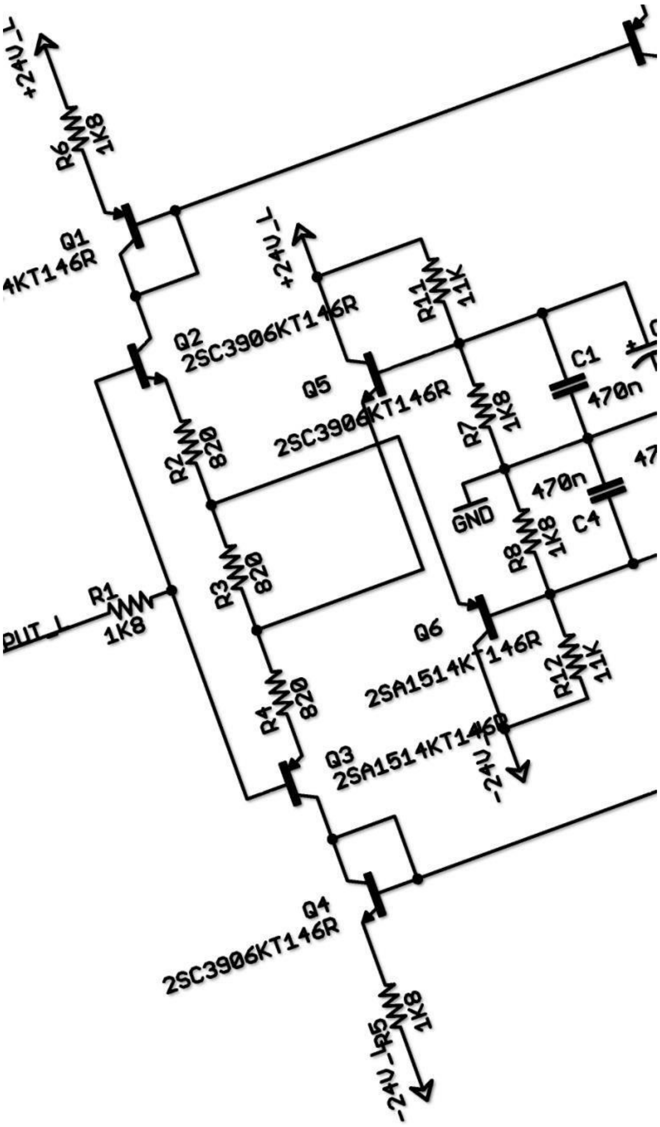
MONASH University
Engineering

ECE2131

Electrical Circuits

Laboratory Notes



2022 Edition

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Electrical and Computer Systems Engineering, Monash University

2022

8 Operational Amplifier Applications I

8.1 Learning Objectives and Introduction

One of the useful applications of an opamp is in processing an incoming analogue signal. This laboratory explores two types of processing – integration and differentiation. The circuits covered in this lab can also be used as active high and low pass filters (compare and contrast with the passive equivalents explored in Lab 5). These devices are also extremely useful in analogue control design and in analogue computing. The aim of this lab is to gain some familiarity with designs that implement these functions, and to investigate the characteristics of these more complicated opamp circuits.

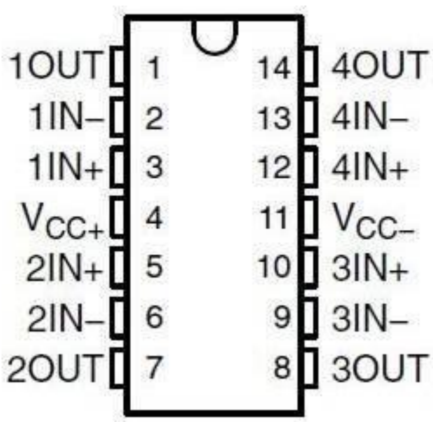
By the end of this lab you should:

- Build and characterise op-amp circuits with frequency dependent feedback.
- Link the concepts of integration and differentiation with 'active' high-pass and low-pass filter
- Use concepts related to the Fourier transform to understand the difference between characterization with a single sinusoid and a square wave input, and the effect of filtering on output waveforms.

8.2 Equipment and Components

- Breadboard.
- Opamp TL074.
- Resistors: 1 kOhm, 1000 kOhm (i.e. 1 MOhm).
- Capacitors: 100 nF, 100 pF.

TL074 Connection Diagram



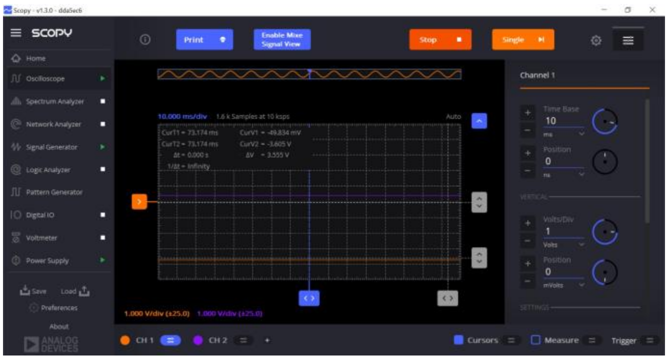
8.3 Experimental Work

8.3.1 PART A – INTEGRATING OPERATIONAL AMPLIFIER

8.3.1.1 Construct the following inverting amplifier circuit on the prototype breadboard. NOTE: The 1000k resistor in parallel with the integrating capacitor is required to ensure the DC stability of the circuit. Explore the operation of the circuit without this resistor. Is the circuit DC stable?

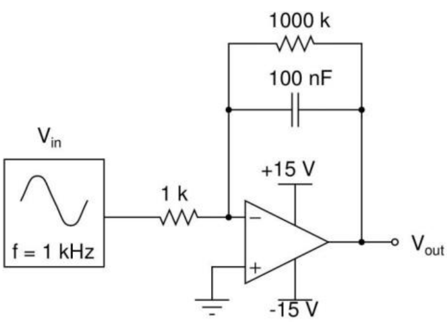
The value of 1V (peak to peak value) and 10Hz is used

The operation of the circuit with the 1000kOhm resistor in parallel with the integrating capacitor will be DC stable.



The operation of the circuit without the 1000kOhm resistor in parallel with the integrating capacitor will not be DC stable.

The DC offset for the circuit with a parallel resistor will be constant while the DC offset for the circuit without the parallel resistor at the capacitor is non-constant.



8.3.1.2 Restore the resistor and change the DC offset of the input signal away from zero (non-zero DC offset), with any suitable frequency and amplitude. Explain the circuit response when the DC offset is non-zero, compared to when the input is zero DC offset.

Positive Offset (50mV)

Based on the visual observation of the graph, when the DC offset of the input signal is positive, the output voltage will be negative. We can show this in algebraic terms with the equation of $Vout = \left(-\frac{R2}{R1}\right) * \left(\frac{1}{1+j\omega C}\right) * Vs$. When the source voltage, Vs is positive, the output voltage will be negative as it can be seen in the equation above.

Negative Offset (-50mV)

Based on the visual observation of the graph, when the DC offset of the input signal is negative, the output voltage will be positive. We can show this in algebraic terms with the equation of $Vout = \left(-\frac{R2}{R1}\right) * \left(\frac{1}{1+j\omega C}\right) * Vs$. When the source voltage, Vs is negative, the output voltage will be positive as it can be seen in the equation above.

8.3.1.3 Set the signal generator DC offset to 0V, and adjust the signal generator to produce $2V_{p-p}$ ($\pm 1V_{peak}$) SINE wave at a frequency of 1 kHz. Verify the basic integration operation of the circuit for this input signal. How does the gain relationship of the circuit compare with your expectations from the preliminary quiz? Show your theoretical analysis of this op-amp circuit.

Verifying the basic integration operation of the circuit

Since the given frequency is 1000Hz and that the wave is assumed to be a SINE wave, we can write the input signal as a function of sine wave in the following form, Vin = sin (ωt) , where ω is equal to 2*π*t which equates to 2000 π. Thus, Vin will be sin (2000π + 90°).

Verifying the basic integration operation of the circuit

$$-\int \sin(\omega t)\, dt$$

$$= \frac{1}{w} * \cos\, (\omega t)$$

$$= \frac{1}{w} * \sin\, (\omega t + 90°)$$

Theoretically, the output voltage in the time domain is the integral of the input voltage multiplied with a negative scalar, then the output voltage should be just a cosine waveform.

Theoretical Calculations

$$\frac{Vout}{Vin} = -\frac{R_{parallel}}{R_{input}} * (\frac{1}{1 + j * R_{parallel} * \omega * C})$$

$$= -\frac{1000k}{1000} * (\frac{1}{1 + j * 1000k * (2 * \pi * 1000) * 100n})$$

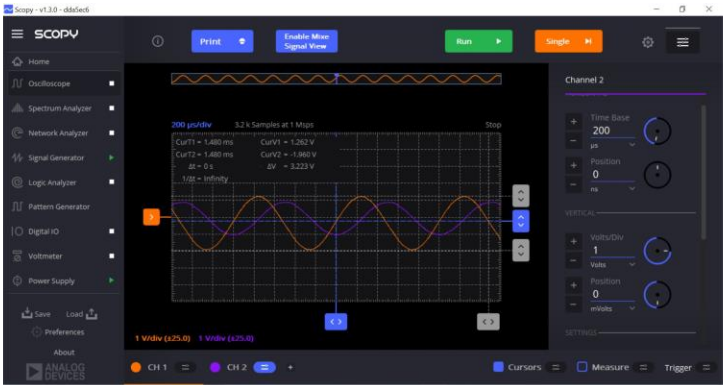
$$= -(\frac{1000}{1 + j * 200 * \pi})$$

$$\frac{Vout}{Vin} = -2.533m + 1.5915j$$

Converting from Cartesian form to Polar form, we will obtain

Gain = 1.592 ∠ 90.09°

The theoretical value for the gain of the circuit is 1.59.



The measured value can be obtained using the formula $\frac{Vout}{Vin}$ is $\frac{3.223}{1.993}$ = 1.61V

The theoretical value (from the preliminary quiz) and the measured value are quite similar to each other.

8.3.1.4 What is the phase shift between the signal generator output and the op-amp output? Comment if this matches your theoretical analysis.

The theoretical value obtained for the phase is 90.09°.

The measured value for the phase of the circuit can be obtained using the formula Δt x f x 360° which equates to 256.655 µs * 1000 * 360° = 92.4°
Both of the measured value and the theoretical value matches quite closely.

8.3.1.5 Increase the signal generator frequency to 10 kHz and then to 100 kHz. Explore the circuit operation. Compare the circuit gain and phase shift at EACH of these higher signal generator frequencies with the previous results. For better understanding, you should use theoretical analysis to verify your results.

10kHz

Theoretical value

$$\frac{Vout}{Vin} = -\frac{R_{parallel}}{R_{input}} * \left(\frac{1}{1 + j * R_{parallel} * \omega * C}\right)$$

$$= -\frac{1000k}{1000} * \left(\frac{1}{1 + j * 1000k * (2 * \pi * 10000) * 100n}\right)$$

$$= -\left(\frac{1000}{1 + j * 2000 * \pi}\right)$$

$$\frac{Vout}{Vin} = -25.33\mu + 0.15915j$$

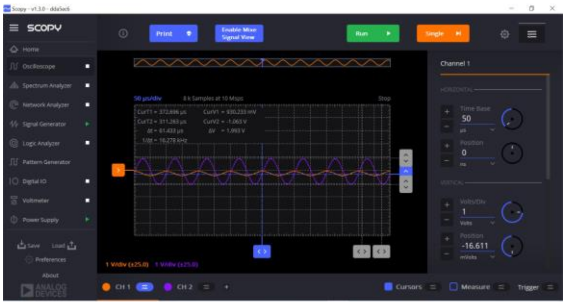
Converting from Cartesian form to Polar form, we will obtain

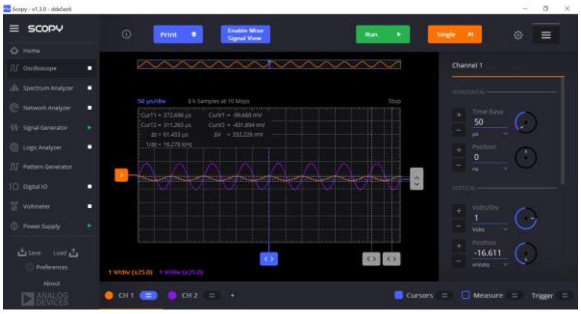
Gain = 0.159 ∠ 90.02°

Theoretical value of 0.159 with a phase angle of 90°

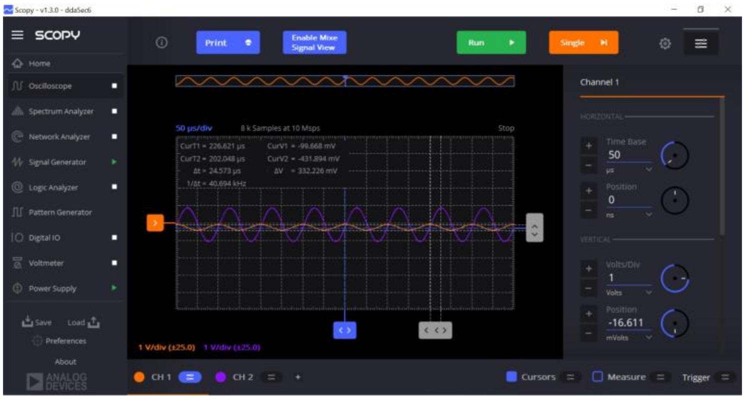
10kHz

Measured Value





The measured value is $\frac{Vout}{Vin} = \frac{332.226\text{mV}}{1.993\text{ V}} = 0.167$



The measured value for the phase of the circuit can be obtained using the formula Δt x f x 360 which equates to 24.573µs * 10k * 360° = 88.46°

100kHz

$$\frac{Vout}{Vin} = -\frac{R_{parallel}}{R_{input}} * \left(\frac{1}{1 + j * R_{parallel} * \omega * C}\right)$$

$$= -\frac{1000k}{1000} * \left(\frac{1}{1 + j * 1000k * (2 * \pi * 100000) * 100n}\right)$$

$$= -\left(\frac{1000}{1 + j * 20000 * \pi}\right)$$

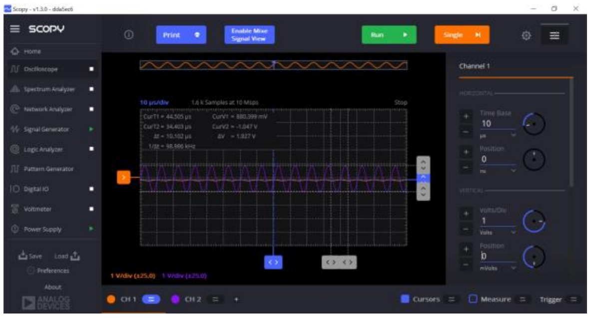
$$\frac{Vout}{Vin} = -0.2533\mu + 0.015915j$$

Converting from Cartesian form to Polar form, we will obtain

Gain = 0.0159 ∠ 90°

Theoretical value of 0.0159 with a phase angle of 90°

The measured value can be calculated as follow

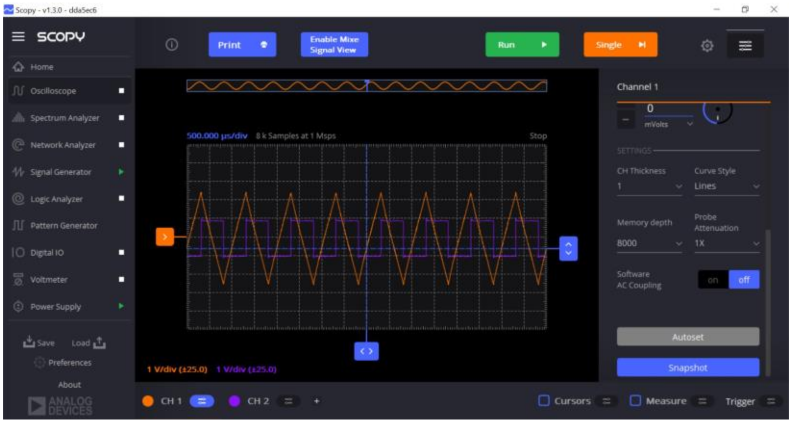


The measured value is $\frac{Vout}{Vin} = \frac{93.023 \text{ mV}}{1.894 \text{ V}} = 0.049$

The measured value for the phase of the circuit can be obtained using the formula Δt x f x 360 which equates to 2.562μs * 100k * 360° = 92.23°

Comparing these values with the previous gain, we see that the gain magnitude decreases with an increase in frequency while the phase maintains quite steady close to 90°.

8.3.1.6 Change the signal generator to a 1kHz $2V_{p-p}$ ($\pm 1V_{peak}$) SQUARE wave. Record and describe the circuit response for this input signal. Comment and explain if this is expected.



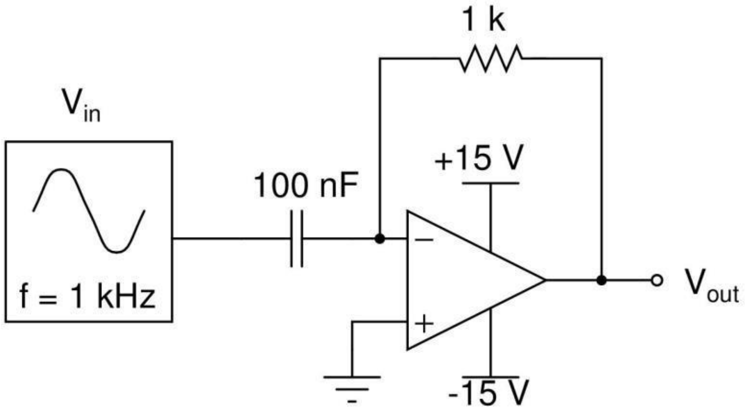
The result is expected. When a square wave is used as the source, the capacitor will charge and discharge but will not have sufficient time to reach the steady state as the time period is smaller than the time constant. As this is an op-amp integrator, the input (the horizontal constant) will be integrated and give an output that is sloped in a straight line. The resulting output will be similar to a triangular wave. When integrating a constant value, we will obtain an upward or downward sloping line depending on whether the value is positive or negative. As a result, we would obtain a triangular waveform. We can conclude that this circuit acts as an integrator circuit.

8.3.1.7 Change the frequency of the SQUARE wave to 10 kHz, and explain any changes that occur in the integrator output.

The output voltage of the graph will still be a triangular waveform but oscillating at a higher frequency. The charging and discharging of the capacitor will occur at a faster rate since it is oscillating at a higher frequency. This will cause a deviation from the steady-state voltage, resulting in much smaller peak amplitude. We can conclude that the circuit act as a low pass filter as the magnitude of the output voltage is also reduced.

8.3.2 PART B – DIFFERENTIATING OPERATIONAL AMPLIFIER

Construct the following differentiating amplifier circuit on the prototype board.



8.3.2.1 Set the signal generator DC offset to 0V, and adjust the signal generator to produce $2V_{p-p}$ ($\pm 1V_{peak}$) SINE wave at a frequency of 1 kHz. Verify the basic differentiating operation of the circuit for this input signal. How does the gain relationship of the circuit compare with the theoretical analysis? Show your theoretical analysis.

Basic Differentiating operation of the circuit

Since the given frequency is 1000Hz and that the wave is assumed to be a SINE wave, $\sin(\omega t)$ and due to the inverting input, the output will have an inverse sign of the input sine.

$$-\frac{d}{dt}\sin(\omega t)$$

$$= -\omega * \cos(\omega t)$$

$$= \omega * \cos(\omega t + 180°)$$

$$= \omega * \sin(\omega t + 270°)$$

$$= \omega * \sin(\omega t - 90°)$$

There will be lag of approximately 90° after the differentiation operation.

Theoretically, the derivative of a sine wave is a cosine wave.

Theoretical Analysis

We can carry out KCL at the inverting input

$$\frac{V_{out}}{V_{in}} = \frac{R_{input}}{Z_C}$$

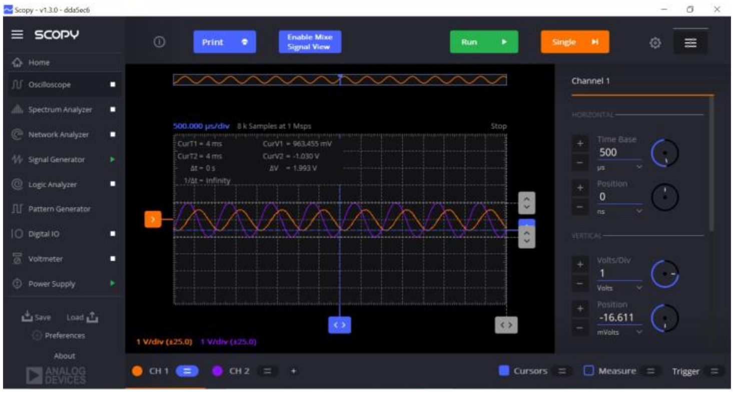
$$= - \left(\frac{R_{input}}{Z_C}\right)$$

$$= - \frac{1000}{\frac{1}{j\,\omega\, C}}$$

$$\frac{V_{out}}{V_{in}} = -1000 * j * 2 * \pi * 1000 * 100n$$

$$= 0.6283 \angle -90°$$

The theoretical value of the gain is 0.6283V with a phase angle of -90°



$$\frac{V_{out}}{V_{in}} = \frac{1.262\ V}{1.993\ V} = 0.633$$

The measured value of the gain is 0.633. The theoretical gain and the measured gain value are quite similar to each other.

8.3.2.2 What is the phase shift between the signal generator and the op-amp output?

The measured value for the phase of the circuit can be obtained using the formula Δt x f x 360 which equates to -259.386µs * 1000 * 360 = -93.38°

8.3.2.3 Increase the signal generator frequency to 10 kHz and then 100 kHz, and explore the circuit operation. Compare and comment on the circuit gain and phase shift at EACH of these higher signal generator frequencies. For better understanding, you should use theoretical analysis to verify your results

10kHz

Theoretical Analysis

$$\frac{V_{out}}{V_{in}} = \frac{R_{input}}{Z_C}$$

$$= - \left(\frac{R_{input}}{Z_C}\right)$$

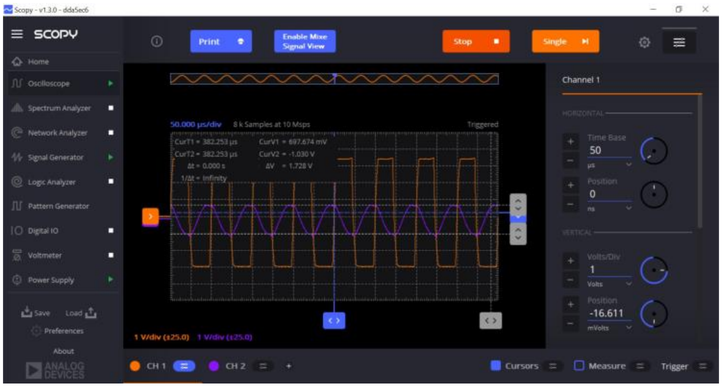
$$= - \frac{1000}{\frac{1}{j\,\omega\,C}}$$

$$\frac{V_{out}}{V_{in}} = -1000 * j * 2 * \pi * 10000 * 100n$$

$$= 6.283 \angle -90°$$

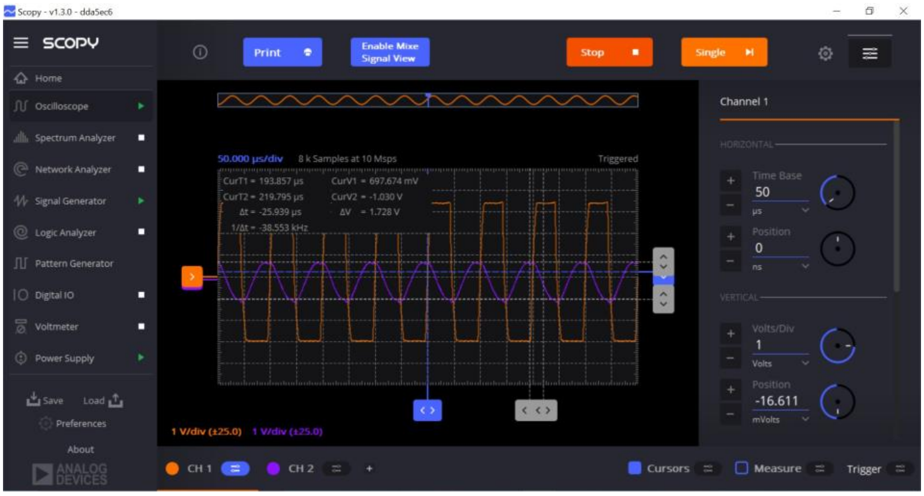
The theoretical value for the gain is 6.283 with a phase angle of -90°

Measured Value



The measured value for the gain is

$$\frac{V_{out}}{V_{in}} = \frac{6.445}{1.728} = 3.73$$



The measured value for the phase of the circuit can be obtained using the formula Δt x f x 360 which equates to -25.939 µs x 10k x 360 = -93.38°

100kHz

Theoretical Analysis

$$\frac{V_{out}}{V_{in}} = \frac{R_{input}}{Z_C}$$

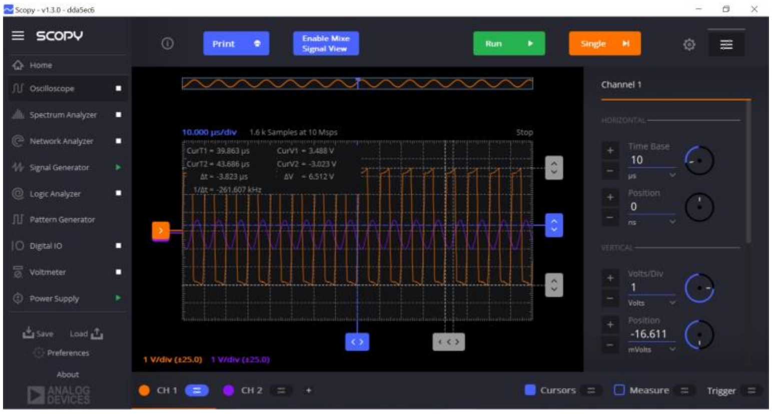
$$= - \left(\frac{R_{input}}{Z_C}\right)$$

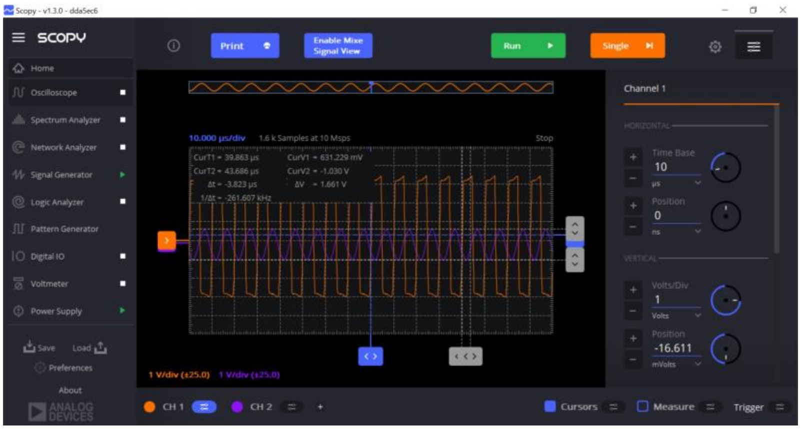
$$= - \frac{1000}{\frac{1}{j\,\omega\,C}}$$

$$\frac{V_{out}}{V_{in}} = -1000 * j * 2 * \pi * 100000 * 100n$$

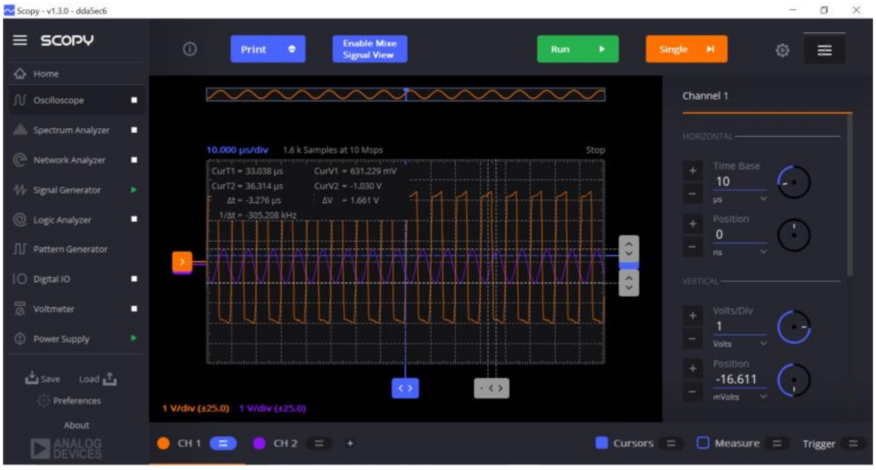
$$= 62.83 \angle -90°$$

The theoretical value for the gain is 62.83 with a phase angle of -90°





The measured value of the gain is $\frac{V_{out}}{V_{in}} = \frac{6.512}{1.661} = 3.92$



The measured value for the phase of the circuit can be obtained using the formula Δt x f x 360 which equates to -3.276µs x 100k x 360° = -117.94°.

Explanation (10kHz)

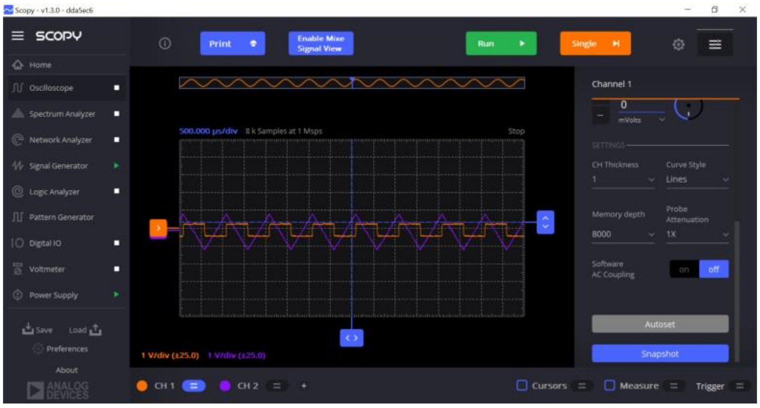
As we can see from the measured values obtained from the graph, there is a deviation from the theoretical value. This could be due to the fact that the output has reached saturation. However, the phase angle has remained quite similar with slight deviation due to the systematic error made during the extraction of data from the graphs.

Explanation (100kHz)

As we can see from the measured values obtained from the graph, there is a significant deviation from the theoretical value as the output has reached saturation. There is also deviation of the value of the measured phase angle from the theoretical value.

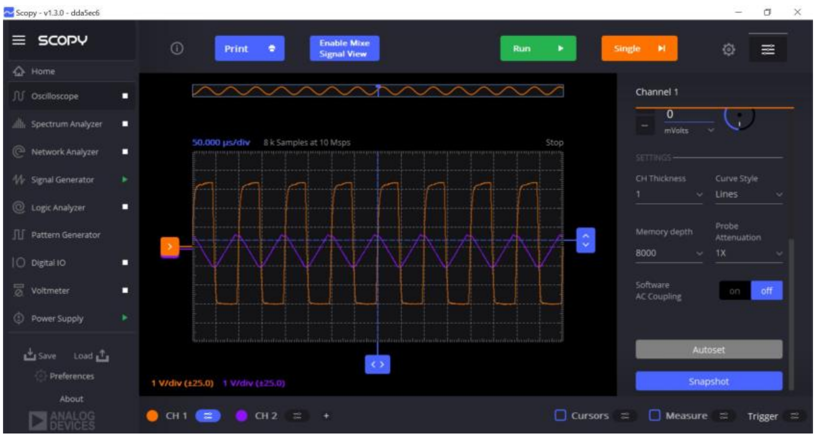
As this is not a practical differentiator op-amp, there are limitations to how high the frequency can achieve. At a high frequency, the gain could exceed the supply rail voltage and cause saturation in the op-amp, leading to unpredictable phase shifts.

8.3.2.4 Change the signal generator to a 1kHz $2V_{p\text{-}p}$ ($\pm 1V_{peak}$) TRIANGULAR wave. Record and describe the circuit response for this input signal. Comment and explain if this is expected.



Yes, this is expected. When the triangular wave is used as the input for the differentiator op-amp, the waveform would be differentiated into a constant step-wave as we can see in the graph above. The capacitor is again not receiving a constant steady input and will not charge at a constant rate.

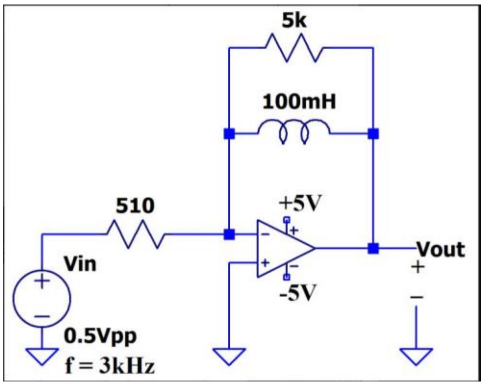
8.3.2.5 Change the frequency to 10kHz. Explain on the differences of the output between 1kHz and 10kHz.



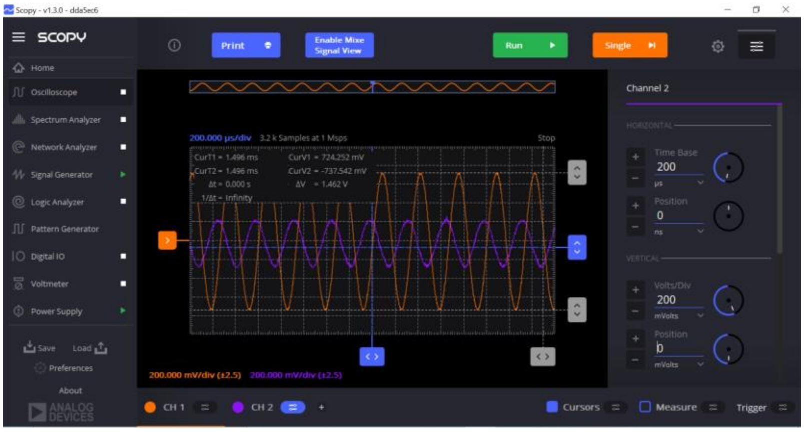
When the frequency is increased, the capacitor will have a shorter time to charge up to steady state. The oscillating transient response of the capacitor is smaller resulting in the circuit having a higher gain as the frequency decreases, resulting in an amplified output. Thus, the 10kHz will have a larger amplitude than the 1kHz output waveform.

Lab Assessment

1. Given Circuit



2. Measured Magnitude of the Gain of the circuit



The measured magnitude of the gain is $\frac{V_{out}}{V_{in}} = \frac{1.462\ V}{485.050\ mV} = 3.01$

3. Measured Phase of the gain of the circuit

The measured value for the phase of the circuit can be obtained using the formula Δt x f x 360 which equates to -114.676µs x 3k x 360° = -123.85°.

4. Theoretical Analysis to get the gain of the circuit

Since i1 = if, we can derive the equation from the Kirchoff's Current Law. We would get

$$\frac{V_s}{R_{input}} = \frac{0 - V_o}{Z_{inductor}}$$

Since $Z_f = Z_L \; || \; R_{parallel}$, we can rewrite the equation to be

$$\frac{(j * \omega * L) * R_{parallel}}{(j * \omega * L) + R_{parallel}}$$

We would derive our final equation to be

$$\frac{(j * \omega * L) * R_{parallel}}{(j * \omega * L) + R_{parallel}}$$

$$\frac{\left(\frac{(j*\omega*L)* R_{parallel}}{(j*\omega*L)+ R_{parallel}}\right)}{R_{input}}$$

Substituting our values into the equation, we would get

$$\frac{\left(\frac{(j * 2 * \pi * 3000 * 100m)* 5000}{(j * 2 * \pi * 3000 * 100m)+ 5000}\right)}{510}$$

The final value (in the cartesian form) that we will get would be 1.22 + 3.236i

The final value (in the polar form) that we will get is 3.458 ∠ -110.66°

5. Comment on the discrepancies

There are possible discrepancies between the measured value and the theoretical value due to the systematic error made by humans during the extraction of data from the graph. This could also be due to the inaccuracies of the graph by Scopy itself.

6. From the formula resistance $Z_{L||R1} = \frac{(j*\omega*L)*R_{parallel}}{(j*\omega*L)+R_{parallel}}$ and $\omega = 2*\pi*f$, we can infer that the equivalent resistance $Z_{L||R}$ is dependent on the frequency since R and L are of known values. Thus, we can say that when the frequency increases, the equivalent resistance will be higher and vice versa.

When applying the value into the formula to acquire our gain

$$Gain = \frac{V_{out}}{V_{in}} = -\frac{Z_{L||\,Rparallel}}{R_{input}}$$

From the equation above, we can say that the gain is directly proportional to $Z_{L||Rparallel}$ which will equate to a larger gain when $Z_{L||Rparallel}$ is larger. When a high frequency is provided, we will obtain a large value of $Z_{L||Rparallel}$. Thus, the measurement that we have obtained from the graphs are relatively accurate. In a nutshell, we will obtain a large gain when the signal source has a high frequency and a low gain when the signal source has a low frequency.

6a. 4f

When the frequency of the source increases, the magnitude of the gain will increase as well. This would lead to a larger amplitude of output voltage, resulting a much a larger output waveform. We can also notice that the phase will decrease.

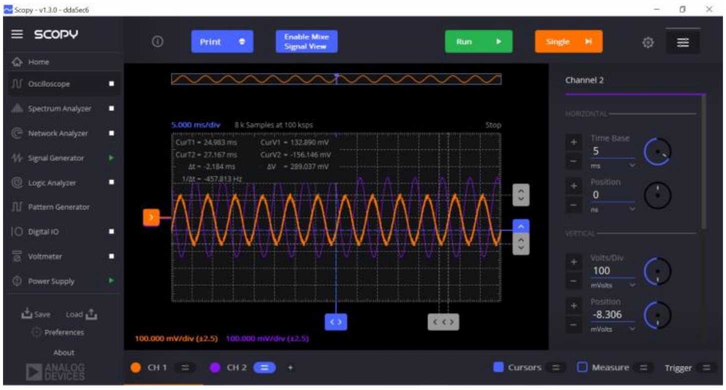
6b. f/3

When the frequency of the source decreases, the magnitude of the gain will decrease as well. This would lead to a smaller amplitude of output voltage, resulting a much a smaller output waveform. We will also notice that the phase will increase.

6c. 10f

When the frequency of the source increases, the magnitude of the gain will increase as well. This would lead to a larger amplitude of output voltage, resulting a much a larger output waveform. We will also notice that the phase will decrease.

6d. f/20



When the frequency of the source decreases, the magnitude of the gain will decrease as well. This would lead to a smaller amplitude of output voltage, resulting a much a smaller output waveform. We will also notice that the phase will increase.

ASSESSMENT

Student Statement:

I have read the university's statement on cheating and plagiarism, as described in the *Student Resource Guide*. This work is original and has not previously been submitted as part of another unit/subject/course. I have taken proper care safeguarding this work and made all reasonable effort to make sure it could not be copied. I understand the consequences for engaging in plagiarism as described in *Statue 4.1 Part III – Academic Misconduct*. **I certify that I have not plagiarized the work of others or engaged in collusion when preparing this submission.**

Student signature: Tan Jin Chun Date: 5/05/2022

TOTAL: ________(/7)

ASSESSOR: ________