University of Minnesota

Department of Electrical and Computer Engineering

EE 2015 Signals, Circuits and Electronics I

Laboratory No. 03:

Variable-Gain Amplifiers, Summing Amplifiers and Intermodulation Products

By: E. Ebbini

Instructor: Emad S Ebbini

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Goal

The objective of this experiment is to build and test a variable gain audio amplifier (100 Hz - 20 kHz), and then upgrade it to a two-channel summer. If time permits, we will examine the intermodulation products when two signals are fed into an amplifier that exhibits nonlinear response.

- Read [1, Chapter 5] for background on operational amplifiers and their basic signal processing functions.
- Read [2, Chapter 1] for characteristics of audio signals and the specifications of audio amplifiers.

I. INTRODUCTION

Audio signals naturally have large dynamic range and their perception by human ears can be highly subjective. Volume control is the most basic signal processing operation in audio systems to allow users to adjust the sound level at their level of comfort. This can be accomplished by using electronic circuits designed to amplify the audio signal components with or without changing their frequency content. Furthermore, the amplifier can be designed to provide fixed gain (FGA), variable gain (VGA), or even automatic gain control (AGC). As you might expect, the level of sophistication of the circuitry increases in order to support VGA and AGC. In this laboratory, we will build and test the performance of a VGA utilizing the LM 741 op amp and discrete circuit elements. This is the line-level amplifier in the audio amplifier cascade shown in [2, Fig. 1.14].

Figure 1 shows a block diagram of the overall system considered in Lab 03 of which the VGA can be viewed as a subsystem. The block diagram representation is a useful form of abstraction that allows the analyst/designer to focus on the input output characteristics or functionality of components or groups of components forming subsystems. Each one of the blocks in the cascade may be implemented by one or more components, but what's important is the transfer characteristics, e.g.

$$H_{\text{Cond}}(f) = \frac{V_i(f)}{V_{s1}(f)} \qquad H_{\text{VGA}} = \frac{V_o(f)}{V_i(f)}$$

The first subsystem is the `Signal Source`, which could be a microphone, a line input, or a function generator. The second subsystem is called `Signal Conditioning` and it usually contains components that brings the signal at the input of the amplifier to a desirable range, especially to avoid saturation. It may also include components to improve the matching between the source resistance and the amplifier's input resistance. The third subsystem is the `VGA`, which is implemented using the

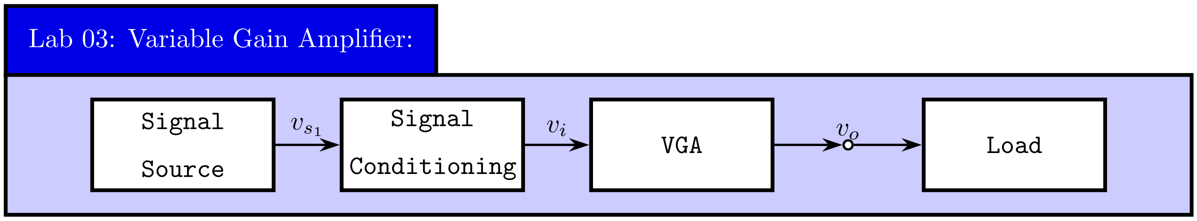
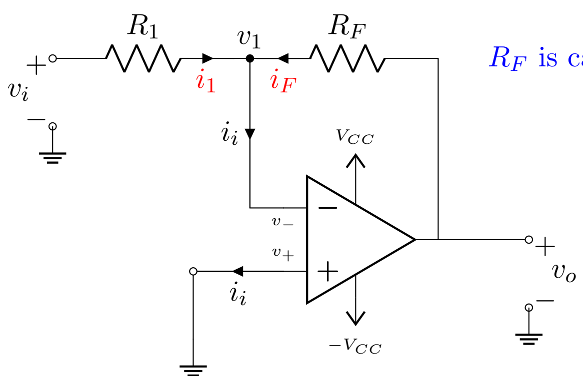


FIG. 1: Block diagram of the cascade from the signal source to the load, including the VGA.

inverting amplifier topology [1, Sec. 5.3]. As discussed in lecture, the schematics for this amplifier are as follows:



R_F is called feedback resistor.

The voltage gain for the inverting amplifier is given by

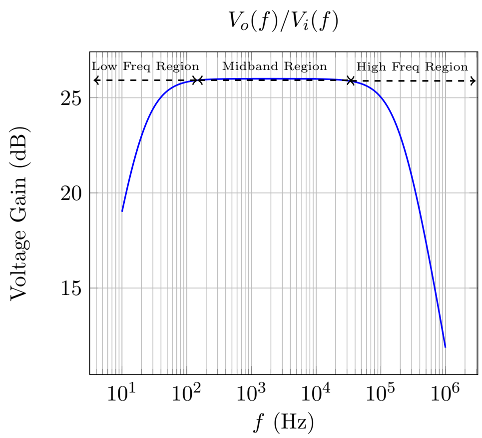
$$G_v = \frac{V_o}{V_i} = -\frac{R_F}{R_1} \quad \text{(Using ideal op amp model)}$$

Summing Amplifier: As discussed in lecture [1, Sec. 5.3], the *summing amplifier* is a simple extension of the inverting amplifier and provides a means of mixing signals from different audio sources, for example, for a two-input summing amplifier

$$v_o = -\left(\frac{R_F}{R_1} v_{i1} + \frac{R_F}{R_2} v_{i2}\right)$$

The output is a weighted sum of the two inputs.

Nonlinear Effects: The output of the amplifier saturates when $v > V_{CC}$ or $v < -V_{CC}$, which puts a limit on the range of v_i values at the input. It should be noted, however, that the amplifier exhibits nonlinear behavior even when the output values are within, but sufficiently close to, the supply voltages V_{CC} and $-V_{CC}$. Therefore, one should characterize the linear range for the amplifier and this is best done by evaluating the spectrum of the output when the input is a clean sinusoidal signal in the midband region, where the voltage gain is maximum (see below). Nonlinearity in the amplifier response generates harmonics in the input signal.



The fourth subsystem is the `Load`, which could be another amplifier stage (e.g., see [2, Fig. 1.14]). In this experiment, however, we use a single resistor as a load. Fig. 2 shows the circuit diagram of the VGA amplifier to be tested in this experiment.

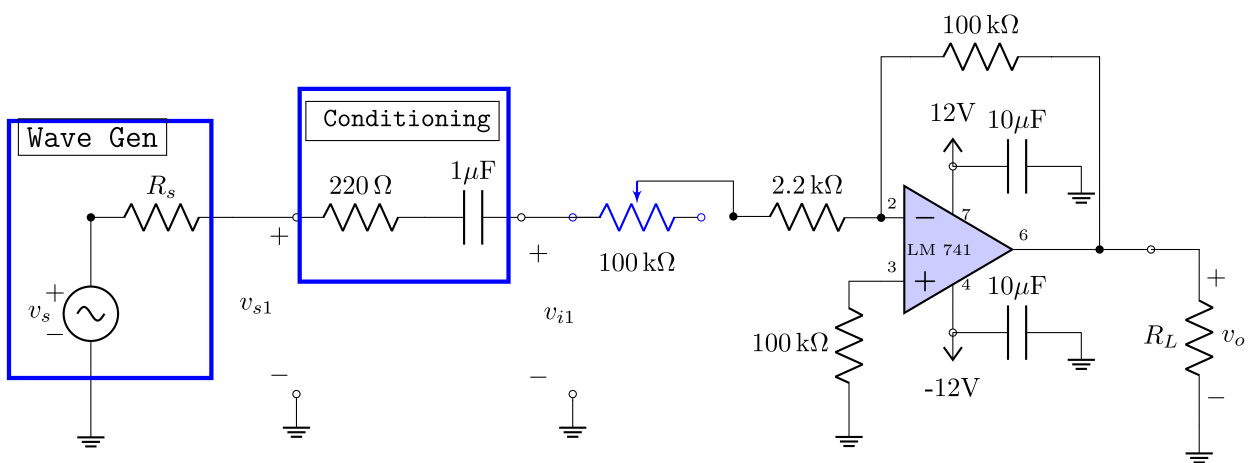


FIG. 2: Circuit diagram for the system shown in Fig. 1: v_{s1} is the voltage at the terminal of the `Signal Source` and v_{i1} is the voltage at the input of the `VGA`. The `Signal Conditioning` circuit is comprised of a DC blocking capacitor and a 220 Ω resistor to bring the source resistance to 270 Ω.

II. EQUIPMENT AND MATERIAL

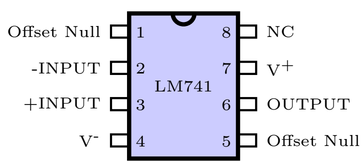
Table I lists the equipment and supplies needed for building and characterizing the variable gain amplifier by completing the procedure(s) in Sec. IV.

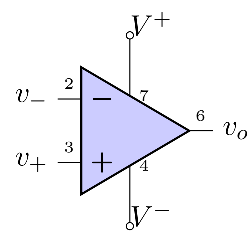
> If you can't find the exact component value in your kit, you may use the closest value available. However, make sure your notebook schematics reflect the values you actually used. The same goes for your report.

TABLE I: Material List for Lab 03

ITEM	QTY	DESCRIPTION
`Keysight DSOX1204G`	1	Digital Storage Oscilloscope
`GW INSTEK`	1	Arbitrary Function Generator
`Lab Kit`	1	LM 741, variety of passive components as needed Refer to Fig. 2
`DMM`	1	Digital multimeter

The LM741 8-pin package and circuit symbol are shown here for reference:





III. PRELAB ACTIVITIES

Read relevant material from the textbook [1, Sec 5.1 – 4] for a description of the operational amplifier and its basic feedback configurations. Section 1.6 in the *Additional Notes* describes the audio amplifier architecture.

Pre-lab Assignment

Consider the circuit shown in Fig. 2. You should draw this circuit in your notebook and wire it up before coming to the lab. In addition, answer the following questions as a group.

1. Why is the external load resistor (R_L) of the LM 741 set at 1 kΩ in Fig. 2? What will happen if $R_L = 100\ \Omega$ and $V_o = 10\ \mathrm{V_p}$?

2. The LM 741 is connected to a DC source of ±12 V. What is the maximum swing (approximately) of V_o before clipping occurs? If $R_L = 1\ \mathrm{k}\Omega$, what is the maximum power delivered to the load ($P = V_\mathrm{p}^2/2R_L = V_\mathrm{rms}^2/R_L$).

3. The gain bandwidth product of a LM 741 op amp is 1 MHz. This means that $Gain \times BW = 1$ MHz or the bandwidth is 1 MHz for a gain of 1. What is the LM 741 op amp bandwidth for a gain of 20? Can we build a hi-fi audio amplifier with the LM 741 op amp with a gain of 200?

4. Calculate V_o/V_{i1}, V_{i1}/V_{s1}, and V_o/V_{s1} for the potentiometer set at $R_a = 0\ \Omega$ and $R_a = 100$ kΩ. YOU WILL NEED THIS FOR YOUR LAB.

IV. PROCEDURE

This section describes the basic procedure for implementing a working model and recording observations.

By completing and understanding the outlined procedure, we will how to build an opamp-based *variable-gain amplifier* and measure its *Gain vs Frequency* characteristics using the `DSOX1204G` scope.

A. Variable Gain Amplifier

Step 1 *Check with your TA before connecting your circuit to the $\pm 12V$ power supply.* S/He will also provide feedback on the layout procedure. Take your time, ASK THE TA for help, and make sure that the connectors are clean with ample space for probing.

Step 2 Since the power supply leads act as antennas for noise, it is important to put two capacitors between the supply lines and ground. A capacitor value of 10 μF should be enough for most noise problems.

Step 3 When the circuit is ready, SHOW IT TO THE T.A. AND HE/SHE WILL CHECK IT AND HELP YOU CONNECT THE POWER SUPPLY.

Step 4 *Use the `DMM` to measure the DC voltages V_i^-, V_i^+ and V_o (pins 2, 3, 6).* The output should be in the millivolt range.

Step 5 *Configure the sinusoidal voltage source, v_{s1}.* Enable the built-in function generator on the `DSOX1204G` by pushing the `[Wave Gen]` key on the front panel. Set the built-in function generator on the `DSOX 1204G` to frequency $f = 800$ Hz and a $V_s = 100$ mV$_\mathrm{p}$: Push `[Wave Gen]` and use the `SoftKeys` to select `Type = Sine, Frequency = 800 Hz, Amplitude = 200 mVpp, Offset = 0 V`.

Connect `Gen Out` (v_{s1}) to your circuit at the 220Ω resistor and connect this point to `Channel 1` of the `DSOX1204G`.

Connect V_o to `Channel 2` of the `DSOX1204G` oscilloscope.

Step 6 *Check the midband Gain range at 800 Hz.* Measure $v_o(t)$ and determine the peek-to-peek value and the gain (V_o/V_s): Push `[Meas]` and use the `SoftKeys` to select `Source=1,2, Type`

`= Pk-Pk, Add Measurement`.

Vary the potentiometer from 0 Ω to 100 kΩ. Determine the minimum and maximum V_o. If necessary, reduce the amplitude of the input voltage to make sure the output voltage is *not clipped*. Determine the minimum and maximum gain (V_o/V_{s_1}). Check to see if it agrees with your pre-lab calculations (Gain values in the 1 – 40 range).

Step 7 *Frequency Analysis of the VGA Output.* Measure the frequency domain fundamental and harmonics (if any): Push `[FFT]` and use the `SoftKeys` to select `Source=2, Span = 20 kHz, Center = 10 kHz`.

Push `[Meas]` and use the `SoftKeys` to select `Source=FFT, Type = X at Max Y, Add Measurement`.

Push `[Meas]` and use the `SoftKeys` to select `Source=FFT, Type = Maximum, Add Measurement`.

Set the time scale to 5 ms/Div (gives a fine frequency resolution of 19.1 Hz)

Connect v_{s1} and v_o to `Channel 1` and `Channel 2` on the `DSOX1204G`.

For this step, Fig. 3 shows an example result with V_{s1} = 460 mV$_{pp}$ at 800 Hz with the gain set to maximum.

> ***Know What You're Measuring.*** *The result shown in Fig. 3 highlights the importance of frequency domain measurements. The input and output waveforms appear to be sinusoidal, which is consistent with the `Wave Gen` settings and the amplifier midband gain (38.5). However, the `FFT` trace shows the fundamental (f_0) and three harmonics ($f_2, f_3, \& f_4$) above the **noise floor**. In other words, we can see evidence of distorion in the frequency domain when it is barely noticeable in time domain measurements.*

☐

Measure the dBV value for all the harmonics above the noise floor and estimate the THD (see Lab 2 Manual). Do this for 3 different gain values and tabulate the results in your report.

> *To measure the dBV value of the harmonics, use the cursor in either horizontal or vertical mode with the `Source` set to `FFT`*

☐

Step 8 *Frequency Response Analysis of the VGA.* Evaluate the frequency response of the VGA using the `DSOX1204G` in the range of 10 Hz - 100 kHz.

(a) *Enable the internal waveform generator by pushing the `[Wave Gen]` button on the front panel.*

(b) *Setup the system shown in Fig. 4:* Push the `[Analyze]` button and use the `SoftKeys` to select `Features = FRA, Setup`.

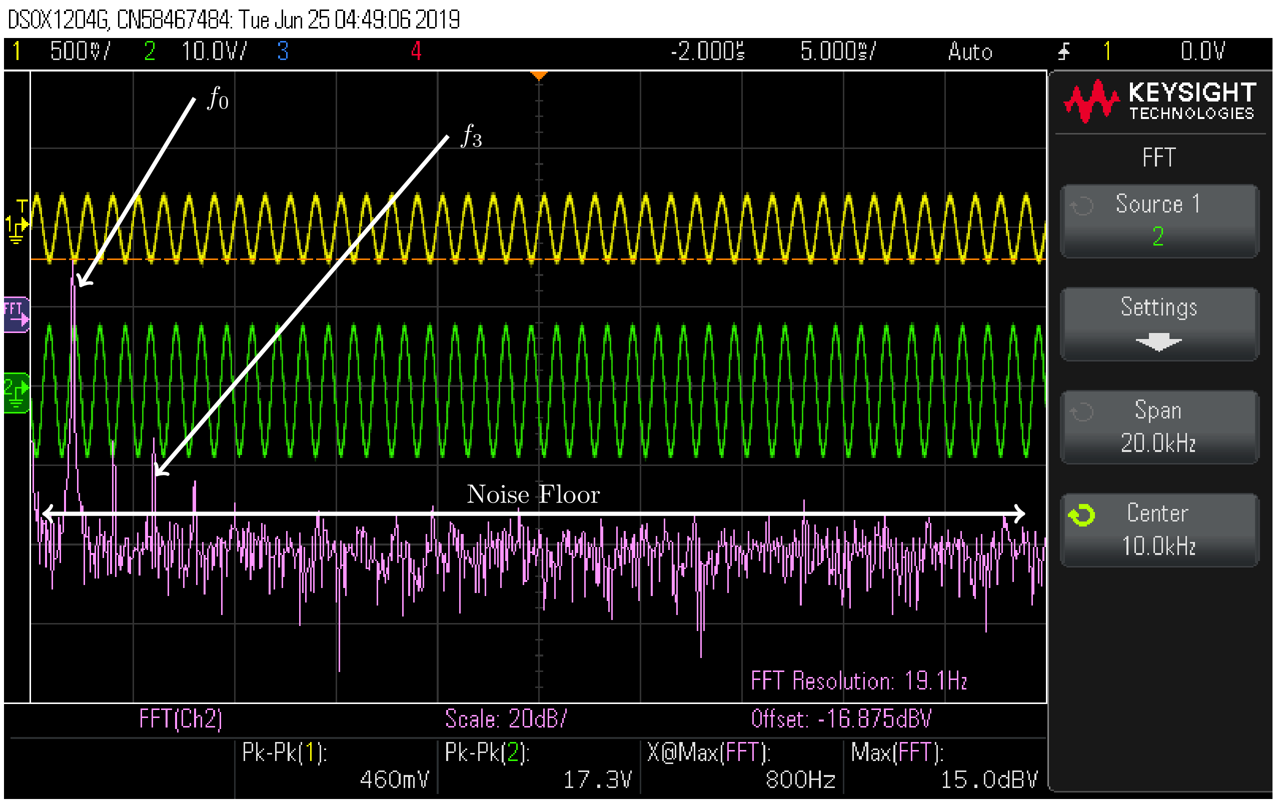


FIG. 3: A screenshot showing the settings of the `FFT` for measuring harmonic content of the VGA output. The spectrum of the output signal shows the fundamental (f_0) and three harmonics ($f_2, f_3, \& f_4$) above the noise floor.

Within the `Setup` Menu use the `SoftKeys` to select `Sources=[In=1,Out=2]`, `Min Freq=10 Hz`, `Max Freq = 100 kHz`, `Amplitude = 200 mVpp`, `Output Load = 50 Ohm`, `Pts per Decade = 40`, `Back`.

Within the `Analyze` menu use the `SoftKeys` to select `Transparent = false`, `Run Analysis`.

(c) Once the analysis is complete, *push* `[Save to USB]` *to save a screen shot of the result.*

Determine the 3-dB bandwidths in all three cases. Remember, the 3-dB bandwidth is when V_o drops to 0.707 (or $\approx 1/\sqrt{2}$) of its value at midband (or by 3 dB).

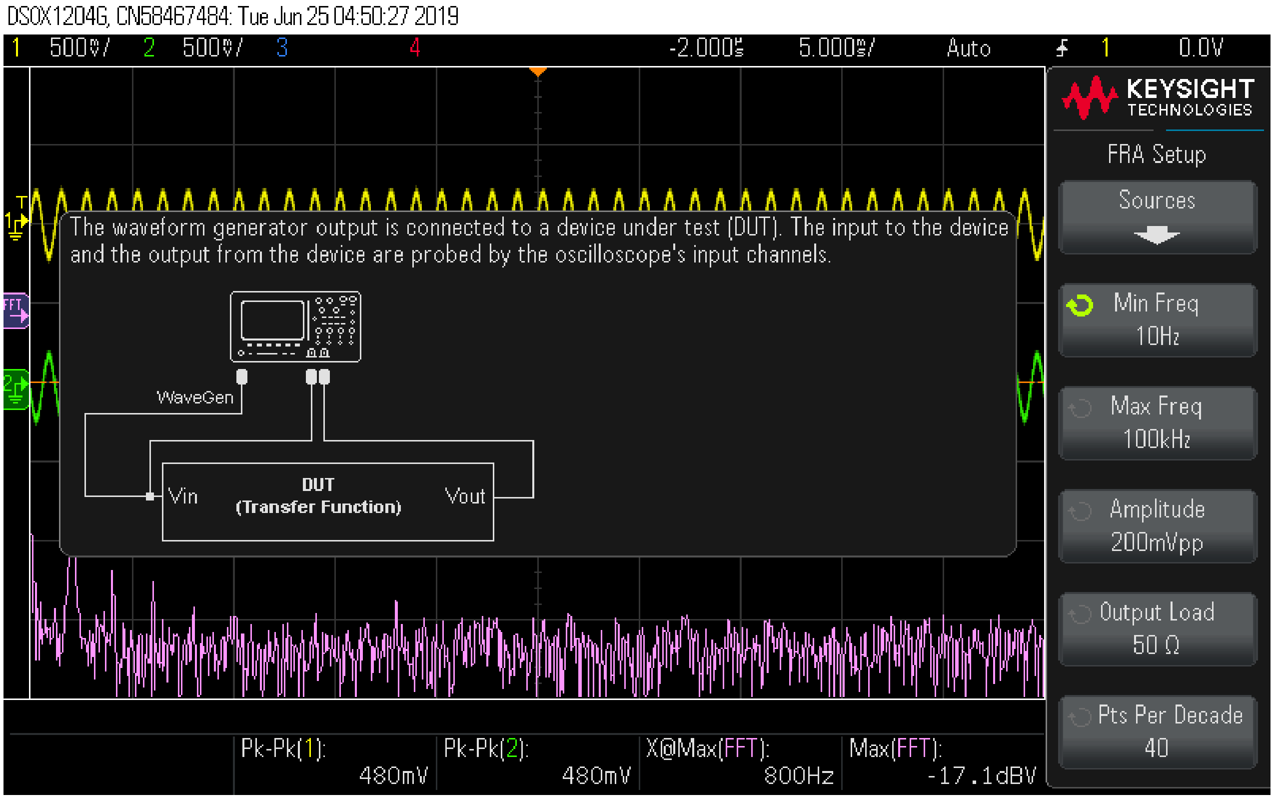


FIG. 4: A screenshot showing the connections needed to perform frequency response analysis.

To measure the 3-dB corner frequency, push the `Move Marker SoftKey` *and the* `Entry` *knob. An orange inverted triangle will appear on the blue magnitude response curve. Turn the* `Entry Knob` *to position the marker in the midband. Record the dB value in the midband and then move the marker to the right until the marker indicates a 3-dB drop from the maximum. The position of the marker indicates the 3-dB corner frequency. Figure 5 shows a screenshot from the* `DSOX1204G` *with the marker placed at 3-dB corner frequency of a VGA similar to the one being tested in Lab 03 (midband gain of 32.2 dB).* ☐

This completes the in-lab procedure for the single-channel variable gain array audio amplifier with a gain of $\approx 1 - 40$ *(*$0 - 32$ *dB).*

B. Two-channel Summer

Consider the two-channel summing amplifier shown in Fig. 6. As the name implies, signals from two sources, v_{s1} and v_{s2} are summed and amplified by the LM 741 circuit [1, Sec. 5.4]. Furthermore, it is the same as the VGA circuit with the addition of a second source and replicating the components

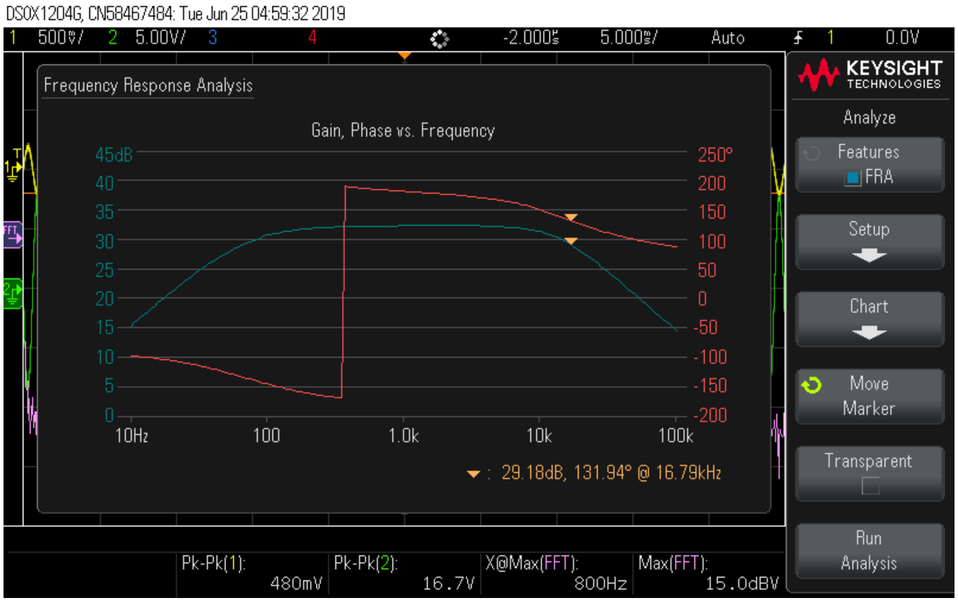


FIG. 5: An example Frequency Response Analysis result from the `DSOX1204G`. The blue curve shows the Gain in dB. The inverted orange triangle marks the upper 3-dB corner frequency of the VGA (midband Gain of 32.2 dB)

in the signal path $v_{s1} \longrightarrow v_{i1}$. Once the circuit is wired up, perform the following steps:

Step 1 *Turn the power supply off.* Connect the circuit shown in Fig. 6. In this circuit, v_{s1} is generated using the `DSOX1204G`'s built-in waveform generator and v_{s2} is generated using and external waveform generator `AFG-2125`.

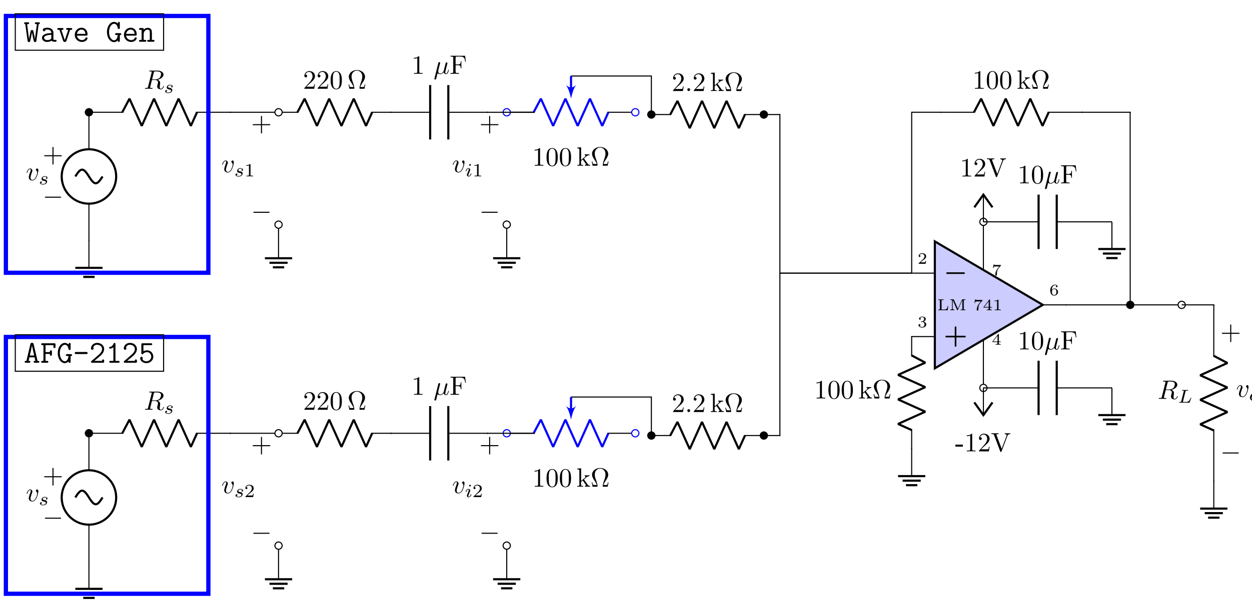


FIG. 6: Circuit diagram of a two-channel summing amplifier with variable gain

Step 2 *Redraw the entire circuit (with the op amp) in your notebook.*

Step 3 *Connect* **`Gen Out`** *to v_{s_1} and set it at 1 kHz and 200 mV_{pp}. Check v_o.*

Step 4 *Turn off the built in source. Connect the* **`AFG-2125`** *source to V_{s_2} and set it at 800 Hz and 200 mV_{pp}. Check V_o.*

Set **`TimeScale = 2 ms/Div`**

Connect V_{s2} to **`Channel 3`** *of the* **`DSOX1204G`**.

Step 5 *Now, turn on both sources and watch the output waveform.* Measure V_o in the frequency domain including all the harmonics (if you find any).

Step 6 Spend 5-10 minutes with the potentiometer and signal sources 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 or oscillation.

This completes the in-lab procedure for the two-channel mixer with a gain of $\approx 1 - 40$ (0 32 dB).

C. Intermodulation Products (Optional)

Step 1 Turn off the `AFG-2125` for now. Set the frequency of the built-in function generator to 1 kHz and increase the source voltage V_{s_1} (and/or the gain of the amplifier) until you drive the amplifier into clipping. A V_s around 0.65 V_{pp} and maximum gain will be good. Set V_s to get a fundamental of 17-18 dBV (at 1 kHz) and a third harmonic around -10 dBV (at 3 kHz). Measure V_{ppk} in time domain and write it down. Look at the frequency domain representation and measure all the harmonic levels (up to 7 f_0 or more if you wish).

Step 2 Now, turn on the `AFG-2125` source with $V_{s_2} = 200$ mV_{pp} and $f = 600$ Hz and set the gain to 10. The resulting output voltage at 600 Hz should be -3 dBV in the frequency domain or 2 V_{pp} in the time domain. Notice the jungle of frequencies which tum 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). Measure the frequency and dBV of f_1 and f_2, and of at least 9 of these products. The strong products will be $2f_0 - f_1, 2f_1 - f_0, 3f_0 - f_1, 3f_0 + f_1, \ldots$. Some of them will be below 600 Hz!

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 a set of 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 Fig. 7).

Step 3 Connect the source to V_{s_1} and set it at 1 kHz and V_{pp} = 200 mV. Check V_o. This example

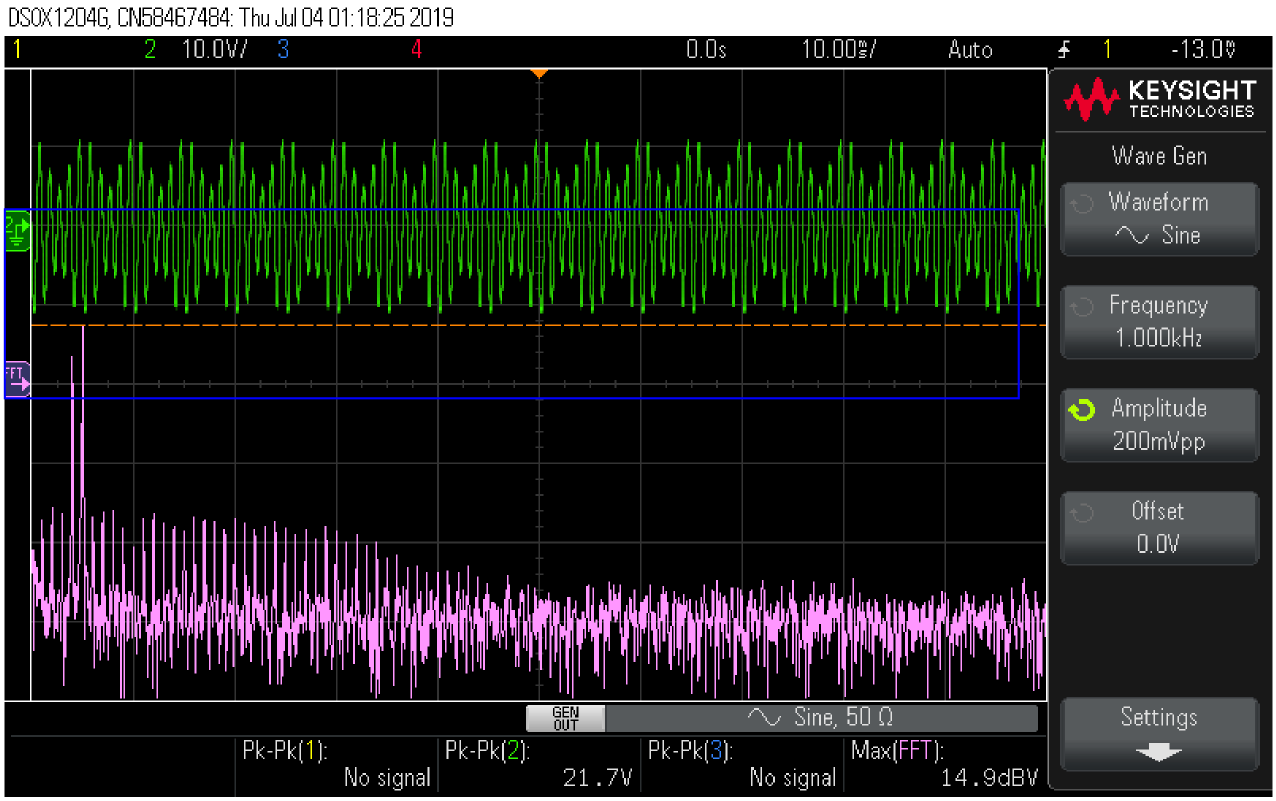


FIG. 7: An illustration of the of the intermodulation product in the frequency domain.

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!

D. SUGGESTED ACTIVITIES

V. REPORTING ACTIVITIES

One report will be required from each group by the due date posted on Canvas. We require group reports rather than individual ones with the expectation of higher quality content and organization.

A good laboratory report is a modified version of a technical report containing the following sections:

- *Summary*: A succinctly written single paragraph given a general description of the overall objective, methodology and main conclusion of the experiment.
- *Introduction*: Provide some background material about the nature of the experiment and the significance of the questions to be answered by the experiment design.
- *Theory*: Key mathematical formulas underpinning the reported results, e.g. voltage gain, input resistance, etc. Your theory section should be a recapitulation, not a regurgitation of textbook material. Formulas described fully in the textbook can be referenced by their numbers in N & R, but key formulas most relevant to the measurements/results described in the report should be included in a concise form.
- *Equipment*: A list of equipment used in the experiment should be provided. Major equipment should be named for easy reference in the report, e.g. `DSOX1204G`.
- *Procedure*: This should reflect the Procedure given in the Lab Manual. The report should include documentation from your lab notebook summarizing your observations (e.g. oscilloscope screen shots) associated with each step.
- *Results*: A concise summary of the measurements in table and/or figure form should be included. The figures and/or tables should give the reader an idea about the level of variability of a specific measurement. For example, when measuring the dB level of harmonic components from the `FFT` on the `DSOX1204G`, especially when these values are just above the noise floor.
- *Discussion*: Any limitations of the experiment that might qualify the conclusions are addressed in the discussion section. Most importantly, this section should give the reader an idea about any anomalies in the observations or measurements. Give a brief statement about possible reasons and significance. If significant, speculate on possible mitigations even if there is no time to test them in the lab. In many ways, a well written discussion section can be the most valuable part of a worthy technical report.
- *Conclusions*: Summarize the main results, margins or statistics of error, significant discrepancies (if any) and possible mitigations.

We encourage the students to start planning their reports while working on the experiments. For example, using your favorite word processor, prepare a template report containing the suggested list of sections and start filling material as it becomes available, e.g. from reading, sample results/observations, data analysis, etc. This will make it easier to finalize your report when the deadline comes.

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[1] Nillson and Riedel, *Electric Circuits*, 11th Edition, Pearson, 2018.

[2] Emad S Ebbini, *Circuits and Electronics for Information Processing*, Additional Material for EE 2015 & EE 2115 at University of Minnesota, 2019.

Appendix - Measuring Harmonic Contents Using Cursors

Cursors are horizontal and vertical markers that indicate X-axis values and Y-axis values on a selected waveform source. You can use cursors to make custom voltage, time, phase, or ratio measurements on oscilloscope signals.

Cursor information is displayed at the bottom of the screen. X Cursors X cursors are vertical dashed lines that adjust horizontally and can be used to measure time (s), frequency (1/s), phase (), and ratio (%).

When used with the FFT math function as a source, the X cursors indicate frequency.

Y Cursors Y cursors are horizontal dashed lines that adjust vertically and can be used to measure Volts or Amps, dependent on the channel Probe Units setting, or they can measure ratios (%). When math functions are used as a source, the measurement units correspond to that math function.

The Y cursors adjust vertically and typically indicate values relative to the waveform's ground point, except math FFT where the values are relative to 0dB.

For the best vertical accuracy on peak measurements:

- Make sure the probe attenuation is set correctly. The probe attenuation is set from the Channel Menu if the operand is a channel.
- Set the source sensitivity so that the input signal is near full screen, but not clipped.
- Use the Flat Top window.
- Set the FFT sensitivity to a sensitive range, such as 2dB/division.

For best frequency accuracy on peaks:

- Use the Hanning window.
- Use Cursors to place an X cursor on the frequency of interest.
- Adjust frequency span for better cursor placement.
- Return to the Cursors Menu to fine tune the X cursor.