Experiment No. 5

Variable Gain Amplifiers; Summers; Intermodulation

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Purpose

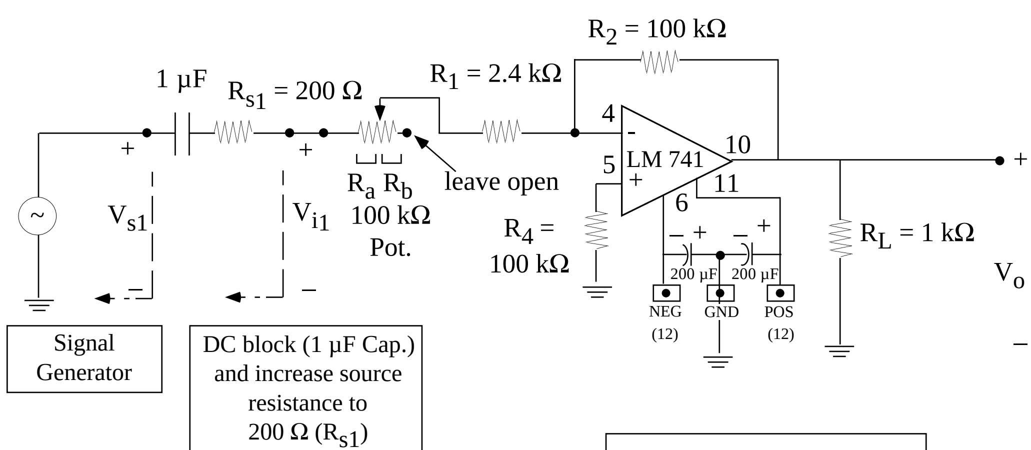
To build and test a variable gain audio amplifier (100 Hz – 20 kHz), and then upgrade it to a two-channel summer. Also, to see the intermodulation products when two signals are fed into a non-linear amplifier.

❏ Read this experiment and answer the pre-lab questions before you come to the lab.

5.1 Variable Gain Audio Amplifier:

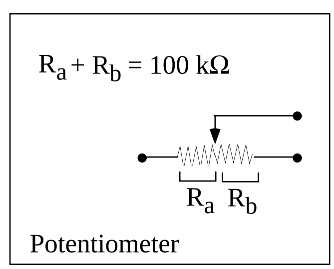
Equipment: The whole Agilent rack.

An inverting variable-gain amplifier suitable for audio frequencies is shown below:



$$V_{cc}^{+} = +12\ V$$

$$V_{cc}^{-} = -\ 12\ V$$



1. ❏ Draw the circuit in your notebook

2. Assemble the circuit on the breadboard. When the circuit is ready, show it to the T.A. and he/she will check it and help you connect it to the power supply.

VARIABLE GAIN AMPLIFIER:

3. ❑ Measure the DC voltages V^-, V^+ and V_O (pins 4, 5, 10). They should all be in the mV range.

4. Set the source at 1 kHz and V_S = 200 mV ppk and connect it to the amplifier. Connect V_{S1} to Channel 1 of the scope.

5. ❑ Connect V_O to Channel 2. Vary the potentiometer from 0 Ω to 100 kΩ. Determine the minimum and maximum V_O. Determine the minimum and maximum gain (V_O/V_{S1}).

   Check to see if it agrees with your pre-lab calculations (Gain ~1-40). Check the frequency domain representation at both gain positions. Basically, if your amplifier is linear, and you are not clipping the output (amplifier saturation) then you should not measure any harmonics, ($2f_O$, $3f_O$, ...)

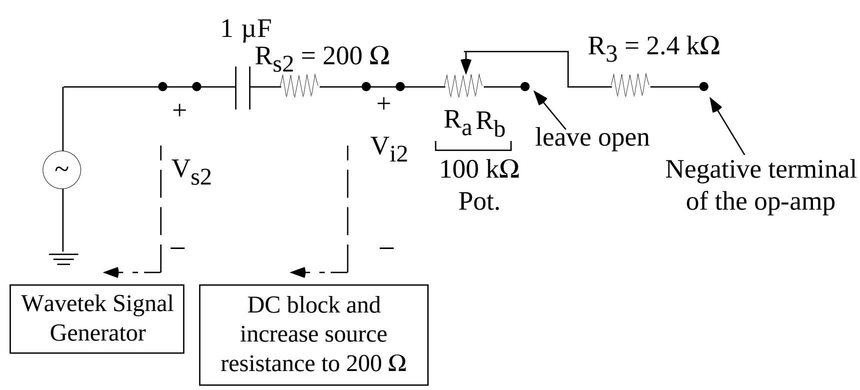
6. ❑ Measure the frequency response from 10 Hz – 1 MHz in a logarithmic fashion (1, 2, 5 frequency hops) for the minimum gain setting ($|G| \simeq 1$), maximum gain setting ($G \simeq 40$) and for the midband gain setting of 10. This can be done by choosing 10, 20, 50, 100, 200, ... Hz and noting V_O/V_{S1} (V_{S1}=200 mV ppk = constant). You can measure the transfer function either in time domain or in frequency domain, as you wish.

7. Something interesting happens for $|G| \approx 1$ (unity gain). You will have a +4-6 dB peak in the frequency response at ~200 KHz. This is due to the internal "compensation" capacitor (C_1 = 30 pF) which ensures stable operation of the op-amp under all negative feedback conditions. At unity gain, the interaction of C_1 with the transistors around it create this peak. This is advanced analog circuit design and you will see it in EECS 413. However, you can always say that you measured it first in EECS 210!

Congratulations; you have built a variable gain audio amplifier with a gain of ~1-40 (0-32 dB).

5.2 Summer and Intermodulation Products:

1. Turn the power supply off. In a different (but close) part of the proto-board, connect the following circuit to the amplifier.



2. ❑ Redraw the entire circuit (with the op-amp) in your notebook.

3. Connect the WAVETEK source to V_{S2} and set it at 800 Hz and V_{ppk} = 200 mV. Choose the gain of channel 2 to be around 10.

4. Connect the Agilent source to V_{S1} and set it at 1 kHz and V_{ppk} = 200 mV. Choose the gain of Channel 1 to be around 10.

2–CHANNEL SUMMER:

5. ❑ Now, turn on both sources and look at the output waveform. The output waveform closely resembles the telephone dial tone! Look at the frequency domain and see the output spectrum. Plot the spectrum of V_O (frequency domain). Again, if your amplifier is linear, then you should only measure f_1 (1 KHz) and f_2 (800 Hz), and no intermodulation products between the two signals ($2f_1$-f_2 , $2f_2$ -f_1, etc. ...).

6. Spend 5 minutes with the potentiometer (to vary the gain of each channel) and signal sources (to vary the frequency of each channel) to get any waveform you wish. You need not be adding only sinusoidal waves. You can try sine waves with triangular waves! However, make sure that you never drive the amplifier into clipping.

Congratulations, you have built a two-channel audio summer, called a "mixer", with a gain of 1-40 for each channel (0-32 dB).

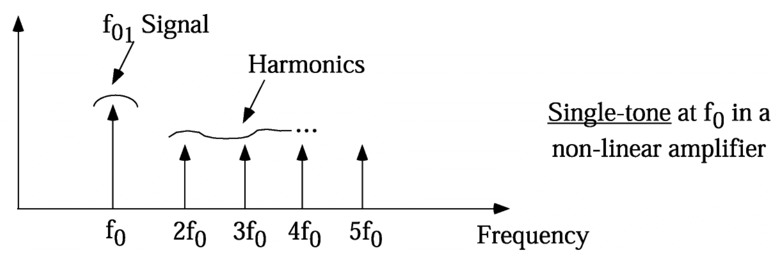
INTERMODULATION PRODUCTS:

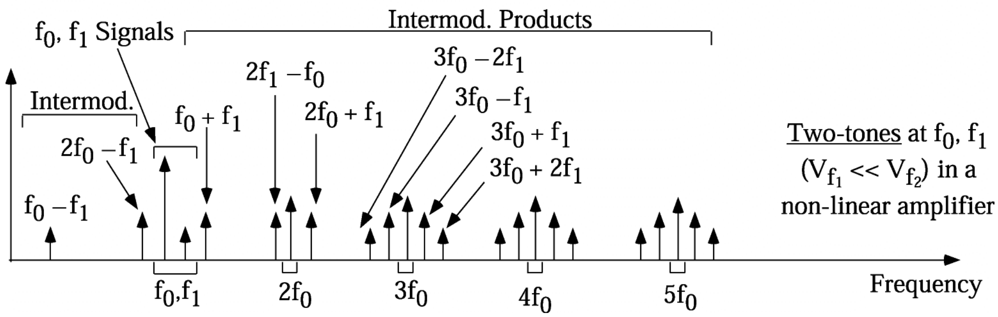
7. ❑ Turn off the Wavetek source. Increase the Agilent source voltage (V_{S1}) at 1 kHz until you drive the amplifier well into clipping. A V_S around 0.65 V_{ppk} and maximum gain will be good. The output signal should have a fundamental frequency component of 17–18 dBV (at 1 kHz) and a third harmonic frequency component of around –10 dBV (at 3 kHz).

8. ❑ Now, turn on the Wavetek source with V_{S2} = 200 mV_{ppk} and f=600 Hz and set the gain to 10. Notice the JUNGLE of frequencies which turn up. These are called intermodulation products. Ask the T.A. to help you here. He/she will show them to you (they are quite obvious).

Explanation:

The summer is the perfect circuit to see the intermodulation product between two tones in a non-linear circuit. Basically, if you have a circuit driven into non-linearity by a large input signal, then it will generate large amplitude harmonics. If a new but much smaller signal is fed into the amplifier, it will mix with all of the harmonics and will create a jungle of frequencies (see figure below).





This example is only with two signals. Can you imagine what will happen if you have 3, 4, 5, ... signals? The simple answer is: HI-FI HELL. SO, THE GOLDEN RULE IS: NEVER DRIVE AN AMPLIFIER INTO THE NON-LINEAR REGION!

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Pre-Lab Assignment

1. This question assumes an ideal op-am (Golden Rules apply): Calculate V_o/V_{i1}, V_{i1}/V_{s1}, and V_o/V_{s1} for the potentiometer set at R_a = 0 Ω and R_a = 100 kΩ. YOU WILL NEED THIS FOR YOUR LAB.

These questions deal with the non-idealities of the LM 741 op-amp.

3. Why is the load resistor (R_L) of the LM 741 variable gain amplifier set at 1 kΩ? Calculate the max. output voltage swing if R_L = 200 Ω.

3. The LM 741 is connected to a DC source of $\pm$12 V with R_L = 1 kΩ. What is the maximum swing (approximately) of V_O before clipping occurs? If R_L = 1 kΩ, what is the maximum power that can be delivered to the load ($P_L = Vpk^2/2R_L = V_{rms}^2/R_L$).

4. You will notice on in Experiment #5 that there is a 100 KΩ resistor connected between the ground and the positive (non-inverting) input of the LM 741 amplifier. Can you explain why this is done? (See Lab #4). Also, why 100 KΩ and not 5 KΩ or 500 kΩ?

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Lab Report Assignment

1. Plot the frequency response of the inverting amplifier for the low medium and high gain (V_o/V_{S1}) settings (dB, *log* f) on the same graph. Explain your results.

2. Calculate the Gain•Bandwidth product at each gain setting. Do your calculations agree with what you expect?

Design:

3. Design a variable gain amplifier with a maximum gain of ~100 and a minimum gain of ~0.5. You can use resistances up to 100 kΩ and a 0-200 kΩ potentiometer. An input resistance of 1 kΩ or above is required.

4. For the amplifier/summer in Experiment #5, assume R_{S1} = 10 kΩ and R_{S2} = 1 kΩ. What is the max./min. gain for V_o/V_{S1}? What is the max./min. gain for V_o/V_{S2}?

   As you can see, there is a resistive divider occurring between R_{S1} and (R_1 + R_a), and between R_{S2} and (R_3 + R_a). Draw a circuit which ensures that both channels have exactly the same gain even if they have different source resistances (you can use other op-amps if you wish). You cannot use potentiometers in your design.

Intermodulation Products:

5. In the lab report of Experiment #3, you calculated the harmonics generated by a non-linear amplifier. Now, you are going to calculate how intermodulation products occur in non-linear amplifiers. A non-linear amplifier transfer function is given by:

   $V_o = A\,V_i + ß\,V_i^2 + \gamma\,V_i^3$ where $A \equiv$ gain of amplifier
   $ß, \gamma \equiv$ non-linear components

   and

   $V_i = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)$ $ß, \gamma << A$

   with $V_2 << V_1$.

   (a) Calculate $V_o(t)$ (neglect all components of V_2^2 and V_2^3 since they are very small). Put V_o in the form: $V_o = A\{ \dots \} + ß\{ \dots \} + \gamma\{ \dots \}$.

   (b) Draw the output spectrum in dB for $V_1 = 0.2\ V_{rms}$, $V_2 = 0.01\ V_{rms}$, f_1 = 1 KHz, f_2 = 1.1 KHz, A = 40, ß = 4, γ = 1.

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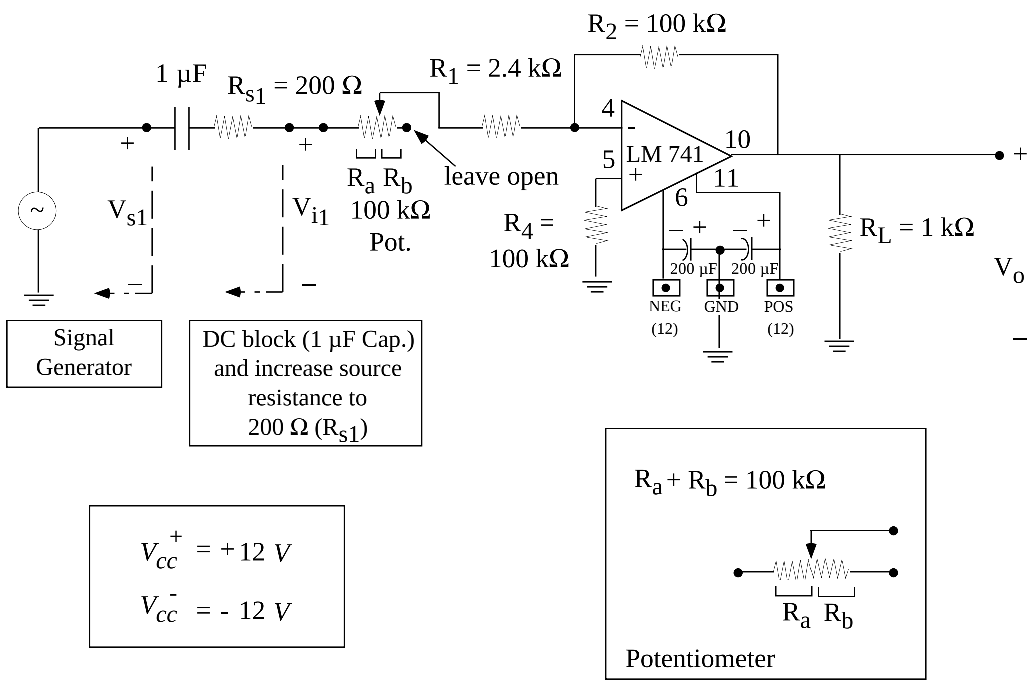
Worksheet/Notes



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