

Assignment # 5  
 ENGN/PHYS 207—Fall 2022  
 Strike Up the Band: Bandpass filter + Amplifiers

Circuits You'll Build (Choose One Application)

Option A: EMG/Bioelectric Measurement

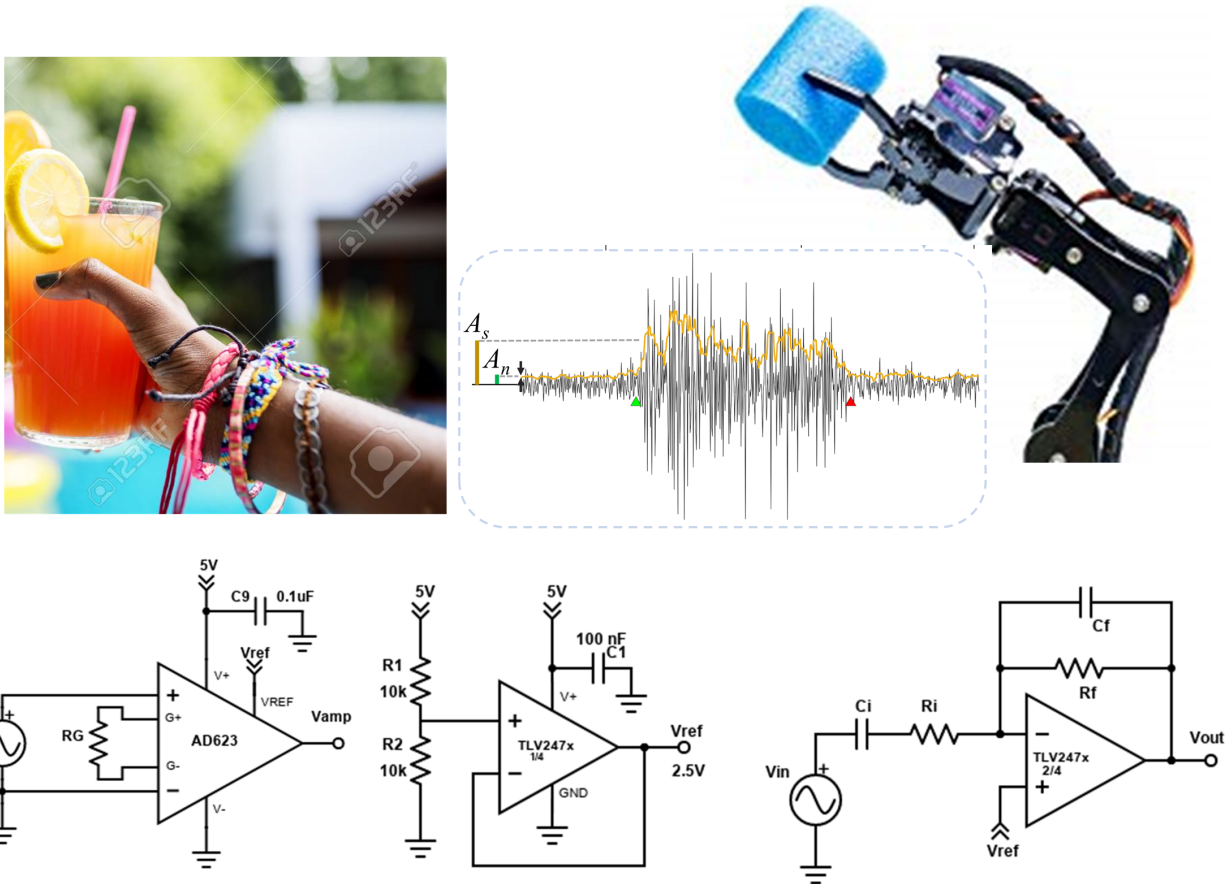


Figure 1: The electromyogram (EMG): Bioelectric measurement of the skeletal muscle contraction are measured with electrodes coupled to the skin surface. The raw signal must be amplified and filtered to extract relevant information. The EMG signal can be used to manipulate a robotic hand. Image adapted from J Erickson et al. Intsy: a low-cost, open-source, wireless multi-channel bioamplifier system; *Physiol. Meas.* 39 035008, 2018. Hand and robot arm photo: google image search.

## Option B: Structural Health Monitoring

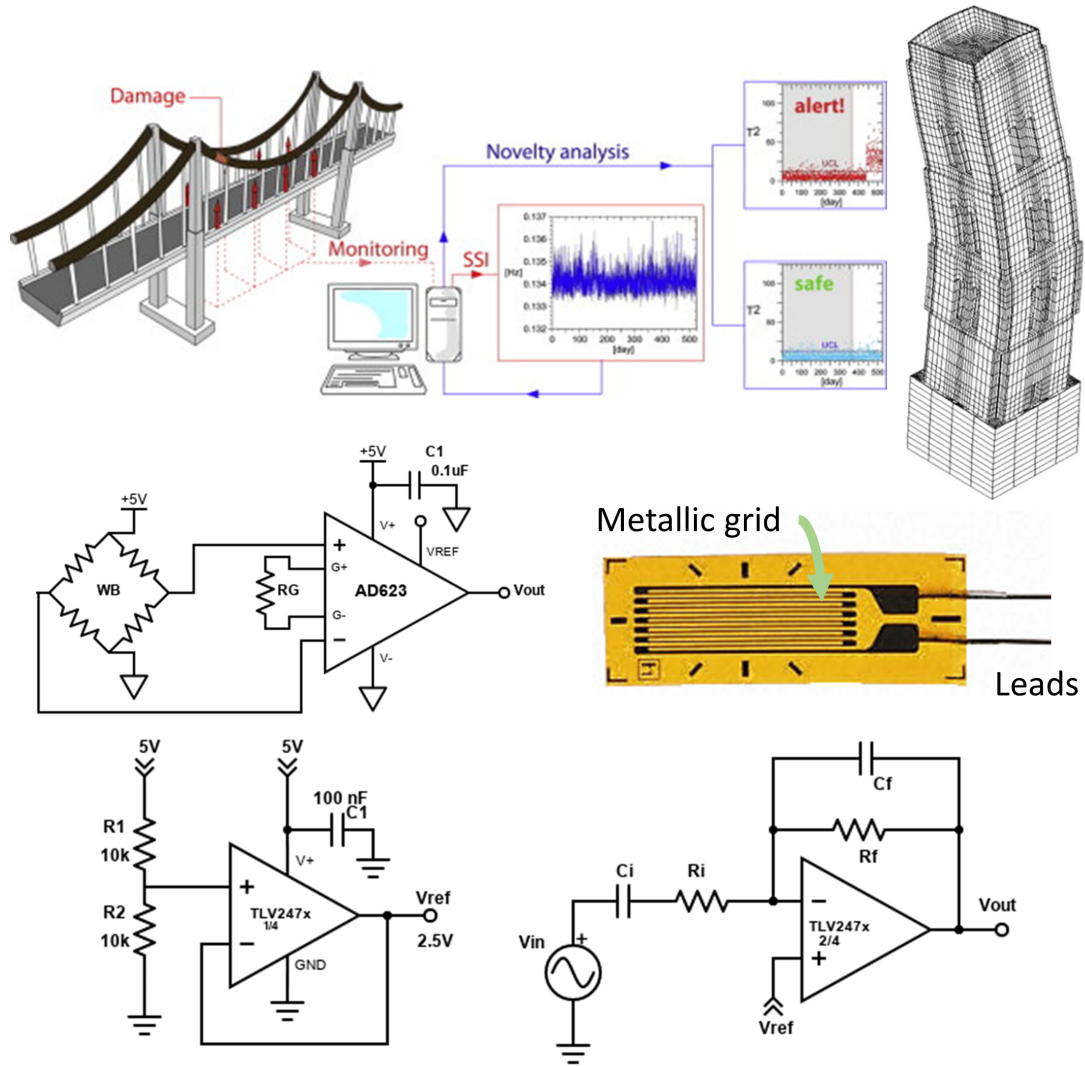


Figure 2: Structural Health Monitoring (SHM) of Bridges and Buildings. Strain gauges are used in a Wheatstone Bridge configuration to monitor vibrations. The raw signal must be amplified and filtered to extract relevant information. Image adapted from (visit them, they are great resources!): Donato Abruzzese et al. Dynamic investigations on medieval masonry towers: Vibration measurement and structural identification; International Conference on Protection of Historical Buildings, June 2009, Omega Instruments, Comanducci et al. Journal of Wind Engineering and Industrial Aerodynamics, 2015: 141, 12-26.

## Structural Health Monitoring: Good (?) Vibrations

Airplane wings oscillate due to vibrations in the engine mounted to them and air flowing over them. They must not fail or the consequences are likely catastrophic. Building shake when the earth moves and when people move—hopefully in a safe manner. Bridges bounce up and down when cars drive over them. They must not fall down. In this design problem, you'll build an actual system that can be used to carefully measure vibrations in a frequency range of interest! We'll focus on a recent real-world case of measuring and mitigating unwanted vibrations in the Harvard Physics quantum science nanofabrication lab!<sup>1</sup>

**Design Problem Statement:** Design, Build, and Develop proof of concept for a circuits system capable of measuring and analyzing building vibrations in a frequency range of 10-200 Hz. The primary sensor is a Wheatstone bridge consisting of 4 strain gauges and excited by a 5V source. The expected maximum strain is about 1-2%. A usable output signal has an amplitude of  $\geq 1V$ .

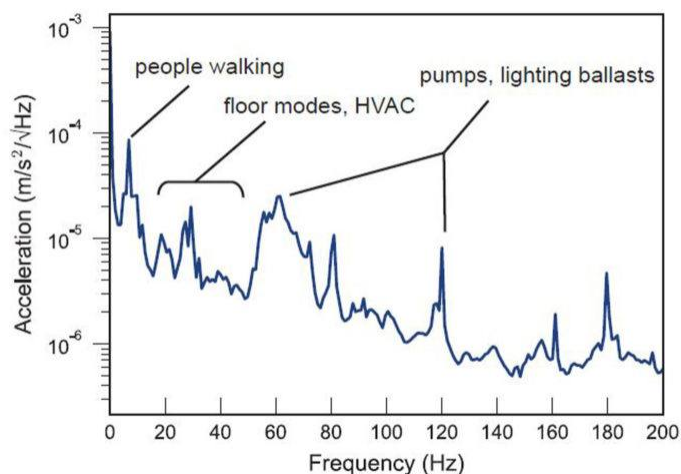


Figure 3: Vertical acceleration spectrum, measured on the basement foundation of the Laboratory for Integrated Science and Engineering at Harvard University. Image credit: J Gibbons, HGA Architecture: <https://hga.com/design-and-characterization-of-a-low-vibration-laboratory/>

## EMG Robot Arm: Helping Hand

The prosthetics field has been undergoing somewhat of a revolution the past decade, thanks to advances in miniaturized electronics, high performance batteries, and machine learning techniques. The prerequisite for such a prosthetic device is to non-invasively measure the electrical activity associated with muscle contractions and convert it to a desired robotic arm/hand motion. Electrodes placed on the skin can measure the electrical signal associated with muscular contractions, if the signal is properly filtered and amplified. This is the Electromyogram (EMG). The EMG

<sup>1</sup>Interesting and accessible read from on the analysis the design firm carried out here Design and Characterization of a Low-Vibration Laboratory by Joe Gibbons, 2021

is processed and interpreted by a computer or microprocessor to convert a pattern of muscular activity measured with electrodes on the skin surface into commands that move motors in a desired manner. So wouldn't it be fun and interesting to build the EMG hardware that measures electrical signals generated by muscular activity?!

**Design Problem Statement:** Design, Build, and Develop proof of concept for a circuits system capable of measuring the EMG from contractions of the forearm muscle with an expected frequency range of about 5 - 250 Hz. The primary sensor is a pair of electrodes electrically connected to the epidermis. The expected maximum raw muscle contractions are expected to generate a signal about 100-500  $\mu\text{V}$  peak-peak. A usable output signal has an amplitude of  $\geq 1\text{V}$ . Don't amplify too much—the Arduino saturates at 5 V.

**Safety Considerations:** For safety reasons, under no circumstances should you connect your EMG circuit to a human subject without first consulting the instructor! When you are ready the instructor will consult with you to properly connect EMG skin surface electrodes as well as help safely connect power supplies to the robot arm motors.

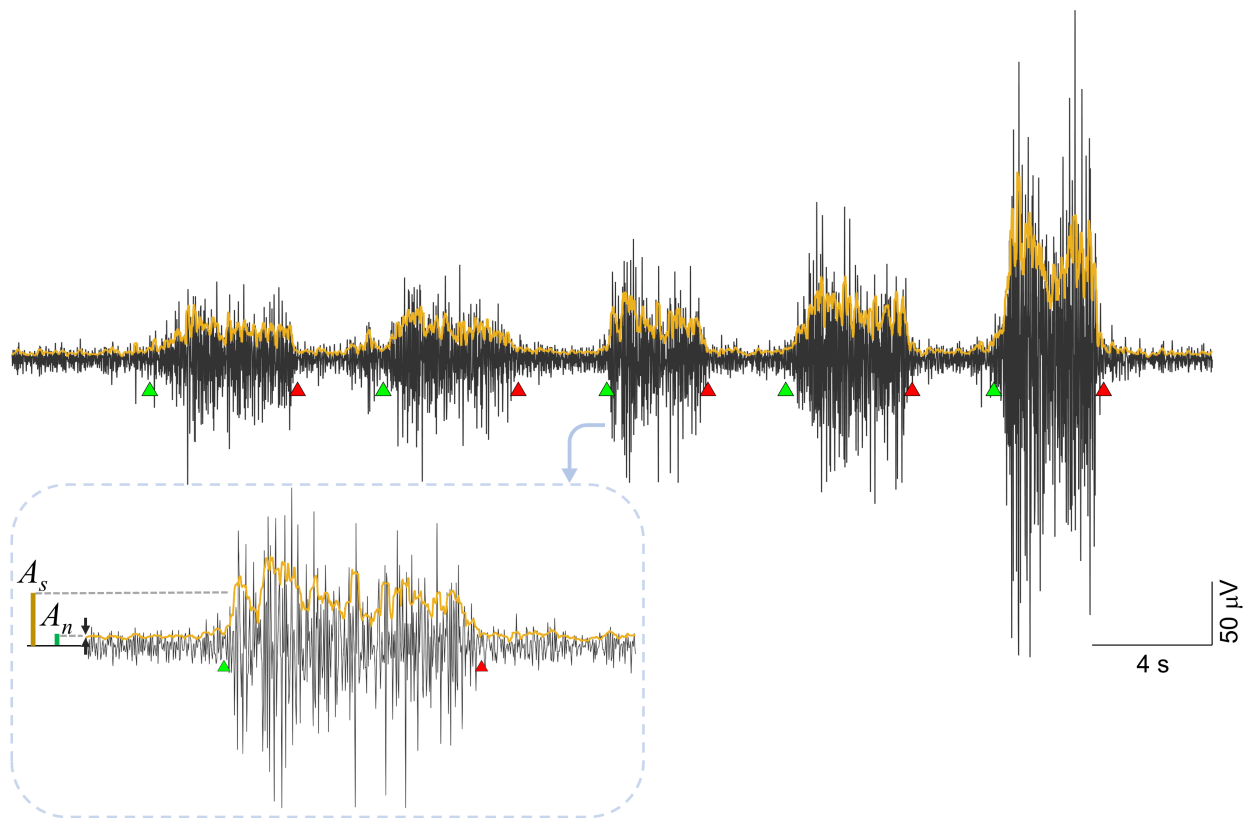


Figure 4: Example EMG (black trace) measured from the forearm over 5 contractions of the forearm muscle with increasing strength. The average signal intensity trace (orange) is shown overlaid. It is a rectified and smoothed version of the EMG trace. Green and red triangles indicate on and off times of each contraction. The inset at bottom left shows the fine temporal detail of the 3rd contraction. The labels  $A_s$  and  $A_n$  indicate the signal and the noise levels from which the SNR is computed.

## Skills and Concepts You'll Learn

Regardless of which adventure you choose to take, these are the skills and concepts you'll learn, strengthen, employ:

1. Filters: Band pass filter design
2. Amplifiers: op-amp buffer and active filter design
3. Instrumentation amp design and use
4. Analog circuit system integration
5. Oscilloscope measurement modes ac vs dc

## Useful Reference Material: Datasheets

TI TLV247x datasheet (linked here), page 3 shows the package pinouts. Be sure to refer to the proper one either TLV2472 (2 op-amps inside a single IC); or TLV2474 (4 op-amps inside a single IC).

AD623 instrumentation amp: see data sheet (linked (linked here)). Pinout is illustrated on page 10 under "Pin Configuration and Function Descriptions." Amplifier voltage gain formula for is listed on page 23 under "Theory of Operation". Welcome to the wonderful world of finding one useful tidbit swimming in an ocean of too much information!

When perusing the datasheets, keep in mind we're using *single supply* power for this build. This means we use +5V and ground, or more generally  $+V_{dd}$  and ground. This is in called contrast to a dual supply which offers  $+V_{dd}$ ,  $-V_{dd}$ , and ground (e.g. +5V, -5V, and ground). This necessitates we center an oscillating signal around the mid-point of our working range aka  $V_{dd}/2$ . Assuming we use the Arduino +5V and GND, this is 2.5V. The op-amp buffer is used to create a  $V_{dd}/2$  reference often referred to as a rail-splitter. Its output serves as the reference offset voltage for the active BPF and AD623.

## Road Map: Building Circuit Systems

No matter which application you choose, your final circuit will look something like the one shown in Figure 5.

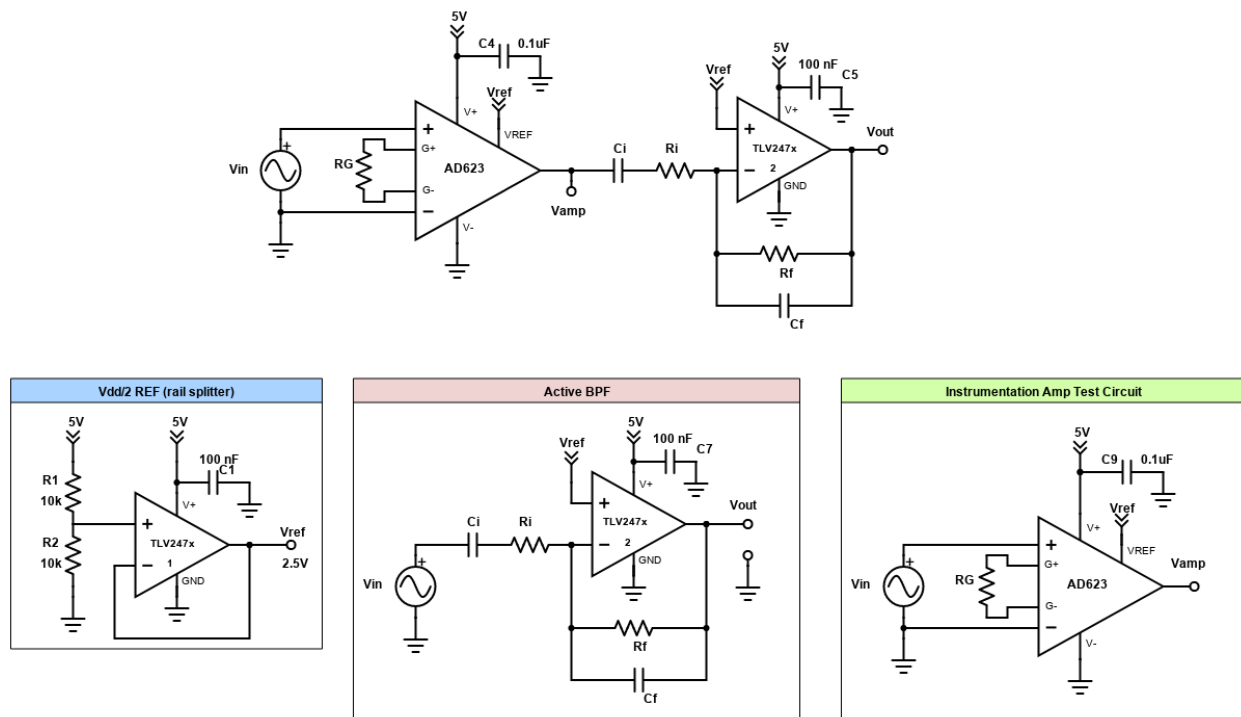


Figure 5: Top: The full Monty, showing the instrumentation amplifier output coupled to the input of the active band-pass filter. Bottom: individual building blocks: Rail splitter, Active BPF, Instrumentation Amplifier

When building bigger, more complex circuits system is crucially important to **Break It Down into Bite-sized Chunks**. This means we need to build and verify each individual block works, one at a time. Only once all individual blocks are confirmed to work properly is it time to connect them one-by-one, testing and verifying each linkage still results in a properly functioning circuit. Eventually, this builds up to the full system. Be patient and work methodically. Swinging for the fences—connecting everything in one fell swoop—often leads to a batting average of 0.000. Below is a suggested road-map to this effect.

1. Build the  $V_{dd}/2$  reference with buffer. Verify that the output is  $\approx V_{dd}/2$ .
2. Design and wire the inverting active BPF. Two considerations here: 1) What are your cutoff frequencies (pass band)? What amplification do you want to set with the ratio  $R_f/R_i$ ? The latter isn't super important because you also have the AD623 to work with and its sole job is to amplify.
3. Measure input-output relationship of the active BPF using the oscilloscope. Verify the amplifier actually amplifies with the expected ratio  $-R_f/R_i$ ; then do a quick sweep to verify the cutoff

frequencies are where you expect them to be. Also, verify the voltage gain in the pass band is what you expect it to be.

4. Wire and do basic test with AD623 instrumentation amp. To generate a suitable amplitude input test wave, you may need to divide down the smallest amplitude wave AWG can generate. Connect one input of the AD623 to the AWG's output; connect the other input to ground. Carefully measure the output. Do you see the signal being amplified as expected. You may want to engage ac mode so that you see only the time varying content. Or you may want to use dc mode which shows you the constant offset + any time-varying wiggles. Leave this as a free-standing block for now—do not connect it to the input of the active BPF just yet. Speaking of....
5. Time to integrate! Connect the instrumentation amp and active BPF. Do another quick test to make sure the total voltage gain (instr. amp  $\times$  active BPF) is what you expect; do a quick sweep through frequency to verify the cutoffs are still ok. If so, time to take data to quantify and plot decibel gain  $G(f)$  vs.  $\log_{10} f$ .
6. Time for the big show! AWG is outta here. Time to connect the actual sensors into the system. If you are you doing the building vibrations problem, you will use a 4-strain gauge Wheatstone bridge and flick a cantilever beam to generate the signal. If you are doing the EMG, your very own arm electrically connected via soft pre-gelled electrodes will serve as the signal source. For proof-of-concept you should make simultaneous measurements of the input (signal source)-output (circuit system voltage) relationship, with emphasis on the latter. Is the final voltage signal you measure useable?! You can measure using either picoscope or Arduino. The latter is kinda cool and very applicable thinking ahead of final projects.

# Final Report—What To Turn In

Each student must submit their own decibel gain vs frequency plot generated in MATLAB. Of course, you may collaborate but at the end of the day, the code and plot needs to be 'owned' by each individual student. The rationale is that this everyone should master this fundamental, transferable, an valuable lab skill.

For the remainder of the report, you may work with your lab partner. You may choose to do a written report (4 pages max!) OR a video lab report (5 minutes max!). For either medium, present the following core elements, which should look and feel familiar.

1. **Final circuit diagram.** Lay out the system in glorious detail such that any interested party could replicate it.
2. **Design rationale.** Inform the reader how the system works in general and specific terms. What does each functional block do? (The metaphorical forest). Why did you choose certain component values (the trees).

Stage [B] is an active band pass filter. We set the gain to 20x because ..., and we set the band pass range to x to y Hz because ... We know the BPF amplification is set using the formula .....thus we chose chose Rf and Ri values of xyz ”

3. **Circuit behavior: magnitude response.** Make a beautiful graphic that compares theory vs. experiment. Be sure to sweep out a sufficiently large frequency range so you can establish the gain in the passband, the cutoff frequencies, and the roll-off of your filter. The final plot MUST BE DONE IN MATLAB. Concisely compare and contrast actual circuit behavior vs. what was drawn up on paper. Be quantitative!
4. **Proof of concept.** Preferably post a video of your circuit in action. Alternately, show a series of figures. Either way, this section should establish that your design allows you to clearly measure a signal directly related to the strength of muscle contraction.
5. **Conclusions and Future work.** What was the net result—did the circuit behave as expected and do the job it needed to? What might you change in the future to improve functionality?
6. **Appendix:** Include any derivations, theoretical considerations that expand upon the core you wanted to communicate in the main text. Arduino Code goes here too.