EE283 Lab 8
Operational Amplifiers
Active Filter

Objective:

To understand how operational amplifiers (op amps) can be used to create an active lowpass filter which passes DC and low frequency signals but attenuates high frequency signals.

Theory:

Figure 1 shows the schematic for a lowpass filter using an operational amplifier.

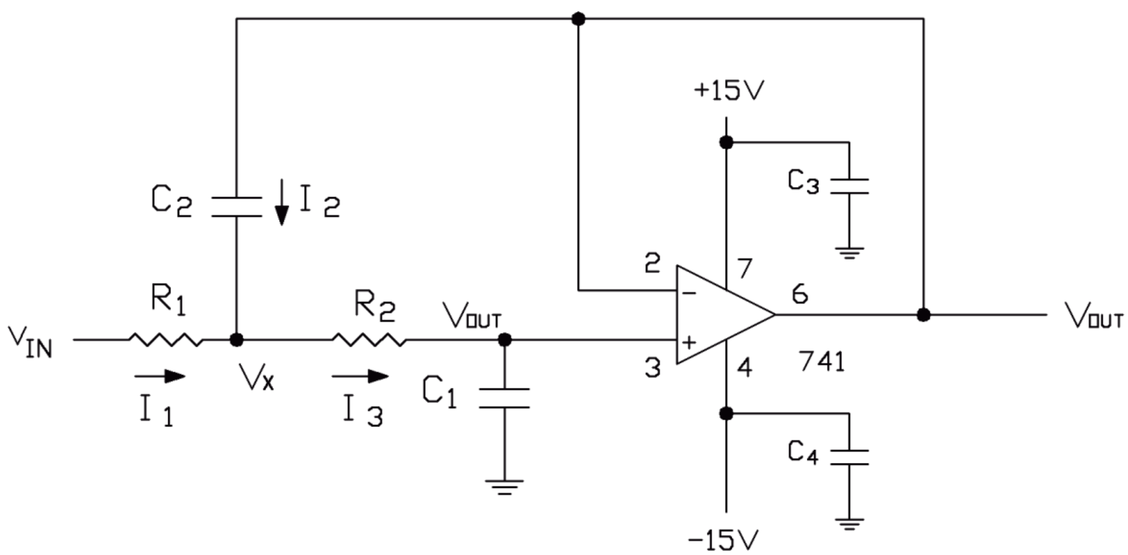


Figure 1
Lowpass Filter Using an Operational Amplifier

There are several types of active lowpass filters but this circuit configuration is called a Sallen-Key Filter. The filter is called an active filter because it uses an operational amplifier (as opposed to a filter with just passive components such as resistors, capacitors or inductors).

At DC or very low frequencies the capacitors can be considered open circuits and the resulting circuit can be seen as a simple noninverting amplifier with a voltage gain, V_{OUT}/V_{IN} of 1. At very high frequencies the capacitor, C_1, acts like a short circuit which prevents any high frequencies from reaching the noninverting input of the op amp. Therefore the high frequency voltage gain, V_{OUT}/V_{IN} is zero. To determine what the voltage gain is at other frequencies requires the use of Laplace transform equations and the use of the three simple rules in designing circuits using operational amplifiers:

- The inverting input (V^-) and the noninverting input (V^+) each have a very high impedance and can neither source or sink current.

- The high amplifier gain, A_V, forces (by means of negative feedback) the inverting input voltage to be equal to the noninverting input voltage. i.e. $V^- = V^+$.
- The amplifier output resistance is reduced to zero ohms by means of negative feedback.

The derivation of the Laplace transform equation for the lowpass filter shown in Figure 1 is shown in Appendix A. As shown in the appendix the voltage gain at any frequency is given by the equation:

$$\frac{V_{OUT}}{V_{IN}} = \frac{\frac{1}{R_1R_2C_1C_2}}{S^2 + S\frac{(R_1 + R_2)}{R_1R_2C_1} + \frac{1}{R_1R_2C_1C_2}} \quad \text{EQ 1}$$

Where $S=j\omega=j2\pi f$. From equation 1 it can be seen at DC (f=0) the voltage gain is 1 and at very high frequencies S becomes very large and the voltage gain is 0. At a frequency of f_0 the voltage gain is 0.707 (-3db). If

$$\omega_0^2 = (2\pi f_0)^2 = \frac{1}{R_1R_2C_1C_2}$$

$$\text{then} \qquad f_0 = \frac{1}{2\pi\sqrt{R_1R_2C_1C_2}} \qquad \text{EQ2}$$

Equipment:

- Tektronix TBS 1064 Oscilloscope
- Tektronix AFG 1022 Function Generator
- Keithley 2231A-30-3 Power Supply
- LM741 Operational Amplifier
- Breadboard

Procedure:

Figure 2 shows the top view of the 741 operational amplifier which is going to be used in the filter. The notch or dot at the end of the package denotes the pin layout as shown in the figure. This amplifier has to be installed on the breadboard in the manner shown in Appendix B – the leads on each side of the package must straddle each side of the “trench” in the breadboard. The figure in the appendix shows a 14 pin package but the LM741 has only 8 pins. The orientation is still the same. Make sure all of the pins are inserted into the breadboard holes properly. Do not use force to insert the op amp.

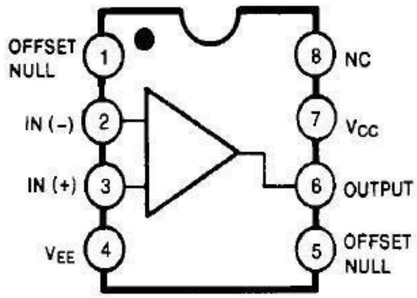


Figure 2
LM741 Pinout – Top View

To supply the ±15 V_{DC} voltages use the two variable power sources in the Keithley 2231A-30-3 Power Supply. They are to be connected as shown in Figure 3.

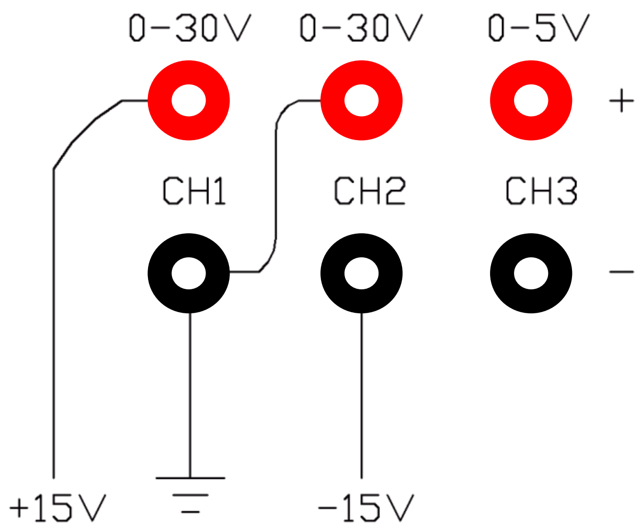


Figure 3
Power Supply Connections

Make sure the voltages are adjusted to 15 volts before connecting them to the breadboard.

Construct the filter circuit shown in Figure 1. Use the Tektronix AFG 1022 Function Generator Output 1 for the AC voltage source, V_{IN}. The component values are:

- $R_1 = R_2 = 1K$
- $C_1 = C_3 = C_4 = 0.22\mu F$
- $C_2 = 0.44\ \mu F$ (two 0.22µF capacitors connected in parallel)

Capacitors C_3 and C_4 have no effect on the gain or frequency response of the lowpass filter. The 741 operational amplifier has a very high gain (~2 million) and can oscillate if the amplifier supply voltages have very long leads. The capacitors provide a low impedance for the supply voltages to prevent oscillations. These capacitors should have short leads connecting them from the amplifier power supply pins to the ground of the C_1 capacitor.

Connect Ch 1 of the Tektronix TBS 1064 Oscilloscope to V_{IN} (Output 1 of the Tektronix AFG 1022 Function Generator) and connect Ch 2 of the Tektronix TBS 1064 Oscilloscope to V_{OUT} (pin 6 of the operational amplifier). Set V_{IN} to 5 volts peak and the frequency to 100 Hz. Record the frequency and the peak output voltage (it should be 5 volts for a gain of 1) in an Excel spreadsheet. Increase the frequency to 200 Hz and again record the frequency and peak output voltage. Continue increasing the frequency in 100 Hz steps and recording the frequency and peak output voltage until you see the output voltage decrease to approximately 4.3 volts. At this point change the frequency increment from 100 Hz to 10 Hz continuing to record the frequency and peak output voltage at each frequency. When the peak output voltage has decreased to less than 3.0 volts increase the frequency increment to 100 Hz and continue to record the frequency and peak output voltage at each frequency until the frequency has reached 2000 Hz.

Add two more columns to your Excel spreadsheet. In the third column calculate the filter gain, $V_{OUT}/V_{IN} = V_{OUT}/5$. In the fourth column calculate the filter gain in decibels (db). The filter gain in db is given by the equation Gain (db) = $20*\text{Log}_{10}(V_{OUT}/5)$. For this lowpass filter the filter gain in db should always be 0 or negative. Your Excel spreadsheet should look like that shown in Figure 4.

Frequency (Hz)	V_{OUT} (Volts peak)	Gain ($V_{OUT}/5$)	Gain (db)
100			
200			
.			
.			
1900			
2000			

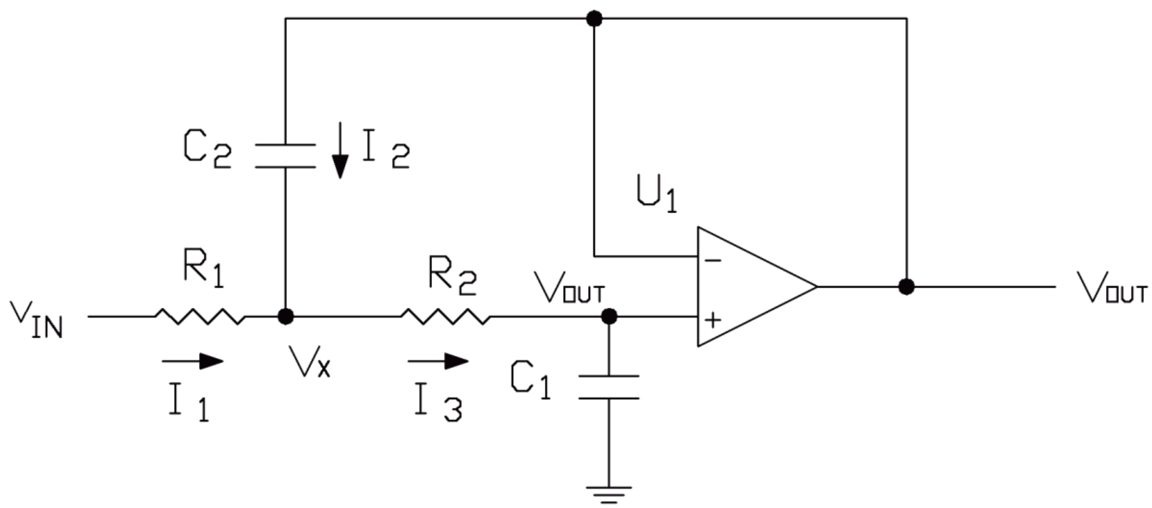
Figure 4
Sample Excel Spreadsheet

Create a graph in Excel using the data in Figure 4. The vertical axis is to be the Gain (db) and the horizontal axis is to be the frequency. The horizontal axis is to be logarithmic. To change the axis to logarithmic put the cursor on one of the frequency values on the horizontal axis and right click. In the box that opens select “format axis” and then check the box that says “logarithmic scale” then close. Make sure you have enough minor grid lines showing. This graph and the data in your Excel spreadsheet (similar to Figure 4) are to be included in your report. Indicate on the graph and in your data the frequency, f_0, where the filter gain decreased by -3db. You do not have to include oscilloscope graphs in your report.

Using either LTspice or PSpice simulate the lowpass filter shown in Figure 1. In LTspice use a voltage source for V_{IN}. This voltage source has to be an AC voltage source. To do this put the cursor over the voltage source and right click. In the box that opens click on “advanced” and then put a 1 in the AC Amplitude box. Then add a “spice directive” to the simulation – it should look like this “.AC dec 1000 100 2000”. Don’t forget the decimal point before the AC. This command tells the simulation to sweep the AC voltage source from a frequency of 100 Hz to 2000 Hz in decades using 1000 points (frequencies) per decade. Put a cursor on V_{OUT} and determine the frequency, f_0, where the output voltage is at -3db. The simulation circuit and frequency response graph showing the -3db frequency should be shown in your report and the background of each must be white.

In your report include a table showing the -3db frequencies, f_0, calculated from equation 2, the measured data and the simulated data. How do they compare?

Appendix A:



$$I_3 = I_1 + I_2$$

$$\frac{V_X - V_{OUT}}{R_2} = \frac{V_{IN} - V_X}{R_1} + (V_{OUT} - V_X) SC_2$$

$$\frac{V_X}{R_2} - \frac{V_{OUT}}{R_2} = \frac{V_{IN}}{R_1} - \frac{V_X}{R_1} + V_{OUT}\, SC_2 - V_X\, SC_2$$

$$V_X\left(\frac{1}{R_2} + \frac{1}{R_1} + SC_2\right) = V_{OUT}\left(\frac{1}{R_2} + SC_2\right) + \frac{V_{IN}}{R_1}$$

$$V_X = \frac{V_{OUT}\left(\frac{1}{R_2} + SC_2\right) + \frac{V_{IN}}{R_1}}{\frac{1}{R_2} + \frac{1}{R_1} + SC_2} = \frac{V_{OUT}(R_1 + SR_1R_2C_2) + V_{IN}R_2}{R_1 + R_2 + SR_1R_2C_2}$$

$$I_3 = \frac{V_X - V_{OUT}}{R_2}$$

$$V_{OUT} = \frac{I_3}{SC_1} = \frac{V_X - V_{OUT}}{SR_2C_1} = \frac{V_X}{SR_2C_1} - \frac{V_{OUT}}{SR_2C_1}$$

$$V_{OUT}\left(1+\frac{1}{SR_2C_1}\right)=\frac{V_X}{SR_2C_1}$$

$$V_{OUT}\left(\frac{SR_2C_1+1}{SR_2C_1}\right)=\frac{V_X}{SR_2C_1}$$

$$V_{OUT}(SR_2C_1+1)=V_X$$

$$V_{OUT}(SR_2C_1+1)=\frac{V_{OUT}(R_1+SR_1R_2C_2)+V_{IN}R_2}{R_1+R_2+SR_1R_2C_2}$$

$$V_{OUT}\left(SR_2C_1+1-\frac{R_1+SR_1R_2C_2}{R_1+R_2+SR_1R_2C_2}\right)=\frac{V_{IN}R_2}{R_1+R_2+SR_1R_2C_2}$$

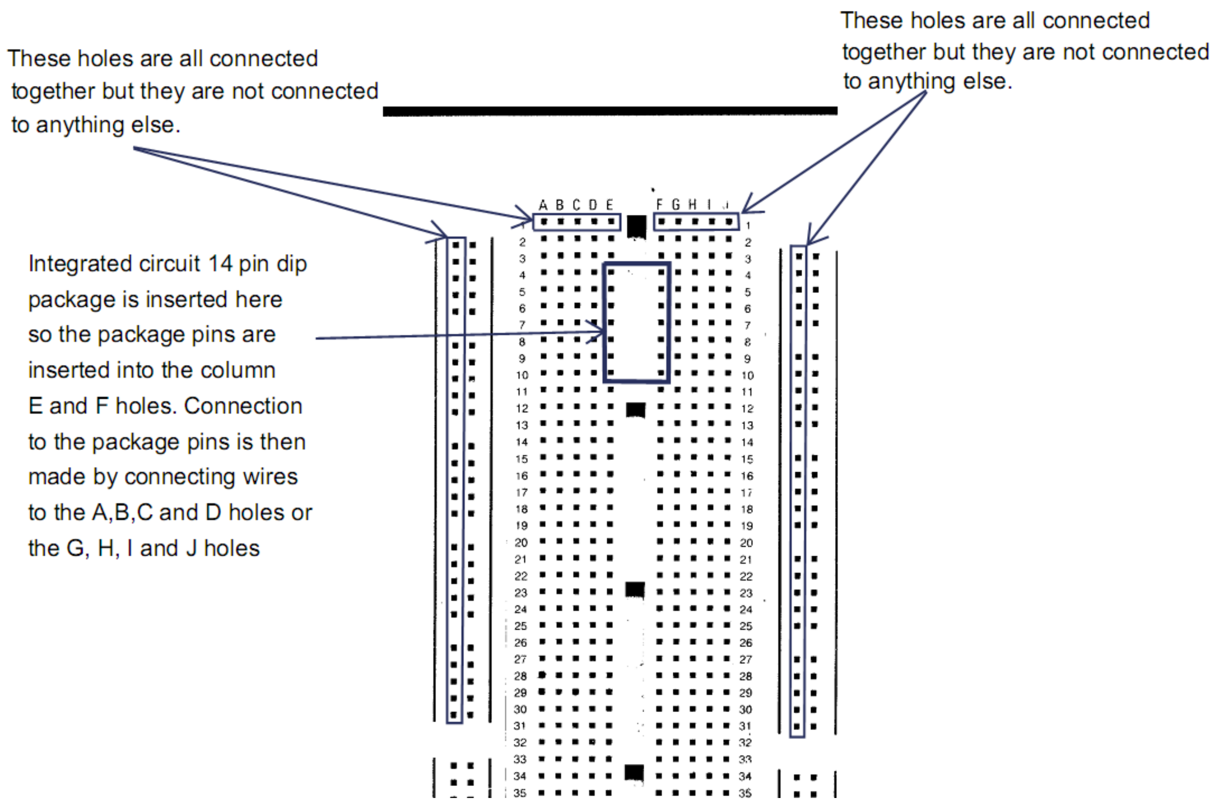
$$V_{OUT}\big((SR_2C_1+1)(R_1+R_2+SR_1R_2C_2)\text{-}R_1\text{-}SR_1R_2C_2\big)=V_{IN}R_2$$

$$\frac{V_{OUT}}{V_{IN}}=\frac{1}{S^2R_1R_2C_1C_2+S(R_1C_1+R_2C_1)+1}$$

$$\frac{V_{OUT}}{V_{IN}}=\frac{\frac{1}{R_1R_2C_1C_2}}{S^2+S\frac{(R_1+R_2)}{R_1R_2C_2}+\frac{1}{R_1R_2C_1C_2}}$$

$$\omega_0^2=\frac{1}{R_1R_2C_1C_2}$$

Appendix B:


These holes are all connected together but they are not connected to anything else.
These holes are all connected together but they are not connected to anything else.
Integrated circuit 14 pin dip package is inserted here so the package pins are inserted into the column E and F holes. Connection to the package pins is then made by connecting wires to the A,B,C and D holes or the G, H, I and J holes

EE283 Laboratory Exercise 8 Form Report

Name:______________________ Section:_____ Station:_____ Date:___________

Setup figure here

Frequency (Hz)	V_{OUT} (Volts peak)	Gain (V_{OUT}/5)	Gain (db)
100			
200			
.			
.			
1900			
2000			

Sample Excel spreadsheet for filter data
(spreadsheet must contain all measured data for all frequencies)

Excel frequency response graph here

Spice circuit here

Spice frequency response graph here

-3db frequencies - f_O

Calculated from EQ 2	From measured data	From Spice simulation

Conclusion here