ENGR 1121 Lab 4
Ballistocardiograph

February 17, 2014

In this lab you will construct a circuit which can sense your heart rate from an ordinary bathroom scale. Known as a ballistocardiograph (BCG), the principle is that the reaction force at the ground fluctuates a little bit as the heart impulsively ejects blood with each beat. There is a slight recoil, which we can sense. Because the measurement is so sensitive, we will do a simultaneous ECG that will help us identify and correlate the two signals. You will be using the same ECG circuit that you used in Lab 2 for doing this part of the measurement. An example of the final result is shown in Figure 1.

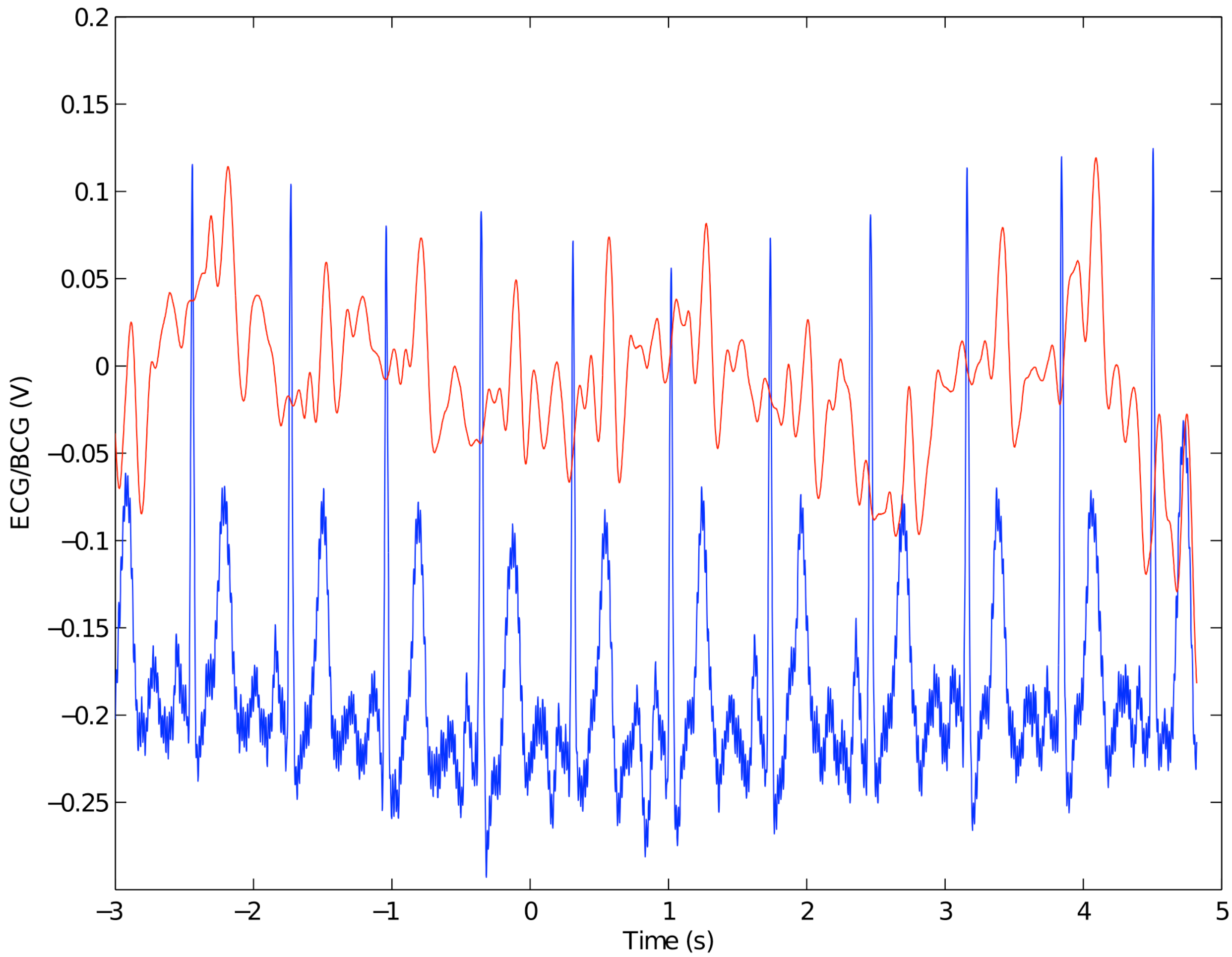

Figure 1. Comparison of simultaneous ECG (blue) and BCG (red) signals. Note the correlation between the second bump in the ECG signal and the impulse in the BCG.

The basic principle of the circuit is that we must very aggressively filter out both the noise at high frequencies (in this case, high relative to the ~1 Hz signal) and the DC offset from your constant mass. The filters must have a narrow frequency response in order to isolate your pulse. It is important in this circuit that you keep your wires clipped short and close to the breadboard.

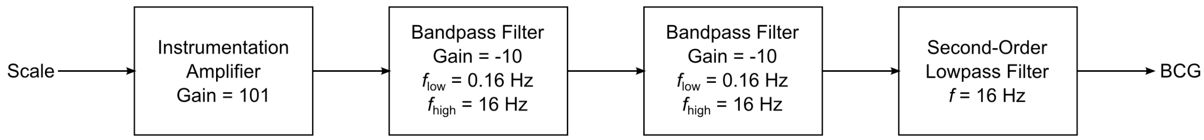

Figure 2. Block diagram of the BCG circuit.

A block diagram of the BCG circuit is shown in Figure 2. Because each block is essentially buffered by an op amp, the blocks do not interact with each other and can be built, tested, and analyzed in isolation. You should build each block in turn and then test after each new additional block.

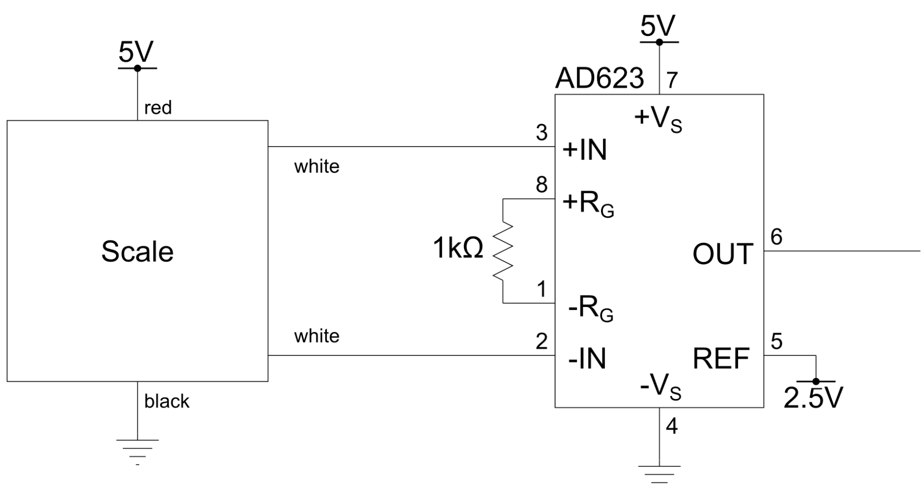

Figure 3. First stage of the circuit. Instrumentation amplifier interfacing with the strain gauges in the scale. The strain gauges inside the scale form the Wheatstone bridge.

The first stage is the bridge circuit and the instrumentation amplifier. This block works in much the same way as it did in last week's lab. The only difference is that the resistors for the bridge are the strain gauges located in the each of the four legs of the bathroom scale. Last week, one resistor in the bridge was a strain gauge while the other three were fixed. In the scale, the strain gauges are internal to the mechanical system and the four wires that come out of the scale can be wired to your circuit as shown in Figure 3. Because the strain gauges are more precisely manufactured than standard resistors, there is no need to balance the bridge with a potentiometer. Because there are only a few scales to share among the class, you will need to build and debug your circuit and then come to the front of the class to test.

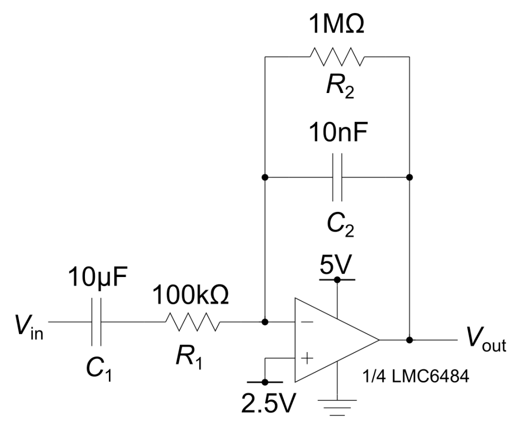

Figure 4. Second-order bandpass filter circuit based on the inverting amplifier op-amp topology. The passband gain of the circuit is given by $-R_2/R_1$. The starting frequency of the passband is given by $1/(2\pi R_1C_1)$ and the ending frequency of the passband is given by $1/(2\pi R_2C_2)$. For this circuit, the passband gain is -10, the low-frequency corner is at about 0.16Hz, and the high-frequency corner is at about 16Hz.

Next, you should build the bandpass filter stage shown in Figure 4. This filter is based on the typical inverting amplifier op-amp topology. Instead of two resistors to set the gain, we instead use two impedances whose values change as a function of frequency to provide us with a bandpass filter characteristic. The gain of this circuit in the passband is given by $-R_2/R_1$. Its low-frequency cutoff is given by $1/(2\pi R_1C_1)$ and its high-frequency cutoff is given by $1/(2\pi R_2C_2)$. With the component values we have chosen, the gain is -10, the low-frequency cutoff is at about 0.16Hz, and the high-frequency cutoff is at about 16Hz. The roll-offs on either side of the passband are first-order for this circuit, meaning that each decade increase in frequency above the high-frequency corner results in another 20dB (i.e. a factor of 10) of attenuation. Similarly, each decade decrease of frequency below the low-frequency corner results in another 20dB of attenuation. Measure the frequency response of your filter with the Analog Discovery's network analyzer instrument and make a Bode plot of its gain and phase responses.

By cascading two of these filter stages, we obtain a second-order roll-off on either side of the passband. The output of each stage is buffered by the op amp, so you can just connect the filters and they do not interact with each other. Build a second copy of this circuit and cascade it with the first one you built.

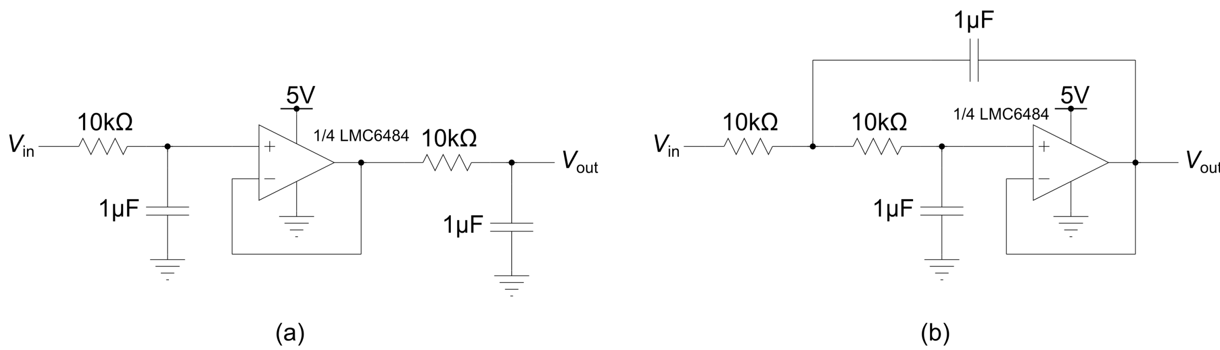

Figure 5. Second-order lowpass filter circuits with a cutoff frequency of 16Hz implemented using (a) two first-order *RC* lowpass filters with a buffer between them and (b) a Sallen-Key circuit. The two circuits should have very similar frequency responses. The Sallen-Key lowpass filter's output is buffered by the op amp, whereas the *RC* cascade is not.

Next, you should build and characterize a second-order lowpass filter stage. Two possible circuit choices are shown in Figure 5. Figure 5(a) shows a second-order lowpass stage made by cascading two first-order *RC* lowpass filters with a buffer in between. Figure 5(b) shows a Sallen-Key lowpass filter, which is a commonly used second-order filter topology requiring only a single op amp. The two circuits should ideally have the same frequency response. The Sallen-Key filter's output is directly buffered by the op amp, whereas the *RC* cascade is not. You are free to use either circuit. Build one and measure its frequency response with the Analog Discovery's network analyzer tool and produce a Bode plot of its gain and phase responses. Once you have characterized your second-order lowpass filter, add it to the overall BCG circuit, as shown in Figure 2.

Before you perform your final BCG/ECG measurement, you will need to construct the ECG circuit that you used in Lab 2. You will need to obtain a second AD623, but you can use the fourth op amp on your LMC6484 to make the final gain stage for the ECG circuit. When running your final measurement, it helps to take off your shoes as you stand on the scale. It is als important that you stay very still on the scale; the BCG signal is very subtle and it is easy to lose the signal if you sway too much. Also, note that due to the high gain in the system, when you first stand on the scale it takes several seconds for the circuit to settle down and only display the regular heartbeat.

Finally, note that the signal is quite sensitive to electrical noise in the room. We have found that you pick up a lot of noise from the room lights, which is transmitted to the long wires in the strain gauges from your feet. We have found that if you use a conical shaped aluminum foil “hat” it will deflect the electromagnetic radiation from the room lights and improve the results (see Figure 7). While it may look silly, we have it on good authority that the results are much improved.

Figure 7. Example of aluminum foil used to shield your body from electrical noise from the room lights.

Deliverables

1. Experimental Bode plots of your filter stages. The experimental results should be compared to the analytical result, which you will derive. You should work through the analysis yourself, put in the proper values of *R* and *C* for your filter. State the final equation that relates the filter input voltage to output voltage in your lab report.

2. Good final simultaneous ECG and BCG traces, similar to that shown in Figure 1.

3. A picture of your beautiful circuit.

Grading

10 points for everything correct.

1) 3 points total for good experimental Bode plots.
    a. 2 points off if result looks incorrect.
    b. 1 off for decent results but poor/unclear axis, plotting, or labeling
2) 3 points for a good analytical curve compared to the experimental Bode plot data points.
    a. 1 off if derivation is incorrect, but a reasonable effort.
    b. 1 point off if result looks good but you don't include the final equation.
3) 3 points for good ECG/BCG trace
    a. 2 points off if you took data, but the data looks poor.
    b. 1 point off if data looks fine, but plot is not well-labeled, no axis, no units, etc.
4) 1 point for off for a crappy circuit.