effectively, the **lower the gain** of the amplifier, the **larger the bandwidth**, visualised in *figure 4*.

For **audio applications**, the **reduced gain is still large enough**, and can easily be increased through further amplification stages.

The gain-bandwidth product is calculated by:

$$Gain\ Bandwidth = Low\ Frequency\ Gain\ \times Bandwidth \tag{6}$$

Where bandwidth is the -3dB Corner Frequency.

The value obtained should be **constant, independent of the gain** it is measured at, and gives a measure of the gain that can be achieved at a certain frequency.

The third part of the lab investigates the use of op-amps as power amplifiers, with the first circuit shown below in *figure 5*.

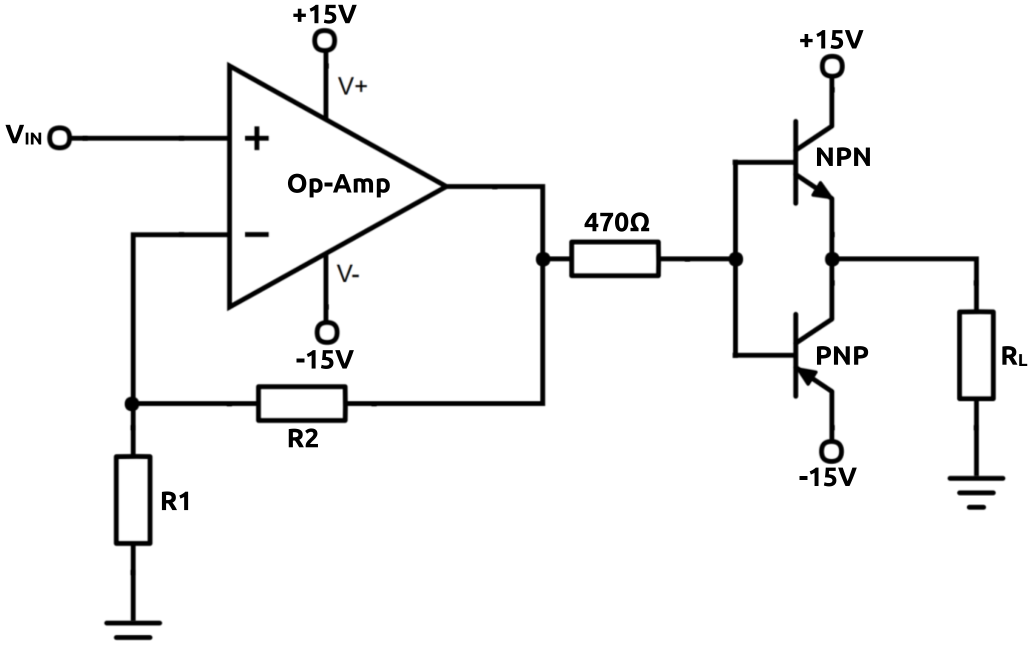

Figure 5: Power amplifier – feedback from op-amp output.

The op-amp, R1 and R2 are configured as a **non-inverting amplifier**, and provide **voltage gain**, while the **NPN/PNP transistors** configured as back-to-back emitter followers provide **power gain**.

The NPN/ PNP transistors in a **'push-pull' configuration operate as a class B amplifier**, where one transistor **amplifies the positive** part of the input signal while the other **amplifies the negative** part. These two signals are then **combined** to produce the complete waveform (*figure 6*). [3]

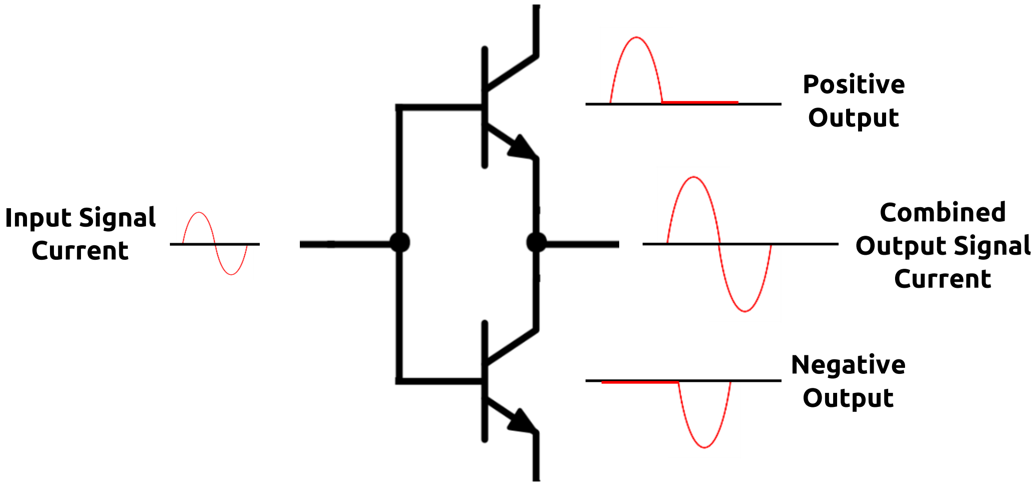

Figure 6: Signals in Push-Pull configuration.

However, the output signal is **not a direct replica of the input signal**, because the base-emitter voltage (V_{BE}) causes a **voltage drop** of **0.7V**, causing the output signals amplitude to always be 0.7V less than the input. When the input voltage **falls below 0.7V**, the transistor will **shut off**, and will only conduct again when the input falls to -0.7V.

This causes 'cross-over distortion', visualised in *figure 7*. [4]

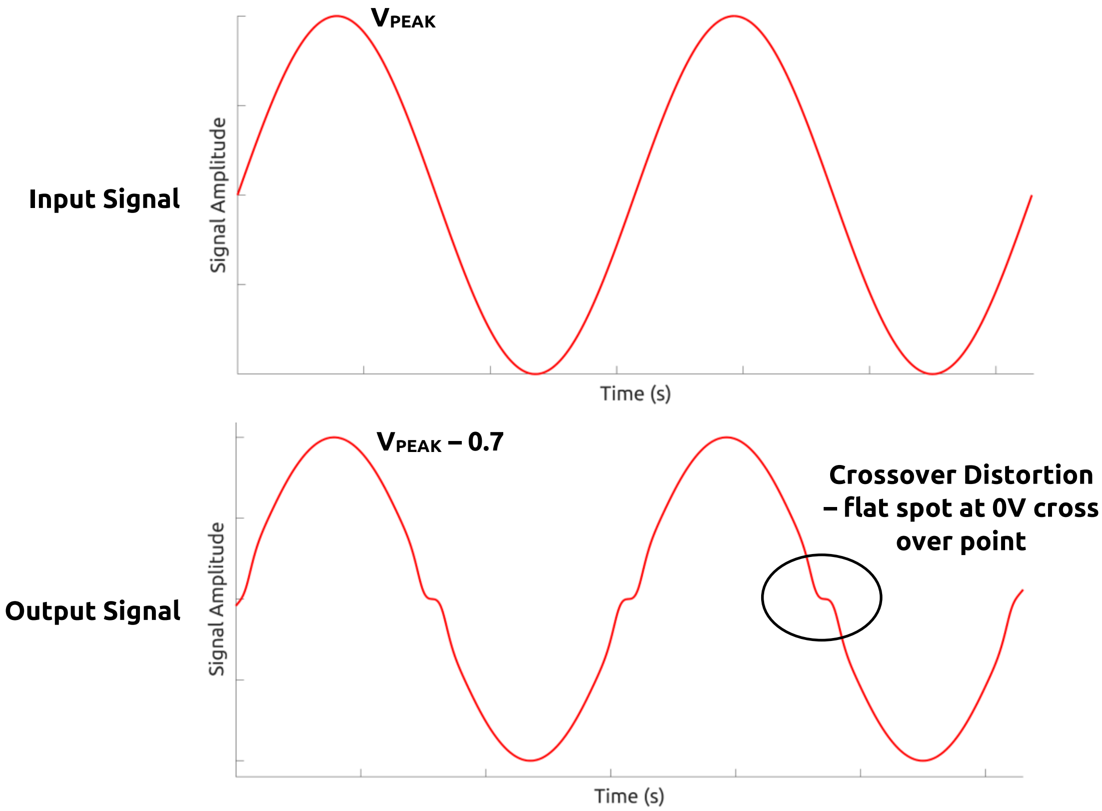

Figure 7: Example of Crossover Distortion.

There is a flat spot at each crossover point, caused by the transistors switching in response to the input signal.

The second circuit in *figure 8*, has feedback from the output of the power stage.

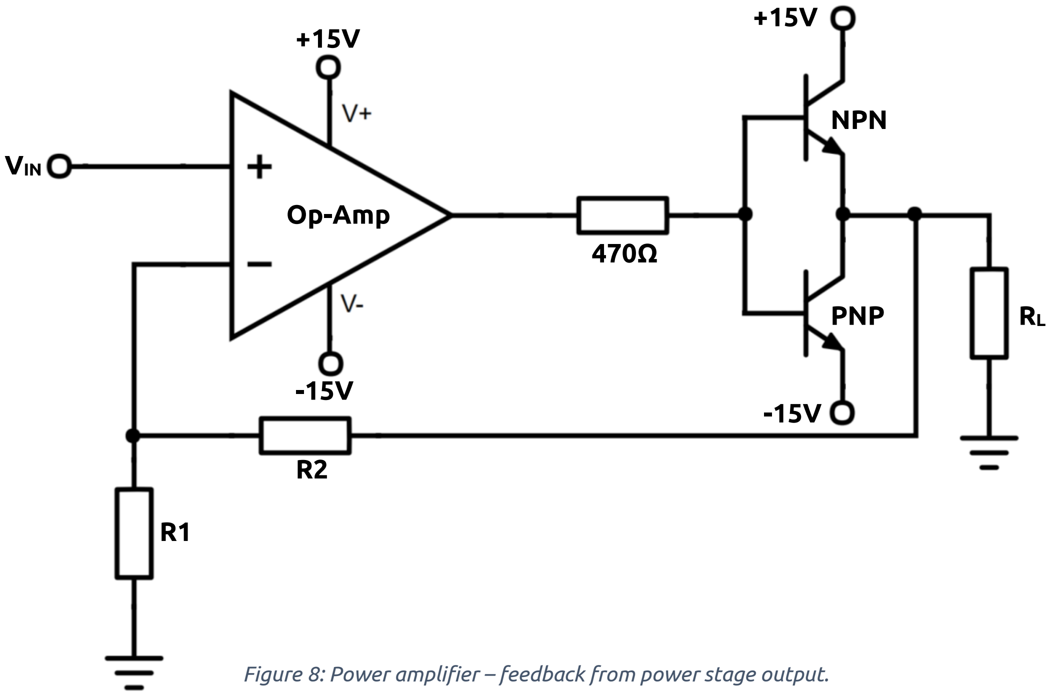

Figure 8: Power amplifier – feedback from power stage output.

The feedback will cause the **op-amps output** to **increase by 0.7V**, eliminating the voltage drop associated with the previous circuit.

Method & Results

Lab 1 – Experiment 1:

Experiment 1 involved looking into the effects of measuring equipment on a circuits performance.

Set up the circuit in *figure 9*, where the **capacitor value is to be determined**.

Use a 20kHz square wave at $1V_{pk-pk}$ as the input signal.

Connect a standard BNC cable from the circuit to the oscilloscope, and measure the voltage and rise time.

Add a second BNC-BNC from the same point to a different oscilloscope channel, so that 2 BNC cables are measuring simultaneously. Measure and record to new voltage and rise time.

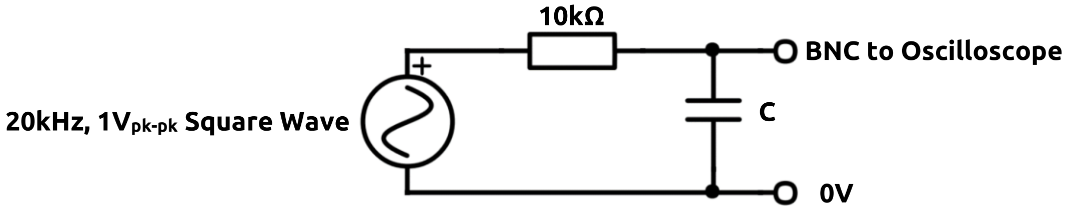

Figure 9: RC Circuit.

Results below (*figure 10)*:

	Pk-Pk Voltage Across Capacitor (mV)	Rise Time (μS)
1x BNC-BNC Cable (One Channel)	950	5.11
2x BNC-BNC Cable (Two Channel)	950	6.70

Figure 10: How BNC Cables affect Rise time.

The addition of a **second BNC cable** has **no influence** on the **output voltage**, however it **does affect the rise time**. This is because the **BNC cable has capacitance,** which becomes part of the circuit as a capacitor in parallel with the unknown capacitor in the circuit. The equivalent circuits for both scenarios are shown below in *figure 11*.

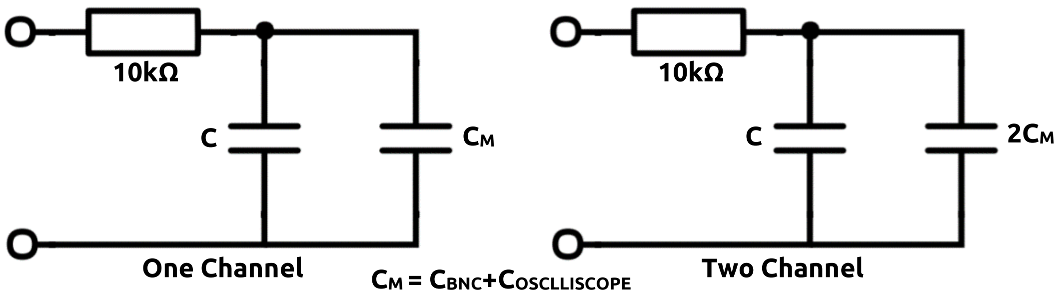

Figure 11: Equivalent Circuit.

Calculate the unknown capacitances using the relationship between the rise-time and the time-constant from (4) via simultaneous equations.

$$2.2\ \times 10k\Omega\ \times (C + C_M) = 5.11\mu S$$

$$2.2\ \times 10k\Omega\ \times (C + 2C_M) = 6.70\mu S$$

$$C = 160pF$$

$$C_M = 72.3pF$$

Considering the size of the unmarked capacitor, it is clear that the **combination of the oscilloscope and BNC capacitance is quite significant**. The value of **C calculated** turned out to be **exact value** of the capacitor.

Lab 1 – Experiment 2:

Experiment 2 looks at how the resistance of measuring equipment affects a circuits performance.

Replace the 10kΩ resistor from *experiment 1* with a 1MΩ resistor, and reduce input signal frequency to 200Hz.

Repeat the measurements for one and two BNC cables.

Results (*figure 12)*:

	Pk-Pk Voltage Across Capacitor (mV)	Rise Time (μS)
1x BNC-BNC Cable (One Channel)	478	258.9
2x BNC-BNC Cable (Two Channel)	324	233.6

Figure 12: How BNC Cables affect Rise time (Oscilloscope Input Resistance).

Both the voltage and rise times are different, due to the oscilloscope input having a resistance (R_i) parallel with its capacitance.

Equivalent circuits (*figure 13).*

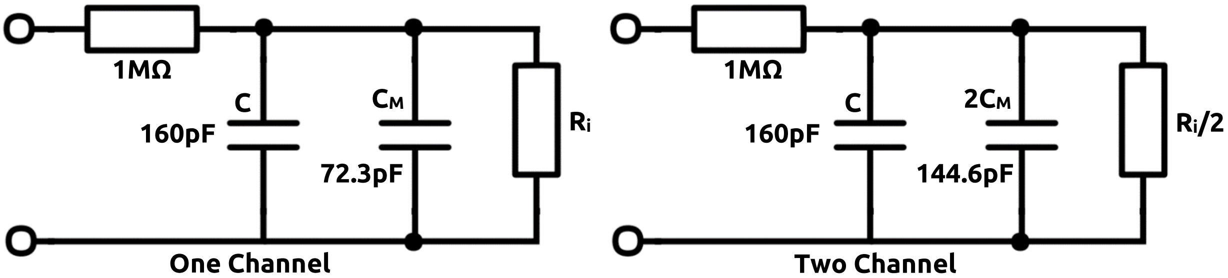

Figure 13: Equivalent Circuit with Input Resistance.

The 1MΩ and R_i act as a potential divider, hence R_i was calculated from the voltage measurements.

From the two-channel data:

$$0.324 = \frac{R_i/_2}{1M\Omega + R_i/_2}$$

Hence:

$$R_i = 959k\Omega$$

Which is close to the actual labelled value of approximately 1MΩ.

Next, the rise time can be calculated from the values of R_i and C_M calculated to be compared with the measured values.

The Thevenin equivalent circuit for both the one channel and two channel configurations are shown below in *figure 14.*

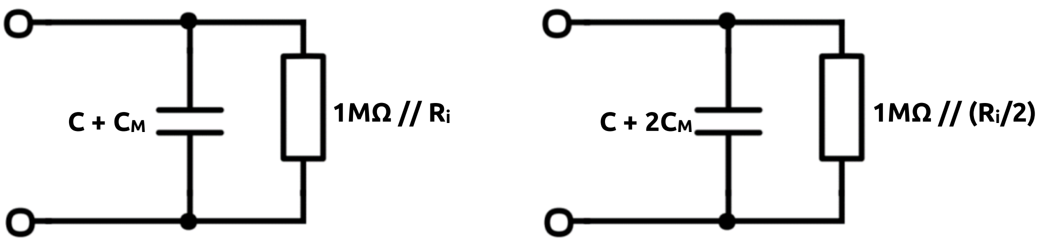

Figure 14: Thevenin Equivalent Circuit.

The total time constant for each circuit can now be calculated, and the rise times can be calculated using (4).

One-channel:

$$2.2 \times \left(\frac{1}{1M\Omega} + \frac{1}{0.959M\Omega}\right)^{-1} \times (160pF + 72.3pF) = 250.14\mu S$$

Two-channel:

$$2.2 \times \left(\frac{1}{1M\Omega} + \frac{1}{\left(0.959M\Omega/_{2}\right)}\right)^{-1} \times (160pF + 2(72.3pF)) = 217.14\mu S$$

Observe that these values are very close to their measured counterparts.

Lab 2 – Experiment 1:

Experiment 1 investigates modelling op-amps as first order systems, and how feedback is used to control the bandwidth.

Using (5), calculate values of R1 and R2 to get a gain of 100, and construct the circuit as previously seen in *figure 2.*

Using a 0.1$V_{pk\text{-}pk}$ square wave at 1kHz as the input signal, measure the voltage and rise time of the output.

From this, the actual gain can be calculated as well as the time constant using (4).

Next, change the **signal to a sinusoid**, and **starting at a low frequency**, increase the frequency until an attenuation **of -3dB is observed**, or 70.8% of the output voltage. Measure and record this frequency, as well as the phase shift of the output signal.

Results shown in *figure 15*:

Voltage Gain	99.08
Rise Time	13.88 µS
Time Constant	6.309 µS
-3dB Frequency	24.8 kHz
Phase Shift	-45.2°

Figure 15: Non-inverting amplifier Measurements (Gain =100).

Use (3) prove that there is a relationship between the time constant and corner frequency:

$$f_0 = \frac{1}{2\pi \times 6.309 \times 10^{-6}} = 25.23kHz$$

Use (6) to calculated the gain-bandwidth product:

$$Gain\ Bandwidth = 99.08\ \times 24.8kHz = 2.457MHz$$

Next, using an **amplifier with a gain of 500**, measure the gain and -3dB frequency.

Results shown in *figure 16:*

Voltage Gain	296.75
-3dB Frequency	17.02 kHz

Figure 16: Non-inverting amplifier Measurements (Gain =500).

The gain-bandwidth can now be calculated again.

$$Gain\ Bandwidth = 296.75\ \times 17.02kHz = 5.05MHz$$

Lab 3 – Experiment 1:

Construct the circuit as seen in *figure 5*, using (5) to calculate the values or R1 and R2 to give a voltage gain of 20.

Using a sinusoidal 1kHz input signal at a suitable amplitude, view the **op-amp output** and **push-pull output voltages** signals together on the oscilloscope.

The waveform is shown in *figure 17.*

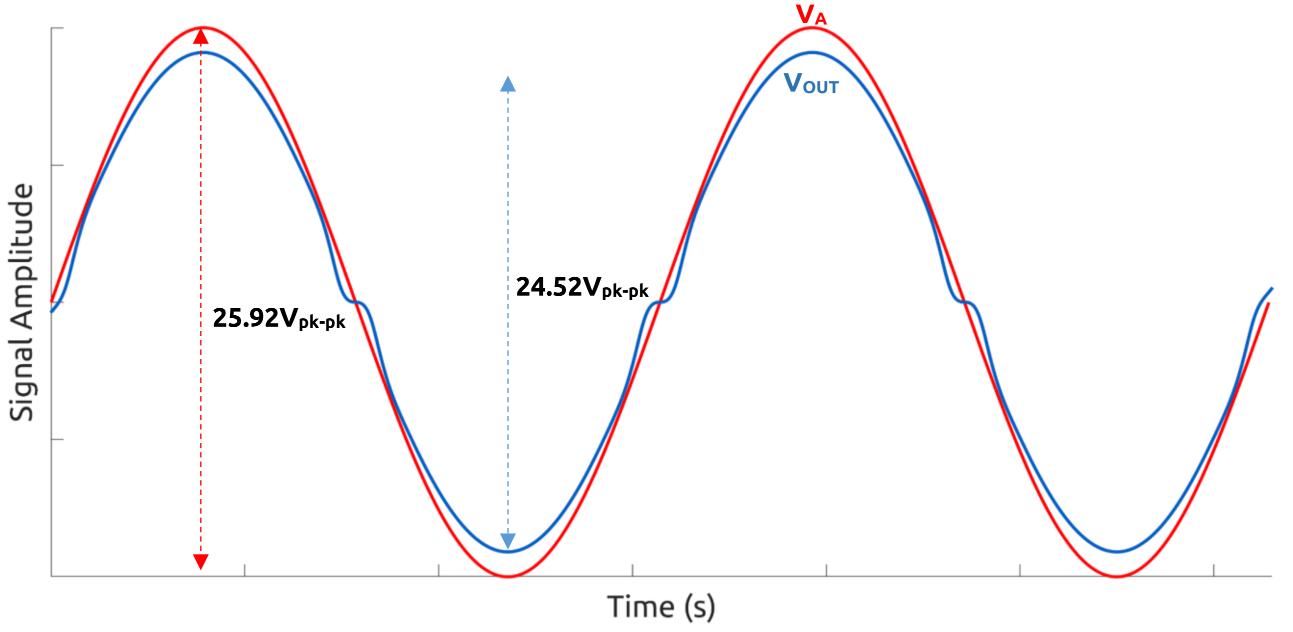

Figure 17: Voltage amp and power amplifier output (feedback from op amp).

The **crossover distortion** as mentioned in the theory can be **clearly seen**, and the **output voltage** is always **trailing 0.7V less** than the input voltage due to the base-emitter voltage.

Lab 3 - Experiment 2:

For experiment 2, **change the feedback** so that it is from the **output of the push-pull stage**, as shown in *figure 8.*

Repeat the procedure from experiment 1.

The new waveform is shown in *figure 18.*

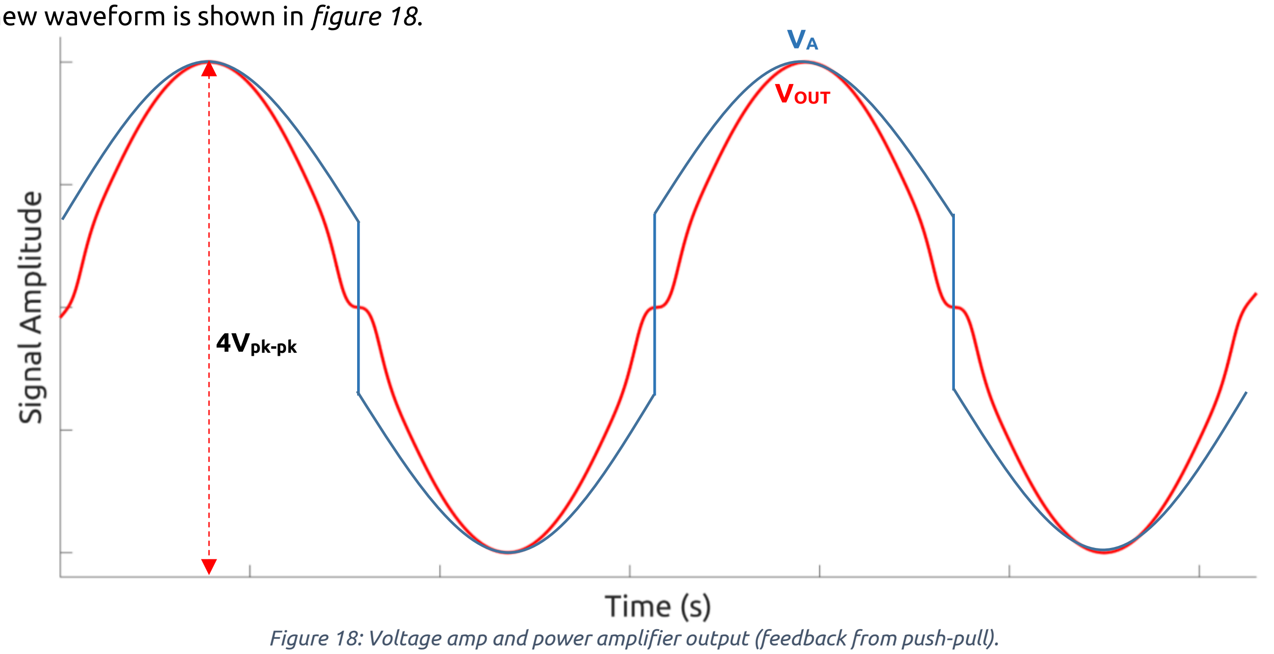

Figure 18: Voltage amp and power amplifier output (feedback from push-pull).

Discussion

In lab 1, when using **standard coaxial BNC cables**, neither of the **results** could be **trusted** because the introduction of the second BNC cable **changed the performance** of the circuit despite there being **no physical change**. The outcome was to realise how the 10:1 oscilloscope probe overcame these problems via capacitance compensation to take accurate measurements.

In the lab 2 experiments, the **measurements led to results that were exactly as expected**. For example, using the first-order relationships gave a corner frequency very close to the measured value, and the phase shift was exactly as predicted.

However, from the theory, the gain-bandwidth product **should have been the same** for both amplifier gains, but a **human error** during the experiment meant the **input voltage** was **not low enough**, hence the output was **saturating**. This meant the gain was not 500, and therefore the corner frequency was not the desired value.

If the gain was 500, the -3dB frequency would be approximately 4.9kHz.

In lab 3 experiment 1, the shape of the output waveforms clearly shows the cross-over distortion as discussed in the theory, where an unwanted 0.7V drop occurs at the output of the push-pulls stage.

In experiment 2, while the amplitude of the output was corrected to be 0.7V higher, it produced a **defect in the output** signal of the op-amp. This could be caused due to the **slew rate**, which is a measure of how quickly the op amp can **react to changes in the input**, and since the output **suddenly turns off** due to cross-over distortion, the op-amps output **overcompensating**, producing those **vertical lines** in *figure 18.*

Neither of these circuits would be ideal for audio amplification since the output it still **distorted** compared to the input. s

Conclusion

Overall, the experiment met its aims and gave me an **understanding of the limitations** that have to be overcome in **amplifier design**. For example, the measurements in lab 2 led to results that were almost **identical to their theoretical counterparts**, giving a very **convincing** display of how op-amps can be modelled as first-order systems.

Furthermore, lab 3 very clearly demonstrated how the effects of feedback can **alter a circuits performance**, and displayed the **unwanted signal defects** that occur with some circuit designs. Due to **time constraints**, I wasn't able to investigate a power amplifier design that **overcame the previous circuits defects**, but I still gained a **solid understanding** of why these defects occur.

References

[1] J O. Bird. "Operational Amplifier," *Electronical and Electrical Principles and Technology,* 5th ed. Abingdon, Oxford, UK: Routledge, 2014, pp. 303-304. [Online]. Available: https://www.dawsonera.com/readonline/9781315882871

[2] I. Poole, "Non-inverting amplifier circuit using an op-amp," in *Radio-Electronics*, Unknown Date. [Online]. Available: http://www.radio-electronics.com/info/circuits/opamp_non_inverting/op_amp_non-inverting.php. Accessed on: Oct. 25th, 2017.

[3] Unknown Author, "Class AB Amplifier," in *Electronic Tutorials,* Unknown Date. [Online]. Available: http://www.electronics-tutorials.ws/amplifier/class-ab-amplifier.html. Accessed on Oct. 26th, 2017.

[4] P. Horowitz and W. Hill, "Bipolar Transistors", in *The Art of Electronics,* 3rd ed. New York, USA: Cambridge University Press, 2015, pp. 107.