Laboratory Manual: Transducers and Instrumentation for Physiological Measurement

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Laboratory Practicals

Lab 0 – Introduction to Laboratory Instruments

0.1 Introduction to the Lab

Students will be organized into groups for the lab practicals. Each group must work cohesively - i.e., all members of the group should be fully aware of all procedures and measurements. Each group should work independently without interfering with the other groups.

The lab table must be tidy when you finish the lab. Put away all cables and connectors. Put instruments in their places.

- Students should read the lab handout for the week before entering the lab.
- All labs have a preliminary report which must be completed before coming for the lab practical.
- After the lab practical is completed the student must complete the final report which must be submitted by the next week - before the next lab.

0.2 Introduction to Lab Instruments

Physiological measurement involves the conversion of a physiological quantity of interest into a form amenable for further analysis. In contemporary physiological instruments the quantity of interest is first converted into an electrical quantity, digitized and then numerically processed. The first step of transduction is the subject of study in this course. The physiological quantities of interest like biopotentials, blood pressure, etc., are time varying quantities and the nature of time variation contains important information about the underlying physiological processes. Therefore it is important that the transduction process is carried out with little loss of information. In this lab we will look at the characteristics of transducers especially their ability to faithfully capture transient and time-varying phenomena. All the transducers that we will study have an electrical quantity that we can observe, quantify and characterize using electronic test and measurement instruments.

There are three instruments that are the mainstay of a Test and Measurement laboratory and you will use them frequently in this course; they are (i) an oscilloscope, (b) a function generator, and (c) a power supply.

The oscilloscope is used to display time varying signals, and the function generator is used to deliver time-varying signals to a system under test.

Aims of this Practical:

1. To understand the functions of an oscilloscope, triggering, scaling, cursor measurement, inter-channel time measurement.
2. To understand the functions of a function generator. Amplitude, frequency, waveshape.
3. To understand the functions of a power supply: voltage an current limits. Thevenin and Norton equivalent.

Apparatus and Components

1. Equipment: Oscilloscope, Function Generator, Power Supply
2. Breadboard, Resistors, wires.

0.3 Oscilloscope

The oscilloscope is an important test instrument that can be used to display, and also store, time-dependent voltage signals. You should become familiar with the oscilloscope controls, especially (i) the vertical scale, sensitivity or gain, (ii) the time scale, or "horizontal sweep" or "time-base", (iii) the trigger or initiation of the horizontal sweep – there are many accessory controls for the trigger, and (iv) in the case of digital storage oscilloscopes, the data storing and transfer functions. An important aspect of digital oscilloscopes is the sampling rate which can be inferred from the samples/screen and sweep time. When using the oscilloscope for accurate measurement we will regard it as the combination of an ideal voltage measuring instrument and an input impedance across it.

0.4 Function Generator

The function generator in the lab can be used to generate time varying voltage signals. These signals that mimic the output of transducers and other real-world sources, can be used to test other sub-systems that comprise the measurement system. The function generator delivers a voltage function, which can be represented as a Thevenin source, i.e., an ideal voltage source in series with an impedance (resistance). The value of the series resistance is important in determining whether the signals will pass undiminished when connected to other circuits.

0.5 Power Supply

The laboratory power supply is a versatile source of electrical energy that can be used for electrical and electronic circuits. It has one or more independent voltage sources. These voltage sources may be fixed at standard values like 3V, 3.3V 5.0V, 12.0V, 15.0V. One or more of the voltage sources may be adjustable. A good power supply will also allow you to set a current limit to prevent damage to devices and circuits. The voltage sources in a power supply are regulated so that regardless of the load, the voltage is fixed. Poor quality power supplies will deviate substantially from this ideal.

The power supplies in the lab have both adjustable voltage and controllable current limit.

0.6 Familiarizing yourself with the Instruments

0.6.1 Oscilloscope:

Understand the use of the following controls (i) channel sensitivity, (ii) time sweep, (iii) triggering the time sweep, (iv) single sweep capture of transient signals. Understand how to make amplitude and time measurements using cursors on the oscilloscope. Understand the concept of ground in all measurements, and the idea of isolated channels in the oscilloscopes in our laboratory.

0.6.2 Function Generator:

Understand the selection of waveform shape, waveform amplitude (minimum, maximum, offset), waveform frequency. Understand sinusoids, pulses, noise waveforms. Understand the use of modulation. Observe how the output amplitude changes when you connect a load resistor across it: use (i) 1K and (ii) 220 Ohms. Set the function generator with the following values and see the waveform on an oscilloscope: Waveshape=sinusoid, frequency=125Hz, peak-to-peak amplitude=20mV, offset=400mV. Use this example to practice setting the oscilloscope based on the expected signal frequency and amplitude, rather than randomly flipping through the knobs.

0.6.3 Power Supply

Connect an adjustable resistance (or use several fixed resistors) and understand how voltage adjustment works with different current settings. Can you set the power supply to deliver a constant current regardless of the load? What are the conditions?

0.7 Preliminary Report

1. What are the common trigger methods in an oscilloscope?
2. Mention 3 advantages of a digital storage oscilloscope over an analog oscilloscope. What advantage does an analog oscilloscope have over a digital one?
3. If an oscilloscope has a sweep setting of 10ms/div, and 1024 points/sweep, what is the sampling rate?

0.8 Final Report

1. Using a 25 kHz sinusoidal signal from the function generator, observe it with oscilloscope time settings of 100ms/div, 10ms/div, 1ms/div. Determine the apparent frequency of the signal in each case.

2. What is the use of the SINC function waveform in the fuction generator? Explain with diagrams.

3. If the power supply voltage is set to 30 volts, and the current limit set to 10mA, then what will be voltage across a resistor that varies from 0 Ohms to 220 Ohms? What is the current?

1 Lab 1 – Input-Ouput Impedance Measurement

1.1 Introduction

A general measurement system will have an electrical source and voltage and current measuring instruments. While it is convenient to think of the sources as well as the measuring instruments as having well-defined properties, in practice, the behaviour of any sub-system block depends on other blocks that are connected to it. Therefore, in practice there are no ideal voltage sources nor ideal voltage measuring instruments. In electrical measurement systems, the output impedance and input impedance of every sub-block (including voltage sources and voltage or current measuring instruments), must be taken into account when connecting them to each other. The notion of source or output impedance follows from Thevenin and Norton equivalents for any electrical source. The notion of input or load impedance follows from the idea that any measuring instrument necessarily draws energy to perform the measurement; therefore, the measuring instrument (or load) can be regarded as the combination of an ideal measuring instrument along with a "load" or energy consuming impedance. In this lab we will measure the input impedance and output impedance of some lab instruments.

Measurement of Impedance

Electrical Impedance is the ratio of the voltage to current. In general, the voltage and current are vectors with magnitude and phase. Therefore, the impedance is also a vector and is usually represented as a complex number for algebraic operations. The impedance usually varies with the frequency and therefore should be denoted as a function of frequency.

When measuring the impedance of a component, if the voltage across the component and the current through the component are known exactly, then the impedance can be calculated.

$$Z(s) = \frac{V(s)}{I(s)}$$

where 's' is the Laplace variable.

1.2 Input impedance of an oscilloscope and output impedance of a function generator

A real oscilloscope can be regarded as an ideal voltage measuring device with a parallel resistance representing the finite current required by its circuitry. Similarly, a signal generator (or function generator) can be regarded as an ideal voltage source with a series resistance representing the finite current delivery capacity of the instrument.

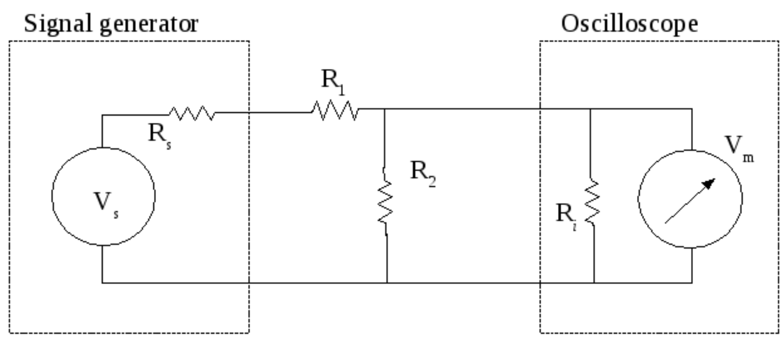

Figure 1.2.1: Measurement setup

The following measurement circuit can be used to determine the output impedance of the signal generator and the input impedance of the oscilloscope. The two resistors, R_1 and R_2 are known precision resistors. The voltage measured by the oscilloscope can be recorded. Using, various values of R_1 and R_2 the values of the input and source resistances can be determined. Use: (a) R1 = 0, and $R2 = \infty$, (b) $R1 = 1M\Omega,\ R2 = \infty$, (c) $R1 = 0,\ R2 = 1k\Omega$. Set the function generator to 2 kHz sinusoid. Adjust the function generator output amplitude and the oscilloscope so that the signal is seen clearly on the oscilloscope in all the cases. Note the readings on the oscilloscope in each case. Do not change the instrument settings between readings. Use these readings to calculate the source resistance of the function generator and the input impedance of the oscilloscope.

1.2.1 Output Impedance of Power Supplies

Set up a simple circuit to measure the source impedance of different cells and batteries in the lab. What is the Thevenin voltage and source resistance of these dry cells?

Power Supply: Set the power supply adjustable voltage to 5V. Set the coarse current setting to zero and the fine current setting to maximum. Use a potentiometer of 1000Ω and decrease the resistance from maximum. What is the voltage versus current characteristic? What is the voltage versus load admittance characteristic?

1.3 Preliminary Report

1. Set up the equations for calculating the input and output impedances as described above. If $R_s = 800\Omega$, $R_i = 1.5M\Omega$, $R1 = 10K\Omega$ and $R2 = 100K\Omega$, what will be the voltage measured?

2. From your experience with AA or "penlight" cells, what do you think is the source impedance of the following: (a) an ordinary dry cell (manganese dioxide), (b) an alkaline cell, and (c) a NiMH cell rated at 1000mAh ?

1.4 Final Report

- Report your experimental results.
- What is the measured source impedance of the function generator?
- What is the input impedance of the oscilloscope?
- What are the source impedances of the cells/batteries that you tested?
- How will you set the power supply to have a current limit of exactly 100mA?

2 Lab 2 – Analog Signal Processing

2.1 Introduction

Operational amplifiers (opamps) are circuit blocks that embody an idealized amplifier; they possess a very large input impedance, a very low output impedance and a very large amplification gain. Opamps are available readily for a few rupees and can be used to build circuits for linear operations like amplification and filtering. Opamps can also be used in non-linear circuits like threshold detectors, rectifiers, etc.

In this lab we'll use opamps for use in amplifiers and filters. In these circuits the opamps should be connected to a power supply - both a positive supply voltage and a negative supply voltage are used to enable the opamp circuit to work with signals that may go positive or negative with respect to a reference. The reference voltage is referred to as the zero voltage or ground voltage. All voltages are measured with respect to this reference or ground voltage.

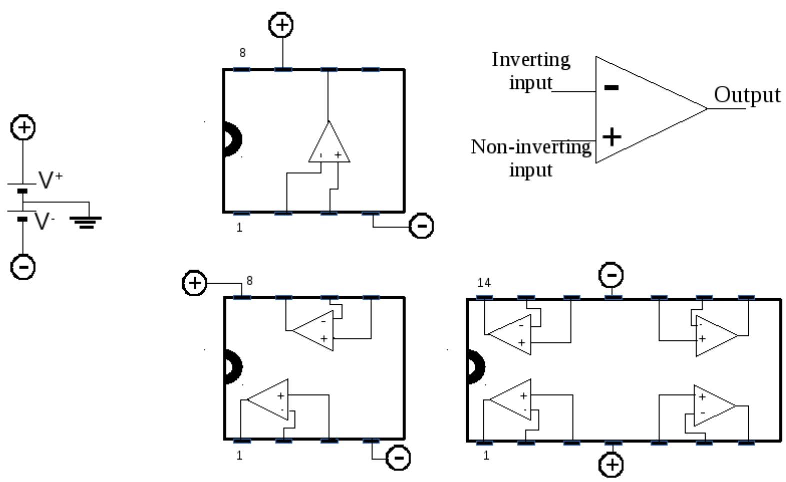

Figure 2.1.1: Operational Amplifier ICs in 3 commonly used packages. (a) single opamp in 8 pin IC, (b) dual opamp 8 pin IC, (c) quad opamp 14 pin IC

2.2 Linear Amplifiers

2.2.1 Differential Amplifier

A differential amplifier can be constructed as in the circuit shown in Fig.2.2.1

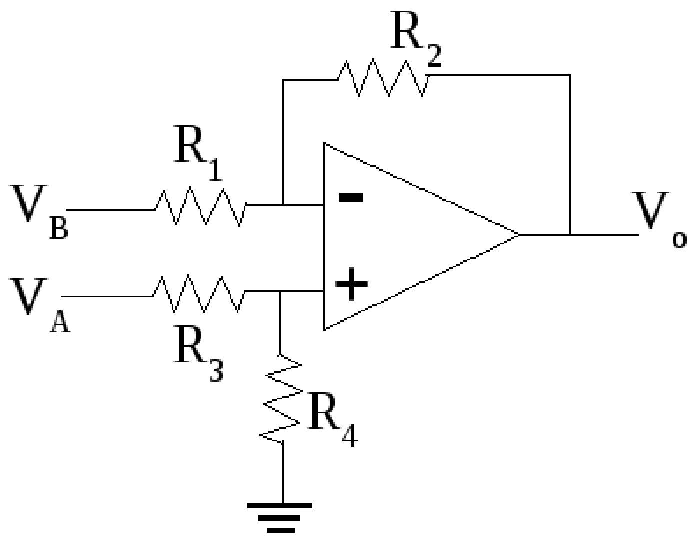

Figure 2.2.1: Differential amplifier

The output voltage is:

$$V_o = V_A \left(\frac{R_4}{R_1}\right)\left(\frac{R_1 + R_2}{R_3 + R_4}\right) - V_B \left(\frac{R_2}{R_1}\right) \tag{2.2.1}$$

For a simple differential amplifier we use $R_3 = R_1$ and $R_4 = R_2$ to get the expression for the output voltage:

$$V_o = \frac{R_2}{R_1}\left(V_A - V_B\right) \tag{2.2.2}$$

The common mode gain of a differential amplifier is defined as:

$$Gain_{common-mode} = \frac{V_o}{\frac{1}{2}\left(V_A + V_B\right)}$$

and the difference mode gain is defined as:

$$Gain_{difference-mode} = \frac{V_o}{\left(V_A - V_B\right)}$$

These gains can be expressed in deciBel as: $G_{dB} = 20\log_{10}(Gain)$
The common mode rejection ratio (CMRR) is usually expressed in deciBel:

$$CMRR = 20\log_{10}\left(\frac{Gain_{difference-mode}}{Gain_{common-mode}}\right)$$

Experimental measurement

Build a differential amplifier with $R_1 = R_3 = 1k\Omega$, $R_2 = R_4 = 10k\Omega$. Determine the difference gain and the CMRR at 10 Hz, 1 kHz and 100 kHz. Use an input signal amplitude of 1V for common mode gain measurement. Use an input signal amplitude of 0.1V for difference mode gain measurement.

2.2.2 Inverting, Non-inverting, Buffer and Summing Amplifier

In the circuit of Fig.2.2.1 if some resistors are removed (made infinite resistance or zero resistance) then the next two circuits are obtained, the inverting and non-inverting amplifiers. A special case of the non-inverting amplifier is the buffer amplifier shown in Fig.2.2.3.

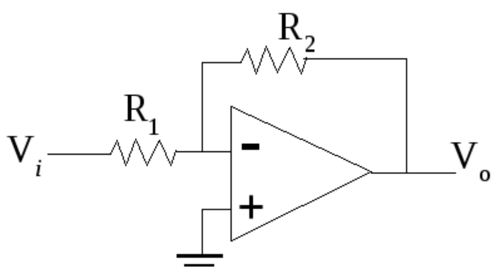

Figure 2.2.2: Inverting amplifier

$$\frac{V_o}{V_i} = -\frac{R_2}{R_1}$$

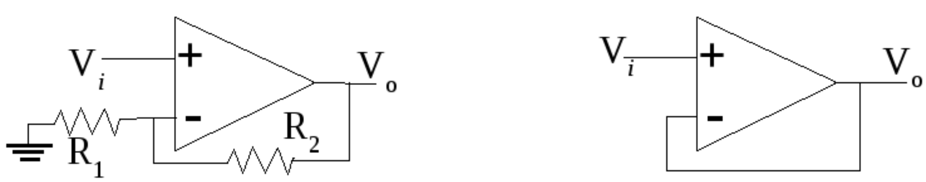

Figure 2.2.3: Non-inverting and Buffer amplifiers

$$\frac{V_o}{V_i} = 1 + \frac{R_2}{R_1}$$

Another modification of these amplifiers is the summing amplifier shown in Fig.2.2.4.

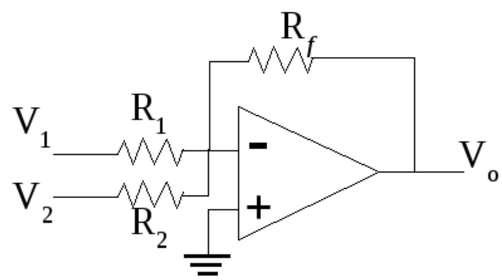

Figure 2.2.4: Summing Amplifier

$$V_o = -R_f \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} \right)$$

Experimental measurement

Build any one of the amplifiers in this section. Select resistors for a gain of about 10. Measure the gain of the circuit, the input impedance and the output impedance.

2.3 Linear, Analog Filters

Filters are important for the removal of unwanted elements or noise in the signals. Frequency filters remove selected frequency components. Practical limitations make filters less than perfect in their frequency selectivity. Active filters are designed with opamps to make their characteristics relatively independent of the circuits that are connected before and after the filters.

The simplest active filters are first order filters.

2.3.1 First order LPF and HPF filters

A first order low-pass filter has a transfer function of the form:

$$H(s) = \frac{A}{1 + s/\omega_c}$$

This transfer function can be realized as an active filter circuit shown in Fig.2.3.1. The cutoff frequency for this circuit is: $\omega_c = \frac{1}{R_2 C}$ and $A = -\frac{R_2}{R_1}$.

A first order high-pass filter has a transfer function of the form:

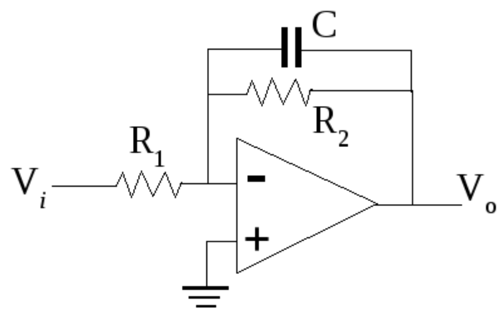

Figure 2.3.1: First order LPF

$$H(s) = \frac{A\,(s/\omega_c)}{1 + s/\omega_c}$$

This transfer function can be realized as an active filter circuit shown in Fig.2.3.2. The cutoff frequency for this circuit is: $\omega_c = \frac{1}{R_1 C}$ and $A = -\frac{R_2}{R_1}$.

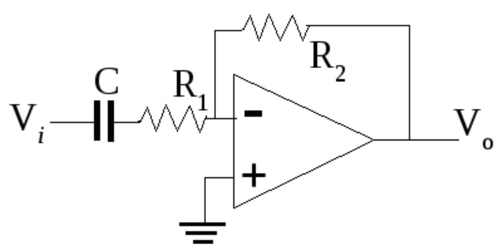

Figure 2.3.2: First order HPF

Experimental measurement

Build one of the first order filters and measure the frequency response.

2.3.2 Second order LPF and HPF filters: The Sallen and Key topology

A second order low-pass filter has a transfer function of the form:

$$H(s) = \frac{A}{1 + s\,(2\zeta/\omega_c) + s^2/\omega_c^2}$$

There are several circuit topologies that can used to implement this transfer function. A very commonly used circuit is that due to Sallen and Key. The Sallen and Key active filter circuit for a second order low-pass filter is shown in Fig.2.3.3. A simple design is to have, $R_1 = R_2 = R$ and $C_1 = C_2 = C$. The cutoff frequency: $\omega_c = \frac{1}{RC}$; the damping factor: $\zeta = \frac{1}{2}(3 - A)$ and the gain constant: $A = 1 + \frac{R_b}{R_a}$.

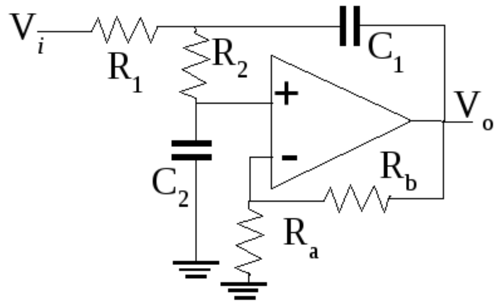

Figure 2.3.3: Second order LPF

A second order high-pass filter has a transfer function of the form:

$$H(s) = \frac{As^2}{1 + s\,(2\zeta/\omega_c) + s^2/\omega_c^2}$$

This is also commonly implemented using the Sallen and Key topology shown in Fig.2.3.4. A simple design is to have, $R_1 = R_2 = R$ and $C_1 = C_2 = C$. The cut-off frequency: $\omega_c = \frac{1}{RC}$; the damping factor: $\zeta = \frac{1}{2}(3 - A)$ and the gain constant: $A = 1 + \frac{R_b}{R_a}$.

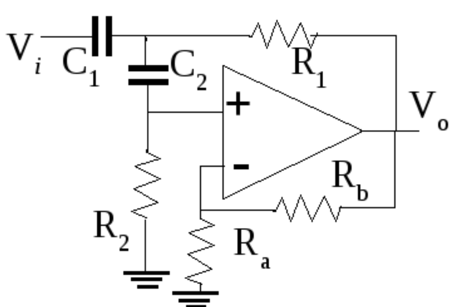

Figure 2.3.4: Second order HPF

Experimental measurement

Build one of the second order filters and measure the following: (a) the frequency response using sinusoids between 1 Hz and 10 kHz, (b) the transient (step) response using a square wave. Design the filter for a cutoff frequency $f_c = 100Hz$ and damping coefficient $\zeta = 0.8$. Repeat the design with a damping coefficient $\zeta = 0.3$.

2.3.3 Multiple Feedback Notch Filters: The Bainter topology

Notch filters are useful in removing a single interfering frequency, commonly the mains interference (50Hz in India, and 60Hz in the USA and parts of Japan). Since the interfering noise is only at a single frequency, the aim is to have a narrow stop band. The transfer function of a general second order notch filter is:

$$H(s) = \frac{1 + s^2/\omega_c^2}{1 + s(2\zeta/\omega_c) + s^2/\omega_c^2}$$

In the case of a notch filter, if the filter stop band is not exactly at the frequency of the interefering noise, then the filter is worse than useless as not only does it fail to remove noise, but it removes a part of the desired signal. Many notch filter circuits are available, usually based on resonant circuits which are very difficult to tune to the correct frequency - small component variation can change the notch frequency. The Bainter notch is a multiple feedback circuit that is quite immune to component variation. Therefore, this is a very useful filter despite its seeming complexity. The Bainter notch filter is shown in Fig.2.3.5.

$$\omega_c = \frac{1}{\sqrt{R_a R_5 C^2}}, \quad \zeta = \frac{1}{R_5 C}, \quad Q = \frac{\omega_c}{\omega_{BW}} = \frac{\omega_c}{2\zeta} = \frac{1}{2}\sqrt{\frac{R_5}{R_a}}$$

where $C_1 = C_2 = C$, $R_1 = R_2$, $R_3 = R_4 = R_a$ and R_6 is large.

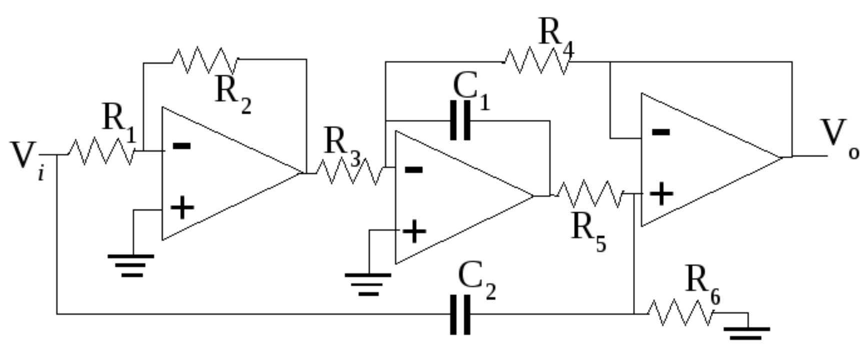

Figure 2.3.5: Bainter Notch Filter

Experimental measurement (optional for extra credit; to be done only if the other circuits have been completed in time)

Build the Bainter notch filter and determine the frequency response of the filter. Use: $R_1 = R_2 = 10k\Omega$, $R_a = 9.2k\Omega$, $R_5 = 129k\Omega$, $R_6 = 120k\Omega$, $C = 0.1\mu F$. Determine the frequency response of this filter.

2.4 Preliminary Report

1. Assuming the properties of an ideal operational amplifier, derive Eq.2.2.1.

2.5 Final Report

Report your experimental observations. Draw the frequency response plots for the filters in Section2.3.

From your experimental measurements calculate the cutoff frequency and in the case of second order filters calculate the damping factor (Hint: use the step response).

References

1. Sallen, R. P. and E. L. Key, 1955. “A Practical Method of Designing RC Active Filters.” IRE Transactions on Circuit Theory, 1955, Vol. CT-2, 74–85.

2. Bainter, James, 1975. “Active filter has stable notch, and response can be regulated,” , Electronics, October 2, 1975, pp. 115-117.