ELEC/PHYS 4680/5680
Quantum Computing Technology Laboratory

Experiment #3: Analog Amplifier Frequency Response

Overview

Part #1a: Estimate GBP of 741 opamp

Background:

Many opamps use an internal voltage feedback configuration where the gain and bandwidth (BW) of an amplifier circuit incorporating the opamp are inversely related to one another, resulting in a constant product (the gain-bandwidth product, GBP—occasionally GBW).

The Scopy application interfaces with the ADALM2000 (M2k for short) data acquisition (DAQ) unit with several virtual instruments, including a network analyzer (not to be confused with a vector network analyzer) that creates a Bode plot of the transfer function, which can be saved as a text or CSV file for plotting and analyzing in MATLAB or similar applications. Such results can be compared to analytical models to determine specific circuit parameters or features (e.g., cutoff frequency).

Goal:

The goal of this lab segment is to determine the GBP of an entry-level opamp, the 741. You will do this by measuring the cutoff frequency of a simple inverting amplifier circuit built around the 741 with various gains (x5, x20, and x100) and then calculating the GBP for each. In doing so, you will gain experience with a basic opamp circuit and network analyzer, and begin learning skills such as interpreting opamp data sheets.

Part #1b: Compare GBP of cascaded circuits

Background:

Given that the GBP of a device limits the bandwidth that can be achieved for a desired gain, opamp circuits are often cascaded (used in series) to avoid this limitation. There are additional benefits to cascading opamp circuits that will be discussed in Experiment #4.

Goal:

The goal of this lab segment is to create a circuit with x100 gain and a bandwidth higher than 10 kHz using the 741 opamp. You will do this by cascading the x5 and x20 circuits you used in the previous task and determining the resulting bandwidth.

Part #1c: High-performance opamps

Background:

Most opamps are of higher quality than the 741 in at least one parameter—often several! The role of a practicing professional engineer or physicist is to consider the technical requirements of a design and to select components that meet or exceed those requirements. In this lab segment, you will focus mostly on the requirement of high bandwidth; you will investigate low noise performance in Experiment #4.

Goal:

The goal of this lab segment is to characterize circuits of various gains containing four high-performance opamps: the AD797, AD848, ADA4898-1, and LMH6624 devices.

Standard Procedures:

ELEC/PHYS 4680/5680
Quantum Computing Technology Laboratory

Note: These standard procedures are in development. Let us know if you see any errors or any other aspects requiring clarification.

General Power Supply/Breadboard Setup:

1. Parts:
   i. Siglent SPD3303X Power supply
   ii. Breadboard
   iii. Patch cords (banana connectors) (4)
2. Connect Ch1 – to black socket on breadboard with black patch cord.
3. Connect Ch1 + to Ch2 – with short green patch cord, and to green socket on breadboard with long green patch cord. Do *not* use the ground (GND) terminal.
4. Connect Ch2 + to red socket on breadboard with red patch cord.
5. With both channel outputs “off,” set each to 1 A. You will set the voltage according to each individual lab section instructions.

General Operation of ADALM2000 (M2k):

1. Remove the BNC adapter card.
2. Start Scopy.
3. Initialize the M2k. It should perform a self-calibration.
4. If the self-calibration is successful, reinsert the BNC adapter card.
5. If, for any reason, you ever need to re-calibrate the M2k, you must remove the BNC adapter card first. You ***will*** get erroneous results if you do not!

M2k *Network* Analyzer Hardware Configuration

1. Parts:
   i. M2k, USB cable, BNC adapter card
   ii. BNC “Y” adapter (1)
   iii. BNC elbows (3)
   iv. BNC “T” adapter (1)
   v. Short BNC cable (1)
2. Connect BNC Y to M2k W1 (output), with one BNC elbow on each remaining branch of the Y.
3. Connect the remaining BNC elbow to M2k 1+ and the BNC T to M2k 2+ (inputs).
4. Connect the short BNC cable between one branch of M2k W1 and M2k 1+.
5. The other branch of M2k W1 will drive the device under test (DUT); M2k 2+ is the network analyzer input. They will be connected as appropriate for each experiment/DUT.

M2k *Spectrum* Analyzer Hardware Configuration

1. Parts:
   i. M2K, USB cable, BNC adapter card
   ii. BNC elbow (2)
2. Initialize the M2k (see above, *General Operation*).
3. Connect one BNC elbow to 1+ and another to 2+.

ELEC/PHYS 4680/5680
Quantum Computing Technology Laboratory

Tasks (1a: *Estimate the GBP of the 741 opamp*)

1. Prepare power supply (PS) and breadboard (see standard instructions).
2. Set up M2k + BNC adapter in Network Analyzer configuration (see standard instructions).
3. Inspect the three evaluation boards (EBs). Each is an inverting amplifier utilizing a UA741 opamp from ST Microelectronics. There are three gains, x5, x20, and x100. Verify the component values under the microscope and record.
4. *Prelab (all):* What is the allowed range on the M2k input? If the maximum output voltage swing of the UA741 is about ±12 V with a ±15 V supply, what is the maximum drive voltage (from the Scopy NA panel) that should be used for each EB gain? Make a table of these values.
5. Verify the PS output is off (buttons dim), and that the Scopy NA is stopped. Set the PS output to 10 V on both Ch1 and Ch2.
6. With the PS output off, install the **x5 gain** inverting amp EB onto the protoboard. Note: you should *always* be sure to turn off the power and stop the NA sweep when switching out the EBs to avoid damage to the components.
7. Taking care with proper strain relief, so as not to pull the EB out of the breadboard (they tend to pop out easily), connect one BNC/SMA cable between M2k W1 and EB input (under the label on the left) and the second between M2k 2+ and EB output. Note: SMA connectors are susceptible to damage if cross-threaded or overtightened. If it is not connecting smoothly, *stop!* Something is wrong. Double check the alignment and/or talk to the instructor. Turn “on” the PS output (toggle the “All on/off” button).
8. Use the M2k NA function to measure the transfer function (Bode plot) of the EB. Select the drive voltage, frequency span, averaging, and points per scan appropriately; record these values in a table. Optimize (and record) your settings to maximize your signal quality without overloading your circuit. Your data should be smooth at low frequencies and consistent with the DC gain and phase of the board as marked. You may also want to choose fewer averages and/or points per scan as you are setting up, followed by more averages &/or data points per scan for your final data. Your report must include a discussion of your selection process. Include data from multiple drive levels, as the GBP may change accordingly—use the maximum BW data for your GBP calculation.
9. *For the individual report only:* Explain why the maximum BW might vary with drive level.
10. Save the data in whatever format you choose for later plotting (using whatever app you choose) to include in your report. Accurately estimate the corner frequency from the data and record. There are two ways to do this: Measure the -3 dB frequency or find the intercept of the flat and 1/f lines on a semi-log scale if you use dB on the vertical axis, or on a log-log scale if you use straight gain (V/V). Demonstrate the method you used. You will also need accurate measurements of the dc gain, which you can obtain off-line by averaging over a reasonable subset of low-frequency data. Turn the PS output “off” (toggle the “All on/off” button”).
11. Repeat 6-9 for the **x20** and **x100** EBs. *You will receive additional instructions for the x100 EB tests.*
12. Calculate and tabulate the GBP for each configuration.
13. *For the individual report only:* How consistent are these results? How might you quantify the consistency? If you had more time and more evaluation boards to configure at will, how would you plan an experiment to better quantify the consistency?
14. *Prelab (graduate students only):* Write the ideal complex transfer function and convert to magnitude and phase that you would expect to see on the Bode plot. You may leave the dc gain (use variable A_{dc}) and corner frequency (use variable f_c) as unknowns. What is the gain at f_c?
15. *For graduate students only:* Using linear units (V/V), not dB, fit the amplitude data only (not the phase data) to this model, extracting the dc gain and corner frequency (A_{dc} and f_c, respectively) in whichever application you choose. Comment on any non-ideal features. How sensitive is the result to your exclusion of points at high frequency?

Tasks (1b: *Compare GBP of cascaded circuits*)

1. Prepare power supplies and breadboard (see standard instructions).
2. Set up M2k + BNC adapter in Network Analyzer configuration (see standard instructions).
3. Now cascade the x5 and x20 EBs, using the short SMA/SMA cable. Perform the same measurements as in 1a. Is there a difference in performance if you use the x5 followed by the x20 vs. the x20 followed by the x5? Compare the performance of this cascaded circuit to that of the basic x100 EB. Note: you will receive special instructions for all net x100 measurements.
4. <u>*For the individual report only:*</u> In principle, all other things being equal (they are not; we will explore this in Lab #4!), what would be the optimum gain configuration of identical opamps to maximize the BW of a two-stage x100 amplifier? For a three-stage x100 amplifier? Note: *Do not look this up; we are only looking for the basic quantitative relationship that you can determine by knowing that the GBP is constant!* If the opamp is a UA741, assuming a 1 MHz GBP, what would be the BW of each configuration (single-stage, optimum 2-stage, and optimum 3-stage)? Also comment on the phase data, relative to that of the individual x100 EB results.
5. <u>*For graduate students only:*</u> Compare your experimental data from 1b.3 to that which you would expect analytically. This should be a solid analysis but you do not need to fit the data. Plotting the expected curve and measured curve on the same graph is sufficient. Do you expect to see a difference between x5 -> x20 vs x20 -> x5? Explain, why or why not. What is the order of the roll-off at high frequencies? Is it consistent with a single pole, two poles, or something else? What would you expect? Finally, there are conditions where it is not optimal to use the same opamp for both stages of a cascaded circuit. What technical requirements might lead to this? (Note: There is no right or wrong answer to the latter; we just want you to think about some aspect of practical applications.)

Tasks (1c: *Characterize high-performance opamp circuits*)

1. Prepare power supplies and breadboard (see standard instructions).
2. Set up M2k + BNC adapter in Network Analyzer configuration (see standard instructions).
3. *Prelab (all):* Review the data sheets (provided on Canvas) of the AD797, AD848, ADA4898-1, and LMH6624 opamps. Create a table of operating parameters including GBP, input offset voltage, maximum bi-polar supply voltage, output voltage swing, and minimum stable gain (if noted), and any others you feel might be relevant. Save this information since you will be adding new parameters to it for Lab #4. Note that some parameters may vary depending on the supply voltage; you will use a ± 6 V supply for these circuits. In cases where a “typical” value is listed in the datasheet, use that; if only a minimum or maximum value is listed, use that and make a note of it.
4. *Midlab (all):* The nominal gains of these circuits are 15, 10, 10, and 100 for the AD797, AD848, ADA4898-1, and LMH6624, respectively (“Box #2”). On the first active lab day, inspect and note the resistor values of each EB and calculate the expected gain. The expected gain will be different from the nominal gain because of limited resistor values.
5. *Midlab (all):* Using the table from 1c.3, note the expected maximum output voltage swing and calculate for each circuit the maximum drive voltage that will not saturate the output.
6. Using the NA function of Scopy, measure and record the actual gain at low frequency (below 100 kHz) of each EB and compare. What is the percent difference of the measured value from the calculated value? The resistors are 1% precision resistors; is the difference consistent with that variation? Note: you will receive additional instructions for the x100 EB.
7. Again using the NA function of Scopy, measure and record the 3 dB BW with various drive signals of each EB. Note that, in general, the large-signal BW is smaller (sometimes much smaller) than the small-signal BW, even if the output is not saturating. See the data sheet for the ADA4898-1 for an example of this.
8. *Prelab (all):* What is the minimum signal that the Scopy NA can source? Input?
9. Your drive signal ranges are likely to be different for each opamp. This may take some trial and error; test at least three drive levels. Record the optimal drive amplitude (that gives the highest BW) for each EB. Use your judgment in selecting the frequency span; it will be quite a bit higher than in 1a or 1b.
10. *For the individual report only:* Compare the measured GBP for each of these circuits to values listed in the respective data sheets. How well do they match (or not)? Qualitatively, how closely do the EB circuit Bode plots match what you would expect from a single-pole model? Comment on any non-ideal features.
11. *For graduate students only:* SPICE macromodels are available for each of these opamps, though that of the LMH6624 is a bit more difficult to find. Using your preferred SPICE simulator, model at least two of the four evaluation boards and compare the results qualitatively (overlay the SPICE and experimental data on the same plots, you do not need to do any curve fitting). Provide the netlist as an appendix to your report. Note that it is not always trivial to export the data from SPICE applications; do your best, and use screen grabs only as a last resort if exporting the data is not possible.