Experiments in Modern Physics P451: Fundamentals of Noise

David Baxter
Indiana University, Bloomington, IN 47405
(Dated: November 9, 2015)

Noise is an inherent element in any physical measurement. Often controlling and/or minimizing noise is a crucial aspect of experimental design, but occasionally the measurement, quantification or characterization of noise can be an important task in its own right. In the Poisson Distribution introductory lab of this course, you spent some time studying the phenomenon that is more generally known as "shot noise", so you already have some appreciation of some of the richness that can exist in the deep study of random events. In this lab, you will be introduced to some important aspects of electronic circuit design for low-level signals, have a chance to explore other types of fluctuating phenomena, and learn about one of the most important results of non-equilibrium Statistical Mechanics.

A. Introduction

The apparatus and most of the procedures for this lab are contained in the TeachSpin manual provided with the equipment (and avaialbe on the course website) [1]. This present description is intended primarily to help guide you to allow you to study the substantial information contained in the TeachSpin manual more efficiently. With the apparatus at hand, you should be able to investiage the thrree most fundamental types of noise in general electrical circuits (Johnson noise, shot noise, and 1/f or flicker noise). Since electrical circuits are involved somewhere in the vast majoirty of physical measurements made today, the study of electrical noise is of very broad utility. You should not feel compelled to investigate all three types of noise (though you are clearly free to do so if you please). In depth study of one or two types will be far more valuable than a prefunctory study of all three, and a more in-depth investigation/calibration of hte filters and amplifieirs in the TeachSpin electronics would be a fruitful way to spend your time as well. This lab also gives you an opportunity to learn a little bit about cryogenic practices (if only downto 77 K) and I encourage you to take advantage this (in particular pay some attention to the use of semiconductor devices as thermometers, and the impact of thermal time constants on the ease with which temperature stability may be achieved). It is also worth noting that Johnson noise can be used as an absolute theremometer.

In reading the TeachSpin manual you may come across some unfamiliar terminology, particularly in reference to the electrical components. The behavior of electrical circuits or components is often characterized in terms of their "Transfer Function" (which is the ratio of the Laplace Transforms of the component's output and the input signals). This function can have zeros in the denominator ("poles" in the language of complex variable theory), and these play a significant role in defining the behavior of the circuit. Higher-order poles tend to define sharper cut-offs for filters, but may also introduce oscillations in the pass and stop bands of the filter. If you want more information on these details, consult a good book on electrical circuits such as [2].

The basic result associated with "Johnson Noise" :

$$\langle V_J^2(t)\rangle = 4k_B T R \Delta f \qquad (1)$$

is perhaps your first exposure to the "Fluctuation-Dissipation Theorem" of Statistical Mechanics [3]. This theorem states that the (dissipative) response of a system perturbed from theormodynamic equilibrium by a small force (staying within linear response) is directly related to the fluctuations that same system exhibits in equilibrium. In the light of this general result, it should therefore come as no surprise that the size of the voltage flucturations (noise) exhibited by a device at (absolute) temperature T, should be directly related to its electrical resistance (which dissipates electrical energy into thermal energy).

As indicated in the abstract to this lab description, shot noise is the more general description of the Poisson Statistics you investigated in one of this course's introductory labs. You may want to review your results from that lab before starting the experiments with light sources and photo-diodes described in chapter 3 of the TeachSpin manual. Among the more important things to keep in mind when studying shot noise in electrical circuits are:

1. Even though we often think of electrical currents (or even those of fluids) as continuous, they are in fact made of individual quantized units of charge and there will be some fluctuations associated wtih the random arrival of those quantized charges at your detector.

2. Event rates in electrical circuits are almost always higher than those you saw in the Poisson statistics lab, but shot noise can still be a limiting factor at low enough currents.

3. Unlike radioactive decays, there may be correlations among motions of electrons through a conductor, and therefore it is possible for the fluctuations of even a very weak current to be less than that predicted by the "shot nose" limit.

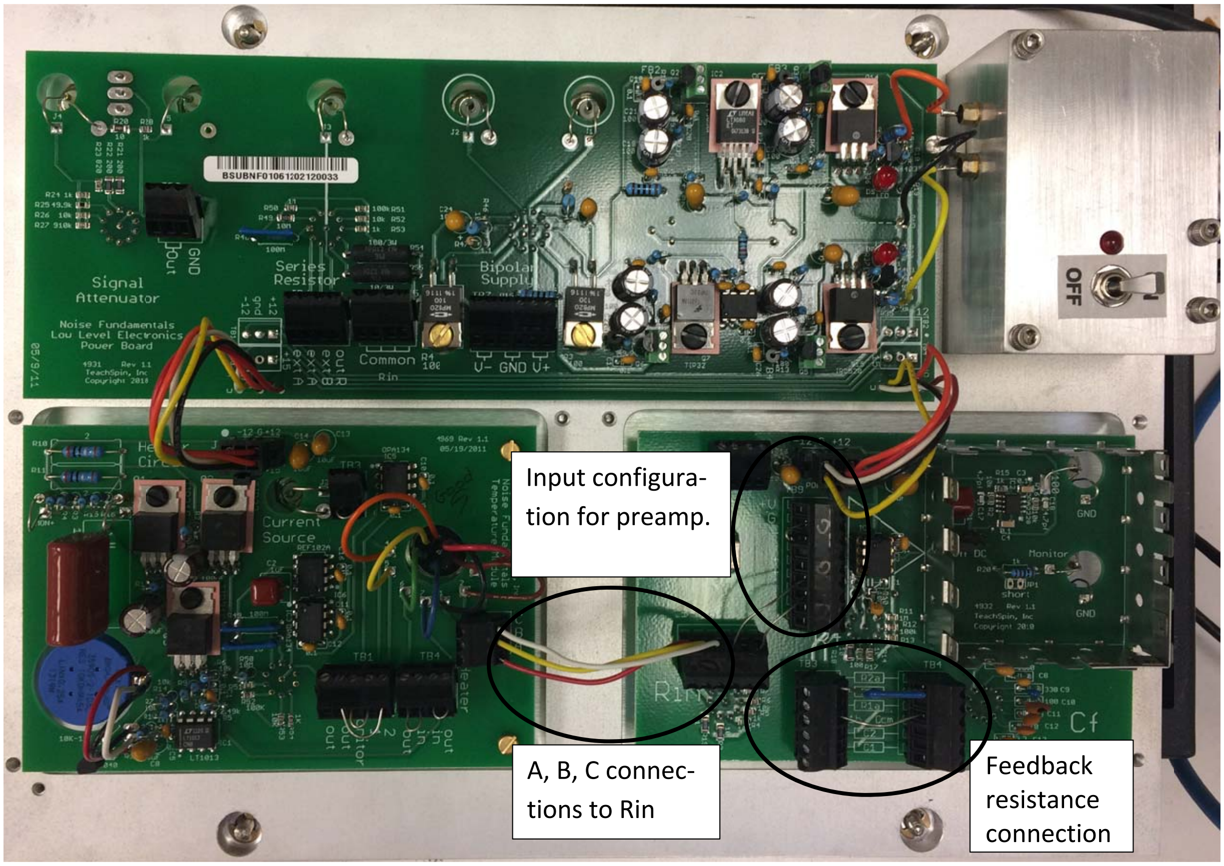

FIG. 1. Picture of the Low Level Electronics front panel's back side when in the default configuration described in figure 1-1b of the TeachSpin manual

Equipment

The majority of the equipment in this lab is contained within the two boxes and the low-temperature probe provided by TeachSpin. You should, however also make use of an oscilloscope and a digital multilmeter (the latter to allow more precise readings of the RMS noise values determined by the output of the multiplier circuit). At the start, you should confirm the configuration of the low-level electronics cirucuitry by opening up the panel ad inspecting the circuits on the back. In doing this, be sure to abide by the warning on page 2-12 of the manual, and make sure that the power to the circuits is off before opening the panel to insure that the circuits do not get damaged by changin the inputs on an energised preamp. Figure 1 gives a picture of the back side of the LLE front panel and highlights the sections that can be reconfigured for the various experiments outlined by TeachSpin. This figure shows the default configuration of TeachSPin's figure 1-1b (although the physical positions of the 1 $G\Omega$ and short options for the feedback resistor are different, so you should account for this if you wish to employ these values for R_f.

Experiments

Before coming to the lab for the first time, you should read chapters 0 thorugh 2 of the TeachSpin manual [1]. This will help to familiarize you with the apparatus, and will also introduce you to a number of concepts and terms with which you may not yet be familiar.

- Start by using the apparatus in its standard mode and determine the value of Botzmann's constant (with your assessement of the uncertaingty of that measurement). In doing so, you may wish to select an appropriate range of input resistance values (if you do so, justify your selection on the basis of you reading of the TeachSpin manual).

- In general, you should expect to follow something like the 12-20 hour "Advanced" option outlined in the "Tactical Matrix" on page 0-5 of [1]. It is up to you to determine how much time you would like to spend on shot noise vs. calibrations of the filters and amplifiers, but you should put some time into exploring the temperature dependence of Johnson noise and experiencing the issues associated with low-temperature operation of systems.

[1] *Noise Fundamentals NF1A Instructor's Manual*, TeachSpin, Buffalo NY 14214-2153 (2010).

[2] P. Horowitz, W. Hill, *The Art of Electronics, 3rd ed.*, Cambridge Univ. Press, (2015).

[3] F. Reif *Fundamentals of Statistical and Thermal Physics* McGraw Hill New York, NY. (1965).