Experiment C-13
Quantitative Studies of Electrical Noise

In this experiment you will employ a spectrum analyzer to investigate several topics related to electrical noise in resistors and amplifiers:
(I) Characterization of amplifier noise
(II) Johnson-Nyquist noise thermometry
(III) l/f or flicker noise
(IV) The advantages of using a lock-in amplifier for low-noise measurements.

References:
I. R. E. Simpson, *Introductory Electronics for Scientists and Engineers* (1987, AIlyn and Bacon, Inc.), Ch. 8.
2. P. Kit tel, W. R. Hackleman, and R. J. Donnelly, Am. J. Phys. 46,94 (1978).
3. F. Reif, *Fundamentals of Statistical and Thermal Physics* (1965, McGraw-Hill, Inc.), excerpts from Ch. 15.
4. S. Machlup, J. Appl. Phys. 25,341 (1954).
5. excerpts from M. B. Weissman, Rev. Mod. Phys. 60,537 (1988). 6. K. S. RaIls and R. A. Buhrman, Phys. Rev. Lett. 60, 2434 (1988).

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(IV) The advantages of using a lock-in amplifier for low-noise measurements.

Part I. Familiarize yourself with the HP 35660A spectrum analyzer. Work through chapters 1-6 of the manual, paying particular attention to characterizing the noise of the P AR 113 amplifier . Use the procedure in section 8 to characterize the gain and filters of the amplifier. (Important: when characterizing the amplifier, use a sufficiently low input signal that the output of the amplifier always has a peak value less than 5 Volts. For instance, if the amplifier is set for a gain of 104 , an input signal with a peak value of less than 0.5 mV is required.)

Part II. Make a quantitative analysis of the noise emanating from resistor #1 (a metal film resistor with a nominal room temperature resistance of 10 k.Q) and resistor #2 (a carbon resistor nominally 10 k.Q at room temperature) without any applied bias, and compare with your theoretical expectations. Do this by attaching the resistor directly to the input of the PAR 113 amplifier, and the output of the amplifier to the spectrum analyzer. Use the spectrum analyzer to measure the power spectral density integrated over a range where there is no signal from sources of external interference (a range somewhere the lO's ofkHz, with a span of 15-25 kHz normally works well). For best results, set the nominal gain of the PAR 113 amplifier to 104, adjust the filters on the amplifier such that the noise from the resistor is not attenuated, and carefully characterize the gain of the amplifier in the range of frequency that you have chosen. You will find it useful to employ the marker functions to integrate the power spectral density over your frequency span, and to use the averaging function to reduce the uncertainty in your measurements of the noise. Study the noise power at room temperature, at liquid nitrogen temperature (77 K), liquid helium temperature (4.2 K), and at several temperatures above room temperature achieved by applying current to the heater using the variac. Determine the value of Boltzmann's constant, and check whether your measurements give the absolute zero of temperature correctly. Pay particular attention to the uncertainties in your measurements of the noise power, for instance by repeating each measurement several times. In what ways are the metal film and carbon resistor similar, and in what ways are they different?

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(a). The leads connecting the resistor to the amplifier have a capacitance in the lOO's of pF range, so that together with the resistor they produce a low-pass RC filter. The voltage signal reaching the amplifier will be reduced by a small but significant amount from the voltage originating the resistor, by a factor approximately given by

voltage reduction factor = <u>1/ ~1 + (27tVRC)2</u>

Here v is the frequency in Hz, R is the resistor value, and C is the effective capacitance. By measuring the integrated noise power over small ranges (10-15 kHz) centered at different frequencies, and assuming that Johnson noise is completely white, you can determine C, and use it to correct your measured value of the noise.
(b). With the present wiring, the heater injects a large amount of noise into the circuit when it is connected. For best results at temperatures above room temperature, use the variac to heat the sample to the desired temperature, and then disconnect it before measuring the noise. The time-

constant for temperature changes is sufficiently slow that a useful measurement can be made before the temperature drifts significantly.
(c) Beware of the fact that the resistors may be temperature dependent.

Part III. Using the box provided, along with a battery and the decade resistor, examine the low-frequency noise emanating from the nominally 100,{2 carbon resistor (#3) as a function of bias current. It is helpful to use the DC coupling mode on the PAR 113 amplifier (the noise signal is already AC coupled to the amplifier due to a high-pass filter in the bias box), to measure over a frequency span of 0 to 800 Hz, and to use a logarithmic scale on both axes. Start with a current of 0.1 amp going through the resistor bridge. *How* close to l/f is the frequency dependence of the low frequency noise? How does this compare to the Johnson-Nyquist noise? Pick a span of frequencies at low frequencies where the flicker noise is dominant (avoiding 0 Hz and multiples of 60 Hz!) and study quantitatively the integrated noise power as a function of bias current as you go to lower currents. Based on this measurement, would you characterize the noise most accurately as voltage fluctuations, current fluctuations, or resistance fluctuations? Why? Compare/contrast the flicker noise in the 100,{2 carbon resistor (#3) and the 100,{2 metal film resistor (#4). *How* does the flicker noise in the carbon resistor vary with temperature?

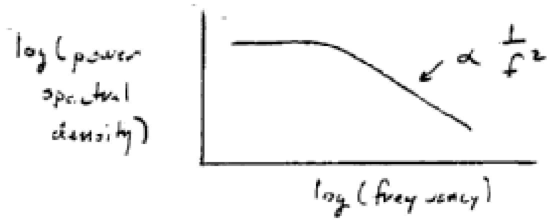
Hint: The amplifier may take a minute or two to settle after each adjustment of the bias current. To minimize this time, and to extend the life of the amplifier, ground the input to the amplifier before adjusting the bias current, and switch back to DC coupling once the current is set.

Part IV. Using the second box provided, containing bias resistors along with a resistor (approximately 10 k.Q) in parallel with a diode, measure the differential resistance (dV/dI) of the resistor-diode combination as a function of bias current in 3 ways:
a) Doing an AC measurement with the lockin amplifier. Study the effects on the noise in the measurement of changing the oscillator amplitude and frequency, and the output time constant.
b) Doing a DC current-voltage measurement in which the voltage across the resistor- diode combination is measured directly by ADC1 (analog-to-digital converter) on the rear of the lockin, and then taking a numerical derivative (using your favorite analysis program). The analog-to-digital converter has a range of -10 V to 10 V, with a resolution of I m V.
c) Doing a DC current-voltage measurement in which the voltage across the resistor- diode combination is first amplified by a factor of 20 (using the PAR 113) before being sent to ADC 1, and then taking a numerical derivative.

Compare and contrast the results. Why does the lockin allow a measurement with significantly less noise than the DC measurements?

Hints: (1) The lock-in programs plot the measured results (either the magnitude of the AC voltage across the resistor-diode combination, or this DC voltage) as a function of the number of points taken as the voltage across the whole circuit is swept by DAC1 on the back of the lockin. You will need to convert the point number to the current going through the resistor-diode combination. The default sweep range on DAC1 is -10 V to 10 V for points 1 to 101 (adjustable under Run Settings/Sweep Op/sweep parameters) so the default current range is
(-10V)/400k.Q. = 2.5 x 10-5 amps to 2.5 x 10-5 amps. A similar conversion (using the bias resistance of about I M.Q.) is necessary to know the AC current going through the resistor-diode combination due to the oscillator voltage, when determining the resistance using the AC technique with the lockin amplifier .
(2) There are some transients which give significant errors in the measured resistance for the first 15 points or so of the AC measurement sweep. It is OK to ignore these and, for instance, concentrate on the 1>0 part of the sweep. (Points 51 to 101 of the default sweep settings.)

References:
1. R. E. Simpson, *Introductory Electronics for Scientists and Engineers* (1987, Allyn and Bacon, Inc.), Ch. 8. A good general introduction to the subject of noise.
2. P. Kittel, W. R. Hackleman, and R. J. Donnelly, Am. J. Phys. **46**, 94 (1978). Description of an experiment similar to ours. However, note that ours is simplified by the use of a spectrum analyzer.
3. F. Reif, *Fundamentals of Statistical and Thermal Physics* (1965, McGraw-Hill, Inc.), excerpts from Ch. 15 on Johnson-Nyquist noise.
4. S. Machlup, J. Appl. Phys. **25**, 341 (1954). Description of how a voltage signal fluctuating randomly between two values, such as might be produced by an atom hopping between two different positions inside a resistor, gives a power spectral density of the Lorentzian form:



5. excerpts from M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988). Review of experimental understanding of 1/f noise, and how it can be produced by the sum of very many Lorentzian noise sources with different average frequencies.
6. K. S. Ralls and R. A. Buhrman, Phys. Rev. Lett. **60**, 2434 (1988). Study of a VERY small metal resistor, in which the noise from individual moving atoms can be seen. A 1/f spectrum emerges from many interacting defects moving simultaneously.

Use and Care of the PAR 113 amplifier

This amplifier contributes the least noise when running on its internal batteries. To begin use, unplug the power cord from the wall and turn the amplifier on. When you are done for the day, if is VER y IMPORT ANT to recharge the batteries. Shut off the amplifier, and plug the power cord back into an outlet. If you fail to do this and let the batteries discharge completely, you will not only waste your time waiting for the battery to recharge, but you can damage the batteries themselves.

The transistors in the amplifier can be damaged if a large signal is connected to the input of the amplifier. There should be no danger of this in the normal course of this experiment. To protect the inputs from short high-voltage transients in Part ill of the experiment, it is good practice to ground the input to the amplifier before adjusting the bias current through the resistor, and switch back to DC coupling once the current is set.

Introduction to the Software for the Lockin Amplifier

1. If the computer is turned off, turn it on. After the booting procedure, type win and hit return to start Windows 3.11.
2. Click on the Lockin icon in the Main Menu under program manager.
3. Once the lockin program is launched, click on Measure/Define Experiment in the Menu Bar. 4. From the list of experiments, click on acsave.tst and wait until it loads.
5. Hit the New Experiment button, and give a name when prompted. This will open a new experiment for you which will run the AC lockin measurement, keeping safe the default parameters in acsave.tst. If you wish to return to the default parameters in the course of your measurements, repeat steps 4 and 5
6. When you are ready to start the DC measurements, click on dcsave.tst in Measure/Define Experiment, then hit the New Experiment button and give this experiment another name.

Please do not change any of the parameters in acsave.tst or dcsave.tst! Feel free to copy these experiments to a different name and then change parameters.

All the parameters in your (renamed) experiments can be changed by going to MeasureIDefine Experiment, and clicking on one of the two buttons Run Setup or Setup Hardware. Look around! It is interesting to change the oscillator amplitude and frequency (under Setup Hardware/Oscillator), and the time constant of the lockin output filter (under Setup Hardware/Output). If you change the oscillator amplitude, you may also need to change the sensitivity setting under Setup Hardware/Input to avoid an overload condition.

To take a measurement, click on Measure/Start Experiment in the Menu Bar .

To save your measurement in an ASCII file suitable for transfer to a data analysis program, go to File in the Menu Bar and click on Export File.

When you are done, please delete your experiment files and your data files from the computer .

For answers to other questions, refer to the 2 manuals of instructions for the lockin and the software.