ELEC/PHYS 4680/5680
Quantum Computing Technology Laboratory

Experiment #4: Analog Amplifier Sensitivity

Part #4a: Understand and quantify noise using power spectral density (PSD)

Background:

Real bias sources (e.g., voltage and current supplies) and sensors (e.g., preamplifiers) contain unavoidable random time-varying structure arising from fundamental processes. This random structure is more commonly characterized as "noise"; it limits the sensitivity of measurements and the ability to control and measure fragile states (e.g., qubits). While there are multiple methods for quantifying noise, one fundamental metric is power spectral density, or PSD.

Goal:

The goal of this lab segment is to familiarize yourself with the language, quantitative relationships, and instruments—spectrum analyzers—used to characterize noise sources and to view the frequency structure of other time-varying signals. The M2k has this functionality through the Scopy interface, though it is not particularly sensitive. Here, you will measure the intrinsic noise (or sensitivity) of the M2k, under various conditions, to better understand its capabilities and limitations. In doing so, you will gain experience with a basic Fast Fourier Transform (FFT) spectrum analyzer and begin interpretation of the language used to describe noise and spectral density.

Part #4b: Intrinsic performance of cascaded amplifiers

Background:

Neither active devices nor passive components are noise-free. Every source (e.g., a resistor or opamp), amplifier (e.g. SR560), and measurement instrument (e.g., M2k) contributes noise to the overall signal—it is the job of the engineer/scientist to minimize that noise contribution, or at least "budget" it for minimum impact. Commercial test and measurement (T&M) instrumentation will often not have sufficient sensitivity to perform the necessary control and/or readout of your physical system. In these cases, an intermediate custom pre-amplifier (whether at low frequency or at RF) is used to boost the signal size above the intrinsic noise level of the final T&M instrument. In our particular case, the M2k does not have the sensitivity required to measure the noise of even low-performance opamp circuits, and a preamplifier will be required. Complicating the situation, while noise contributions are cumulative across a readout chain, they add in quadrature, not linearly, due to their random nature. As a result, noise at early stages of amplification has a much greater impact on overall sensitivity than does noise at later stages.

Goal:

The goal of this lab segment is to understand the interplay between multiple amplifiers when one (SR560) has variable gain and sensitivity and when the other (M2k) is, ummm... not very good. You will explore the intrinsic performance of the SR560/M2k system by grounding the SR560 input and measuring its PSD with the M2k at various gain settings. This process will also demonstrate the difference between output noise and input noise—or, more accurately, *input-referred* noise.

Part #4c: Measuring the PSD of a noise source

Background:

Understanding and optimizing the performance of a T&M system is only the first step toward successfully interfacing with a sensitive experiment—the system must then be used to actually make a measurement! That is, rather than have a grounded input, the T&M front-end (here, the SR560) must be connected to the experiment and must be sensitive enough to detect the signal. This segment also demonstrates noise addition from multiple stages of a readout chain.

Goal:

The goal of this lab segment is to use the T&M system of part 4b to measure the PSD of a noise source; here, the x20 circuit incorporating the UA741 from Experiment 3. In this case, its PSD is so large that it will saturate the SR560 at high gains, but it is also large enough that the highest gains will not be needed to make an accurate measurement.

Part #4d: Characterize the PSD of high-performance opamp circuits

Background:

Relevant parameters of active and passive components used in front-end analog circuits include not just gain, bandwidth, and input-referred spectral density, but also the low-frequency limit below which the spectral density increases above the white-noise/gaussian floor—the 1/f knee. Often, the 1/f knee of high-bandwidth devices (opamps) is much higher than that of lower bandwidth devices. There are very few opamps that combine a GHz GBP with 1/f knee below 1 kHz. Such wideband performance is critical for certain quantum sensor applications, and engineering a functional circuit requires great care in not only design but also in component selection.

Goal:

Now that you have explored the instruments used to evaluate the performance of high-performance, low-noise opamps, you will apply that experience to characterize those opamps directly. You are to compare the noise performance of the opamps from Lab #3c both against their data sheets and against one another, carefully measuring their input-referred noise floor as well as their 1/f knee. You will need a higher-quality SA than the M2k provides, however, and will use the SR1 Audio Analyzers for this segment. Students choosing the Analog module for their capstone project will use this information to design a x100 preamplifier meeting certain specifications (to be presented within the capstone project assignment).

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Standard Procedures:

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. Initialize the M2k. It should perform a self-calibration.
3. If the self-calibration is successful, reinsert the BNC adapter card.
4. 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 don't!
5. *Check the output setting before connecting any devices!*
6. W1 and W2 are the M2k analog output, and 1+ and 2+ are the M2k analog input.

M2k Network Analyzer 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 is the drive of 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+.

SR1 Audio Analyzer Configuration

1. Power on the unit and wait for all configuration and self-tests to complete.
2. The SR1 utilizes a key- and touch-pad-based interface. These instructions focus on the touch-pad interface. The instrument comprises multiple software-configured virtual instruments and functions, organized onto several “pages” shown as tabs on the right side of the screen. Most of these virtual instruments and pages can be ignored for this experiment. Data can be saved using icons at top of screen.
3. Page 2: Analyzer
    - i. Analog Inputs tab: Ch A/B: Range: Auto; Input Config: BNC; Hi Z; DC
    - ii. Hi-Res Converter tab: Sampling Rate: 64k
    - iii. Optional Filters: None
4. Page 4: FFT Analyzer
    - i. Source: Analog A
    - ii. Converter: (~~Hi BW~~/**Hi Res**)
    - iii. Fs: 64 kHz (sets itself according to other settings)
    - iv. Measurements tab:
        - a. Baseband (= 28.8 kHz) or select as needed
        - b. Resolution (Acq. Time): 1 k (32 ms at baseband) or select as needed
        - c. Start: 0; Center (auto); End: 28.8 kHz or select as needed
        - d. Averaging: Continuous; # Avgs: 100 or select as needed
    - v. Meas 2 tab:
        - a. Window: ~~RifeVincent 4-term~~ (default) **set to Blackman Harris+**
        - b. DC Correction: ~~None~~ (default) **set to Average**
        - c. Resolution (Acq. Time): 1 k (32 ms at baseband) or select as needed
        - d. Start: 0; Center (auto); End: 28.8 kHz or select as needed
        - e. Averaging: Continuous; # Avgs: 100 or select as needed
5. Page 5: Spectrum
    - i. Set Scale to Log-Log (check boxes)
    - ii. Set y units to nV/√Hz (drop-down menu)
    - iii. Turn on cursors with “Cursor” button on keypad
        - a. Cursor button toggles between two cursors (blue/green)
        - b. Values at cursors shown at top of graph

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Tasks (4a: *Understand and quantify noise using spectral density*)

1. *Prelab:* Read Chapter 2 of the SRS760 FFT Spectrum Analyzer manual (on Canvas) and https://wiki.analog.com/university/tools/m2k/scopy/spectrumanalyzer. The former contains a basic introduction into FFT spectrum analyzers in general (including units, windowing, and averaging) and the latter provides an overview of the M2k Spectrum Analyzer features within Scopy. This prelab activity will not be a component of *any* of your reports.
2. *Prelab (also TR):* The M2k has two gain modes accessible through Scopy, high and low. After reading through the M2k reference manual (https://wiki.analog.com/university/tools/m2k/users/reference_manual), report on what "high" and "low" mean, in real values (not dB). What is the maximum voltage range at the input (*not at the internal ADC*) for each gain setting? Given that the M2k utilizes a 12 bit ADC, what input voltage does a single bit represent, for each setting?
3. Set up the M2k + BNC adapter in the Spectrum Analyzer (SA) configuration (see standard instructions).
4. In this section, your devices under test (DUTs) are the BNC 50 Ω termination fittings; attach one to the 1+ elbow and the other to the 2+ elbow.
5. Using the Channel 1 settings button at the lower left of the display, set the type to Exponential RMS, the window to Blackman-Harris, line thickness to whatever you like, and gain mode to **low**. You will vary the number of averages depending on the frequency range and resolution; 100 is a good place to start. Repeat for the Channel 2 settings, but set its gain mode to **high**.
6. Using the Sweep settings button at the lower right of the display, set the sweep to Logarithmic, the start frequency to 100 Hz, and the stop frequency to 1 MHz. The center frequency and frequency span will be set by those values. Set the Units to V/√Hz and set (and record!) a resolution BW (RBW) somewhere between the limits of the values on the drop-down menu. This setting will control how long your sweep takes to run and is inversely related to the frequency resolution in the spectrum—a lower RBW will give you great resolution, but take forever to run.
7. Select Run and watch the change in the spectra as additional averages are accumulated.
8. *For Individual Report only:* Why does the spread in values (essentially, the standard deviation) reduce over time? Express your answer at least somewhat quantitatively; that is, how would the spread change (scale) with 1, 100, and 10,000 averages? Note: you don't need to actually take this data, but you should be able to say what *would* happen if you did.
9. Save the spectra to your drive and plot using scientific software (Mathematica, MATLAB, Kaleidagraph, etc.) for the TR.
10. *For Individual Report only:* How do the power spectral densities (PSDs) on Channel 1 and Channel 2 differ quantitatively (expressed as a ratio)? A couple of notes on this comparison. First, pick values at representative frequencies where the PSD is reasonably independent of frequency; don't look at the entire spectrum. Second, you will get a more reliable value of the white noise if you take an average over your saved values (where the PSD is flat) than if you only use the marker value. To what do you attribute this difference? These values represent the minimum signal that can be measured with the M2k on each gain setting; even the smallest value is actually quite large compared to many signals, which means that the M2k is not particularly sensitive. We will address that deficit with the SR560 preamplifier in an upcoming section.
11. *There are no Graduate Report questions for this segment.*

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Tasks (*4b: Intrinsic performance of cascaded amplifiers*)

1. *Prelab:* Read the technical information for the SR560 Voltage Preamplifier found in files SR560c.pdf (the commercial "spec sheet") and SR560m.pdf (the user manual). Specifically, in the user manual, focus on pages 1-3, 5, 7-9, and 13-16 (manual page numbers, not PDF file pages). If you are motivated and curious, you might also peruse Appendix B. This prelab activity will not be a component of *any* of your reports.
2. *Prelab (also TR):* On page 21, the SR560 manual tabulates the "Input Noise," which is really the noise at the output divided by the gain—in other words, the noise "referred to input," or RTI. Make your own table of this information (low noise, or "LN," rows only) but, in your table, replace the final "Maximum DR" column with one containing the expected actual "Output Noise" for each gain. That is, your table consists of noise referred to input *and* referred to output.
3. Connect the 50 Ω BNC termination caps to 1+ and 2+ of the M2k (through the BNC elbows).
4. Set *both* Ch 1 and Ch 2 of the Scopy SA to Exponential RMS, Blackman-Harris, 100 avg, and high gain. Set the Sweep from 100 Hz to 100 kHz and RBW to 24.41 Hz, initially.
5. Measure the noise spectrum of both channels. One channel may have better sensitivity (lower PSD) than the other. If so, use that channel in the remainder of this experiment; otherwise, use Ch 1. Save both spectra.
6. Take the average of your saved data over a reasonable frequency range (where the data is reasonably independent of frequency). What is that value for each channel? Based on your prelab table, for which values of gain will the SR560 noise exceed the base noise (or noise floor) of the M2k?
7. Now power up the SR560. You may notice these boxes are heavy; they contain sealed lead-acid batteries. The batteries allow them to be operated separately from wall power, avoiding 60 Hz pickup that would "contaminate" your signal (vis-à-vis Appendix B).
8. Set the filters to None (using the middle filter button as necessary), coupling to GND, Source to A, no Invert, gain mode to Low Noise, and gain (initially) to x100.
9. Connect the 600 Ω output to the M2k 2+ input directly with a simple BNC cable. Use elbow adapters as appropriate to minimize cable strain.
10. Measure spectra for two values of gain below your answer to 4b.6 up through the maximum gain, or until the red Overload light appears. Save these spectra.
11. Take the average of your saved data over a reasonable frequency range (where the data is roughly independent of frequency). Plot the measured noise and expected noise ("output noise" from your table) vs. gain for all values of gain you were able to test. Convert the measured noise to input referred noise by dividing by gain. Make a second plot of the measured and tabulated input referred noise vs. gain. These plots are not frequency plots; the horizontal axis will be gain and the vertical axis will be noise (of the appropriate type).
12. *For Individual Report only:* Comment on the differences between measurement vs. expectation for both plots, and relate to the sensitivity of the system—when is the result dominated by the M2k and when is it dominated by the SR560? Which of the two would you choose to operate in, and why?
13. *For graduate students only:* Plot the measured noise vs. tabulated output referred noise. Fit these results to what you would expect for a constant additive noise, in quadrature. Comment on the value of the constant term in the fit to your answer in 4b.6 and the general quality of the fit—does it have the expected shape, or not? Plot your fitted equation on the same graph as your data.

Tasks (4c: Measuring the PSD of an active circuit/device)

1. Prelab (also TR): From the UA741 datasheet, find the equivalent input noise voltage. At a gain of x20, what output voltage noise do you expect?
2. For Individual Report only: For which values of SR560 gain does this value exceed the SR560 sensitivity? For which values of SR560 gain does this exceed the M2k sensitivity? (Discuss/justify)
3. Prepare power supplies and breadboard (see standard instructions).
4. Insert the x20 gain UA741 EB into the breadboard socket.
5. Connect the 50 Ω SMA termination cap to the input. Power the breadboard (±10 V).
6. Connect the EB output to channel A of the SR560.
7. Set the SR560 to gain x1 and select AC coupling.
8. Measure (and record/save) the PSD of the x20 UA741 EB at x1 gain between 100 Hz and 100 kHz.
9. Step through all the gain settings from x1 to x2,000; be sure to restart the sampling after each change to reset the averaging. At gain x5,000, the SR560 will likely saturate (the red overload light comes on). It is possible that your circuit may saturate at early x2,000 or late at x10,000, but most will saturate at x5,000. Above a certain gain, the PSD values should be roughly linear in the gain.
10. For Individual Report only: Plot each spectrum. You may notice a great deal of external noise pickup at or above ~50 kHz. Take an average of your data where the PSD is reasonably constant, typically ~1-10 kHz. Tabulate these average PSD values by gain. Graph the average PSD value vs. gain. Divide the PSD value by the SR560 gain to obtain the input-referred value of the PSD, which represents the nominal value of the noise "source." Again, graph the input-referred PSD values vs. gain. Which values are representative of the actual source PSD?
11. For Graduate Students only: You may be noticing a trend to these assignments by now! Fit the data of 4c.9 to the expected form. What are the fitting parameters and what do they signify?
12. For Graduate Students only: If you knew the system noise level very well, you could actually subtract it off from the measurements (appropriately) to get a rough estimate of the value of the noise source PSD even if it was close to the system noise. How might you go about this? Your answer to this question should be quantitative (include an equation), but I am most interested in reading about your thought process in approaching an open-ended question with minimal information provided to you—it is less important that you arrive at the right equation than that you have thought it through carefully and explain well.

Tasks (4d: Characterize the PSD of high-performance opamp circuits)

1. Prelab: Read pages 9-11, 76-78, 127-136, and 191-198 of the SR1 manual carefully, and skim pages 291-304. We acknowledge that this set of instructions may be less clear due to these instruments having just arrived a week ago. Please be patient and feel free to provide suggestions for clarity moving forward.
2. Follow Standard Procedure for SR1 power up and configuration.
3. Connect the BNC shorting cap to Input A. Use the Baseband, Hi-Res setting. Start the measurement and use the markers to record the average PSD centered on 10 kHz. Also save the data to the internal drive &/or a USB stick. This spectrum represents the instrumental noise floor of the SR1.
4. Set the Span to approximately 1 kHz. It will not be exactly 1 kHz due to limitations of the instrument. Be sure the Start Freq. is set to 0.0 Hz. Start a new measurement and use

the marker to record the average PSD centered on 100 Hz. Also save the data to the internal drive &/or a USB stick.

5. You will use the results of 4d.3 and 4d.4 to establish the baseline sensitivity of the SR1.
6. For Individual Report only: Compare the PSD at the output of each of your evaluation boards to this baseline sensitivity of the SR1. Will the SR560 be required or not? Why or why not? (*Hint: Your answer to the first question should be "not."*)
7. Open the low-noise enclosure by removing the top two screws front and back, and the lower two screws on the back. Pull the back panel down slightly and slide the top cover out. Begin with the lowest-gain circuit and move up in gain to the highest gain for the following tasks.
8. Plug the selected EB into the internal socket, noting that the input is closest to the SMA front panel and the output is closest to the power regulators at the back. ***Carefully*** connect the left internal SMA cable to the EB input, using a SMA elbow/right-angle connector. ***Carefully*** connect the right internal SMA cable to the EB output, also using a SMA elbow/right-angle connector. Re-install the top panel. ***Carefully*** re-assemble the back panel, ensuring that the power wires are not pinched. Replace all screws, taking care not to strip the heads or the threads.
9. Short the SMA input of the front panel (left side) and connect the output of the front panel (top right side) to the SR1 Channel A input.
10. Be sure the battery power switch is off, then plug the enclosure power into the battery cable. Turn on the battery.
11. Wait a few seconds for the circuit to settle and then take a spectrum at full span. Use the marker to record the average PSD centered on 10 kHz. Also save the data to the internal drive &/or a USB stick.
12. As in step 4d.4 above, set the Span to approximately 1 kHz. It will not be exactly 1 kHz due to limitations of the instrument. Be sure the Start Freq. is set to 0.0 Hz. Start a new measurement and use the marker to record the average PSD centered on 100 Hz. Also save the data to the internal drive &/or a USB stick.
13. You may notice that there is a true increase in PSD at low frequencies (other than the "window leakage" we've discussed previously) with the ~1 kHz frequency span. It is important to see this increase with sufficient detail to be able to measure the "knee" (where the rise meets the flat) and also the slope. If you do not observe this on the ~1 kHz span, choose a lower span by about a factor of 10 and check again. Repeat until you are at a low enough frequency to see this clearly. Since time is inversely related to frequency and you are looking at very low frequencies, it will take a significant amount of time to take data as you lower the frequency span. You may compensate for this by reducing the number of averages, but not below 10.
14. Repeat steps 4d.7-4d.13 for each EB. To be clear, the primary data for this section of the lab is the noise floor and the 1/f knee frequency; the secondary data for this section (for graduate students) is the slope of the 1/f noise, to be determined from the saved data through regression. Be sure that all your saved data is of high enough quality to determine these quantities.
15. Convert this data to the input referred noise; you will need the EB gain that you measured (not the nominal EB gain) in Lab 3.
16. For Individual Report only: Create a table of the GBP, input-referred white-noise PSD, and 1/f knee for each of the four op-amps as determined by your group's data. Compare to the information available in the data sheets. Discuss possible design tradeoffs an engineer might make when selecting components for a low-noise, wide-bandwidth preamplifier. If noise were not a concern, which of the four opamps would be best for wideband operation? If bandwidth were not a concern, which of the four opamps would

be best for low-noise operation? If the sole design consideration was a low 1/f knee frequency, which of the four opamps would be best? The Analog Capstone project will be to design a two-stage amplifier meeting certain criteria, including noise and bandwidth, so these are very relevant questions.

17. For Graduate students only: Also measure the slope of the excess noise. It will be, roughly, a $1/f^n$ function, where n is nominally 0.5 but is never exactly that value. For your report, fit the PSD to a function that is proportional to $1/f^n$ at low frequencies and is frequency independent at high frequencies. The function will have properties similar to that of the single-poll roll-off function from Lab 3—but it will not be quite the same. From your data fits (non-linear regression), determine the values of the white noise PSD level, the 1/f knee frequency, and n, for each EB.